Framework and tool for rapid assessment of stream susceptibility to hydromodification

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Abstract

Changes in streamflow and sediment loading associated with urban development have the potential to exacerbate channel erosion, and result in impacts to wetland, riparian, and stream habitats, as well as infrastructure and property losses. The typical "one-size-fits-all" management prescription of flow control with retention or detention basins has not been wholly effective, pointing to a need for improved management strategies and tools for addressing 'hydromodification.' We present an approach for developing screening-level tools for assessing channel susceptibility to hydromodification, and describe a novel tool for rapid, field-based assessments of the relative susceptibility of stream segments. The tool is based on the results of extensive field surveys which indicate that susceptibility is the driver of channel response, not the magnitude of urbanization. A combination of relatively simple, but quantitative, field indicators are used as input parameters for a set of decision trees that follow a logical progression in assigning categorical susceptibility ratings to the channel segment being assessed. The susceptibility rating informs the level of data collection, modeling, and ultimate mitigation efforts that can be expected for a particular stream segment type. The screening approach represents a critical first step toward tailoring hydromodification management strategies and mitigation measures to different stream types and geomorphic settings.

Introduction

Urban streams have the potential to provide valuable amenities to people who live near them, but most are still managed in a piecemeal and reactive manner. Although it is well known that the increased surface runoff associated with watershed urbanization intensifies the potential for stream erosion and degradation (Hammer 1972, Booth 1990), many stormwater policies are not protective of geomorphic stability (Roesner *et al*. 2001). Moreover, stream channel responses to urbanization are difficult to predict and vary markedly among geomorphic settings. When faced with the diverse and complex responses of streams in urbanizing watersheds, stormwater and floodplain managers often find themselves in a costly yet ineffective cycle of treating the many symptoms of stream degradation with makeshift solutions (e.g., detention basins) that are based on neither geomorphology nor strategic planning for the streams within their watershed context (Booth and Bledsoe 2009).

As early as 1973, the United States Environmental Protection Agency (USEPA) recognized that alteration of flow and sediment patterns can result in degradation of water bodies and their associated beneficial uses, and ultimately termed this effect "hydromodification" (USEPA 1973, 2007). In recognition of the need to manage the effects of hydromodification, many states have begun to regulate these effects through their nonpoint source pollution control programs, Section 401 Water

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Unfortunately, contemporary management practices have done little to mitigate the effects of hydromodification. Rapid urbanization, legacy effects from past land uses, and lags in channel response create many challenges for the regulatory and management community in addressing proximate and cumulative effects of hydromodification. Most existing stormwater control facilities were designed for flood control (and in some cases water quality). Consequently, they have little effect on promoting geomorphic stability of the streams to which they discharge. Even when designed for water-quality purposes, many management schemes currently use a one-size-fits-all approach to managing hydromodification effects, whereby a single criterion is applied to all streams within a given area. The effectiveness of such generic approaches are mixed at best because factors such as dominant bed material, grade control, channel planform, proximity to geomorphic thresholds, and antecedent responses interact to influence the rate and manner in which streams respond to changes in flow and sediment. Consideration of these factors in management programs requires process-based tools to assess stream reaches in terms of their relative susceptibility to hydromodification effects.

Here, we present the development and testing of a next-generation hydromodification assessment tool. The tool assesses susceptibility of a stream reach to the effects of hydromodification using well-established concepts of fluvial geomorphology and river mechanics to establish rating categories based on regionally-calibrated models that account for specific boundary conditions in both the channel bed and bank. The tool is empirically derived and thus can be applied across a range of conditions and channel types for which calibration data are available or applicable. The overall approach used to develop and calibrate the tool is widely transferable to other physiographic regions and hydromodification management jurisdictions.

An underlying premise of this assessment tool is that streams differ in their resistance to the effects of urbanization such that management activities aimed at mitigating the effects of hydromodification will be most effective when tailored to different stream types. For example, a channel that naturally contains extensive bedrock control or very resistant boundary materials will be less physically susceptible to urbanization than an alluvial stream in readily erodible material.

Stakeholder input invariably plays an important role in the development of hydromodification tools; therefore, we describe both the technical aspects of the tool and a general process of stakeholder coordination within the broader context of hydromodification management. Because the tool is intended to be used to support a range of regulatory, planning, and management decisions, it was tailored to local stakeholder needs and designed with their input. This should ensure that it will have clear benefits to local jurisdictions in their mandate to protect water quality from the effects of hydromodification.

Background

Factors affecting the intrinsic sensitivity of a channel system to hydromodification include the ratio of disturbing to resisting forces, proximity to thresholds of concern, rates of response and recovery, and potential for spatial propagation of impacts. Developing tools for predicting the relative severity of morphologic and physical-habitat changes that may occur due to hydromodification is challenging for several reasons. These challenges include thresholds and non-linearities, lagged responses, historical legacies, a large number of interrelated variables that can simultaneously respond to perturbations, and the continual evolution of fluvial forms and response with changing water and sediment discharges (Schumm 1991, Trimble 1997, Richards and Lane 1997). Whether a channel incises or widens in response to land-use change depends on local variations in boundary resistance, as shown in contrasts between channels in cemented till and weakly-consolidated outwash in the Pacific Northwest (Booth 1990; King County 1991, 1997, 1998a,b), and in contrasts of bedrock vs. alluvial channels in north Texas (Allen *et al*. 2002). Riparian vegetation may also influence channel adjustment and migration (Thorne 1990, Dunaway *et al*. 1994, Friedman *et al*. 1998).

Despite the foregoing difficulties, the need for practical tools in stream management have prompted many efforts to develop qualitative or semi-quantitative methods for understanding the potential response trajectories of channels based on their current state. Most of these methods are based on relatively straightforward observational or empirically-derived measures that aggregate processes over space and time. For example, attempts to predict channel planform based on changes in discharge and slope date back to early work by Lane (1957) and Leopold and Wolman (1957). This work was later expanded to account for the influence of boundary materials (Carson, 1984; Ferguson, 1987; van den Berg, 1995) on pattern thresholds and the potential for planform shifts. Montgomery and MacDonald (2002) presented a qualitative diagnostic framework that "*assesses reach-level channel conditions as a function of location in the channel network, regional and local biogeomorphic context, controlling influences such as sediment supply and transport capacity, riparian vegetation, the supply of in-channel flow obstructions, and disturbance history*." The diagnostic framework includes a qualitative assessment of the relative susceptibility of widely recognized channel types to increases in the frequency and magnitude of flows, as well as chronic increases in coarse- vs. fine-sediment supplies. However, this entirely qualitative approach has limited applicability in hydromodification management because decision-makers need tools for assessing susceptibility both among and within broad classes of urban channels based on site-specific processes and boundary conditions.

Channel Evolution Models (CEMs) provide an attractive framework for understanding channel response and instability across diverse geomorphic settings. The well-known incised channel CEM of Schumm *et al.* (1984) documents a sequence of five stages of adjustment and ultimate return to quasi-equilibrium that has been observed and validated in many regions and stream types (American Society of Civil Engineers (ASCE) 1998, Simon and Rinaldi 2000). Process-based CEMs provide a framework for understanding response trajectories and developing strategies for mitigating the impacts of processes likely to dominate channel response in the future (Simon 1995). The original incised channel CEM has been subsequently modified and expanded upon by many researchers (e.g., Simon 1989, ASCE 1998, Bledsoe *et al*. 2002, Watson *et al*. 2002).

More recent tools for assessing channel instability and response potential, especially in the context of managing bridge crossings and other infrastructure, have included elements of incised channel CEMs and various descriptors of boundary conditions, and resisting vs. erosive forces. Simon and Downs (1995) and Johnson *et al*. (1999) developed rapid assessment techniques for alluvial channels based on diverse combinations of metrics describing bed material, CEM stage, existing bank erosion, vegetative resistance, and other controls on channel response. Although based on a strong conceptual foundation of the underlying mechanisms controlling channel form, these previous methods are either too qualitative or developed with goals and intended applications (e.g., evaluating potential impacts to existing infrastructure such as bridges) that differ from what is needed by many current hydromodification management programs, especially in semi-arid climates. In addition, the assessment ratings provided by these tools are based on aggregated scores that can mask which factors are ultimately driving the final ratings into various categories defined *a priori* using best professional judgment. In many contexts, Clean Water Act permits and local land-use standards are requiring managers to explicitly consider and regulate hydromodification effects. Evaluation tools must, therefore, be rigorous, regionally-calibrated, and defensible; and the procedures used to develop ratings must be transparent, repeatable, and transferable to a variety of geomorphic contexts and urban stream types.

Methods

In this study, we define southern California as the ca. 30,000 km^2 coastal area that is geologically bound by mountain ranges to the north (Transverse Ranges) and east (Peninsular Ranges). Our development of the hydromodification susceptibility assessment tool for southern California was guided by a Technical Advisory Committee (TAC) composed of regional stakeholders including managers, policymakers, and technical experts. TAC input was provided at several critical junctures throughout the entire process from conceptual development and initial metric/indicator selection through iterative field testing of the penultimate versions of field forms, and played a central role in shaping the assessment tool presented herein (Figure 1). Failure to meet the needs of end users would have been considered a failure to meet the most important project objective.

At the outset of this process, the TAC and project team converged on several guiding principles. First, susceptibility should be assessed by combining field reconnaissance with desktop Geographical Information System (GIS) based analysis. The TAC also recommended a transparent and process-based flow of logic. Accordingly, the project team identified decision trees as a logical structure for the tool. The TAC further recommended that the assessment tool be risk-based and calibrated with regional

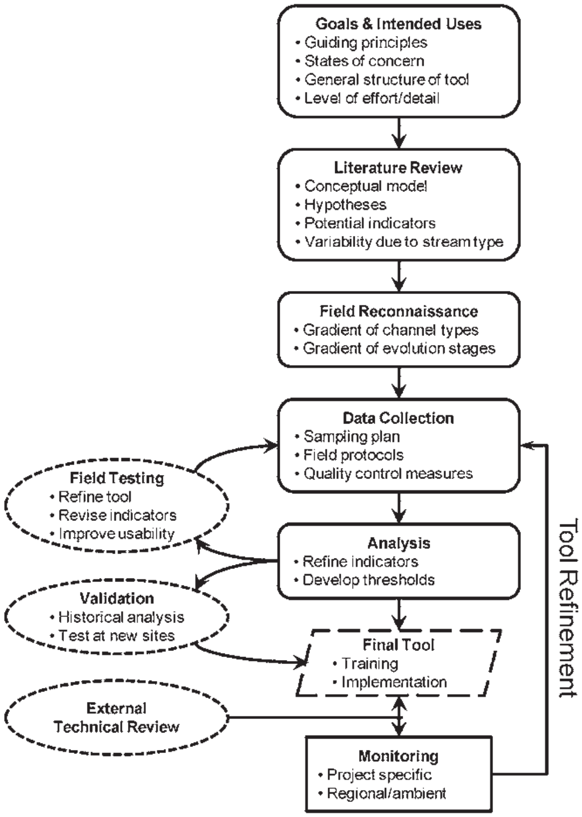


Figure 1. Flowchart of overall process of developing a tool for assessing channel susceptibility to hydromodification. Note that stakeholder input occurs at each step in the process.

data; that is, it would ideally provide a probabilistic framework for assessing the likelihood of accelerating channel adjustment processes and crossing geomorphic thresholds (*sensu*; Schumm 1979, 1980, 1991; Osman and Thorne 1988; Booth 1990; van den Berg 1995; Bledsoe and Watson 2001a) that is based on observations of streams in southern California.

Despite the immense regional complexity in geomorphic settings and legacy effects, the TAC also strongly desired a parsimonious tool that avoids any unnecessary complexity. The tool should provide scientifically-defensible susceptibility ratings that are attained for a particular stream segment in less than a day through the fewest procedures possible. For example, the tool should be streamlined by including early 'off ramps' for situations in which stream susceptibility can be immediately ascertained, such as fully-engineered channels in good condition (Low) and incising sand channel near critical bank height (Very High). In striving for a parsimonious tool, the project team considered an extensive set of candidate geomorphic metrics at several spatial scales as described below. Finally, the TAC and project team restricted the geomorphic settings to which the tool would be applicable by excluding alluvial fans and estuarine confluences.

Site Selection

Study sites representing the major regional channel types (e.g., sand bed, gravel, bedrock controlled) and ranging from minimally disturbed to highly altered by hydromodification were used as the basis for tool development, calibration, and validation. In addition, we identified "reference" sites that existed in undeveloped areas and did not exhibit evidence of hydromodification effects. While most channels of southern California are inherently dynamic, we define 'stable' for the purposes of this tool following Biedenharn *et al.* (1997): "*a stable river, from a geomorphic perspective, is one that has adjusted its width, depth, and slope such that there is no significant aggradation or degradation of the stream bed or significant planform changes (meandering to braided, etc.) within the engineering time frame (generally less than about 50 years)*." Sites were selected based on review of surrounding land cover (based on the National Land Cover Database and local land-use maps), roads, and major agricultural or grazing areas, and TAC and stakeholder input. Based on the initial sites selection process, the project team identified a preliminary set of 52 regional streams with diverse boundary characteristics, planforms, and channel states ranging from 'stable' single-thread to incising, widening, and braiding (*sensu*; Schumm *et al*. 1984, Downs 1995). The set of preliminary sites also spanned a variety of geologic, topographic, and hydroclimatic settings within the study region.

We performed field reconnaissance at the 52 candidate locations and assessed the following factors:

- percent watershed imperviousness and urban land cover, as well as estimated age of sub/urban land uses;
- accessible length;
- dominant bed and bank materials;
- channel evolution stage;
- planform pattern(s);
- location and extent of armoring, grade control, and encroachment; and
- proximity to tributary confluence that would facilitate a survey spanning variability in water and sediment supply.

The candidate locations were reduced to 31 streams with 83 geomorphically-distinct sub-reaches or 'sites' (Figure 2) based on further communication with regional stormwater managers to ensure a wide distribution of accessible sites across regionally-important gradients in slope, bed material, channel type/planform, evolution stage, valley setting, drainage-basin size, geopolitical setting, and extent of urbanization. The general watershed and stream characteristics of the 83 sub-reaches used in assessment tool development are summarized in Table 1. A comprehensive list of watershed and channel characteristics of the study sites is provided by Bledsoe *et al*. (2010a).

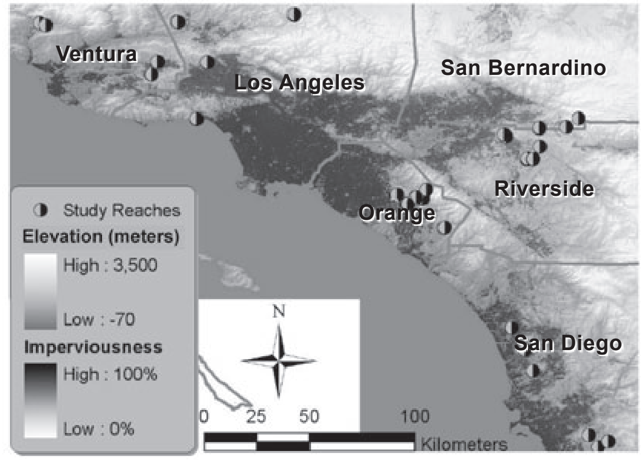


Figure 2. Overview of reaches sampled for assessment tool development.

Field and GIS Data Collection

Bed material, cross-sectional and longitudinal channel geometry, valley setting, and watershed data were collected using standard methods (e.g., Thorne (1998) and Harrelson *et al*. 1994) at each site. Cross-sectional, longitudinal, and other topographic surveys were performed with total stations and levels. Representative cross sections were identified within a study reach away from major fluvial influences such as bends and constrictions. Bed-material gradations were determined with a minimum of 100-particle pebble counts using a half-phi template and/or sieve samples after Bunte and Abt (2001). For sites greater than roughly 20% sand by volume, both sieving and phi-sampling were employed. All grade breaks along the channel thalweg were measured including heads and toes of riffles, knickpoints, and other bedform features.

Landscape- and catchment-scale GIS data were acquired from public-domain sources such as the U.S. Geological Survey (USGS), U.S. Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), and State of California geospatial clearinghouse (CAL-Atlas). Historical and present-day aerial photography from the USGS and Google Earth were used to track changes through time, along with historical USGS quadrangle topographic maps. ArcGIS 9.3 software by Environmental Systems Research Institute (ESRI), including extensions such as 'spatial analyst,' was used to optimize GIS measurements. For tasks such as delineating watersheds and determining flow paths, automated results from processing the National Elevation Dataset (NED; http://ned.usgs.gov/) were verified with aerial photography and field investigations. They were also cross checked with existing shapefiles such as USGS Hydrologic Unit Code (HUC) boundaries and National Hydrography Dataset (NHD) flowlines. All data layers were

Table 1. Summary of key gradients across 83 geomorphically-distinct sub-reaches used in assessment tool development.

Metric Type	Key Gradient	Minimum – Maximum	Mean	Units
Watershed	drainage area	0.1 – 160	17	km^2
	imperviousness	0 – 26	3.6	%
	average annual rainfall	230 – 740	430	mm
	drainage density	0.2 – 3.7	1.3	km/km^2
	average surface slope	0.05 – 0.52	26	
Sub-reach	channel slope	0.002 – 0.15	2.6	
	top width at 2-yr flow	0.2 – 62	11	m
	median grain size	0.125 – 500	26	mm

subjected to independent quality assurance/quality control of watershed boundaries and any discrepancies were remedied.

Hydrology and Hydraulics

To calculate various hydraulic and geomorphic stability metrics, 2-year and 10-year peak flow magnitudes were estimated using models developed specifically for the small watersheds (1.4 to 270 km^2) within the study domain and which incorporate the effects of urbanization (Hawley and Bledsoe 2011):

$$Q_2 = 0.53\, A^{0.67}\, P^{1.29}\, e^{(8.61*Imp)} \qquad \text{Eq. 1}$$

$$Q_{10} = 18.2\, A^{0.87}\, P^{0.77} \qquad \text{Eq. 2}$$

where Q_i is the instantaneous peak flow rate of return interval *i* years (ft^3/s), *A* is the total contributing drainage area (mi^2), *P* is the mean annual area-averaged precipitation via USGS-delineated shapefile using rainfall records from 1900 to 1960 (in.), $e^{()}$ is the mathematical constant *e* (i.e., 2.718…) raised to the power of the parenthetic expression, and *Imp* is the total impervious area using the USGS national impervious raster (2001) and/or more recent coverage, measured as a fraction of the total drainage area (mi^2/mi^2).

Hydraulic calculations were simplified by developing at-a-station hydraulic geometry relationships for each site (Knighton 1998). Normal depth for respective flows was iteratively solved via Manning's equation with field-estimated resistance values and at-a-station hydraulic geometry relationships derived from cross-section surveys at each site.

Selection of Metrics

A variety of potential metrics were considered for inclusion in the susceptibility tool. Initial sets of metrics and schemes for assigning relative weights were identified through a review of previously-published tools for assessing channel stability (Bledsoe *et al*. 2008, Simon and Downs 1995, Johnson *et al*. 1999; Table 2). The goal was to identify metrics that would be indicative of channel adjustment in either the vertical or lateral dimension. Emphasis was placed on metrics that could be rapidly assessed in the field and have a clear and direct physical linkage with channel response. The original pool of metrics considered for inclusion in the susceptibility tool were reduced by grouping the variables by the processes that they represent in either the vertical or lateral dimension (e.g., erosive power vs. boundary resistance vs. proximity to threshold) and ranking the various descriptors in terms of their fidelity to the key physical processes, and their ease of measurement / data requirements. Metrics that required hydrologic modeling and/or time-intensive surveys of channel geometry were excluded based on the practical constraints identified by the TAC. Selection of metrics was ultimately based on a perceived tradeoff between the level of effort required to quantify or measure a particular metric and the degree to which it enhances the physical basis and prediction accuracy of the tool as suggested by statistical analyses of the field dataset.

The susceptibility tool was developed by assessing the degree to which candidate indicators effectively provide interpretable surrogates for the complex physical processes and boundary conditions that affect channel forms and responses. Candidate descriptors of watershed, geomorphic, hydraulic, and sedimentary characteristics were computed for each site and tested for their ability to segregate data into various stability groupings that were consistent with theory. The predictive utility of various metrics was assessed with multivariate regression analysis using best subset, forward, and backward elimination, as well as logistic regression analysis (Menard 1995). Both general linear and power models were examined, with power models proving more robust. The best subsets of multiple-regression models were sorted by their adjusted R^2 values and subjected to meeting parameter and overall model significance (α= 0.10). Metrics were also examined for consistent patterns of inclusion and influence direction in selecting the most significant and interpretable models. Logarithmic transformations were applied, which provided good adherence to the regression assumptions of linearity, homoscedasticity, and independent and normally-distributed residuals. Statistical analyses were performed using SAS 9.2 (2008, SAS Institute, Inc., Cary, North Carolina, USA).

Logistic regression was especially useful in analyzing binomial distributions (e.g., stable vs. unstable) because rather than predicting the individual variable (i.e., 0 or 1) the probability of the response is modeled over a continuous range of 0 to 1 (Christensen 1997, Ott and Longnecker 2001). Such a continuous probabilistic framework has clear

Table 2. Partial list of variables utilized in previously-published tools for assessing channel susceptibility.

Simon and Downs (1995)	Variable[a]	RW[b]	Johnson *et al.* (1999)	Variable[a]	RW[b]
Degree of incision	V, L	3	Shear stress ratio	V	3
Simon six stage CEM for incised channels	V, L	3	Bed material consolidation and armoring	V	2.4
Primary bed material	V	3	Vegetative bank protection	L	2.4
Degree of constriction	C	3	Mass wasting or bank failure	L	2.4
Bed/bank protection	V, L	2	High flow angle of approach to bridge	B	2.4
Streambank erosion – mass wasting vs. fluvial	L	1	Distance from meander impact point	B	2.4
Streambank instability – % banks failing	L	1	Percentage of channel constriction	B	2.4
Woody vegetation cover – “riparian”	L	1	Bank soil texture and coherence	L	1.8
Bank accretion	L	1	Average bank slope angle	L	1.8
Hillslope material	C	1	Bar development	L	1.8
% Hillslope eroding	C	1	Bank cutting	L	1.2
Severity of side slope erosion	C	1	Debris jam potential	B	0.6
			Obstructions, flow deflectors, and sediment traps	B	0.6

[a] V and L indicate variables that describe susceptibility to vertical and lateral adjustments, respectively. C and B denote variables focused on the valley context and bridge crossings, respectively.

[b] Values in the relative weight (RW) column were assigned by the respective authors using expert judgment and indicate which variables have the most influence on the overall susceptibility score on a scale of 1 to 3.

benefits for application in an assessment tool concerned with categorical states. Using logistic regression allows identification of response thresholds, and the *proximity* to such thresholds can be directly assessed as the risk of channel response. The logistic regression function that models the probability of a response (p) as a function of independent variables (x_i) is expressed by the following equation:

$$p = \frac{\exp\left(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n\right)}{1 + \exp\left(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n\right)} \qquad \text{Eq. 3}$$

The resulting S-shaped function represents a probability of response that increases exponentially when x_i is small, and slowly approaches the limit of 1 as x_i becomes large.

The significance of individual metrics in differentiating among sites was assessed using their significance in the statistical models along with standard errors, confidence intervals, and X^2 statistics. Potential effects of collinearity were addressed by keeping the number of independent variables to a minimum. Logistic regression diagnostics were used to assess homoscedasticity, and identify and assess the influence of outliers as a complement to overall-performance assessment. Model performance was assessed via the X^2 statistic that compares the likelihood for the fitted model (L_1) to that of the null model (L_0), in which all β-parameters are zero. The X^2 statistic was computed using three variations of the chi-squared distribution including the Likelihood Ratio (chi-squared), Score (asymptotic chi-squared), and Wald (approximate chi-squared). Associated p-values indicate the level of significance of the fitted model relative to the null hypothesis. The percentage of observations correctly classified also served as a meaningful measure of overall model performance. Once a model was parameterized, we populated matrices of standard ranges of the respective independent variables within the bounds of our dataset for 10, 50, and 90% probabilities of response through algebraic transformation of Equation 3.

Tool Development

From the outset of the project, we hypothesized that incision and braiding in unconfined valleys would tend to occur in settings that are inherently higher in hydraulic energy relative to the erodibility of the channel boundary materials. In identifying a reduced set of metrics for inclusion in the tool, we tested an extensive set of candidate statistical models of unstable vs. stable single-thread, unconfined channels using many types of variables including several measures of erosive energy at 2- to 10-year peak discharges relative to boundary materials, valley setting, and bank characteristics. The following paragraphs focus on describing key predictors of vertical and lateral responses and the rationale for their inclusion. Perhaps more than any other single parameter, specific stream power (ω) has been suggested as a comprehensive descriptor of hydraulic conditions and sedimentation processes in stream channels (Bagnold 1966; Schumm and Khan 1972; Bull 1979; Edgar 1973, 1976; Nanson and Croke 1992; Brookes 1988; Rhoads 1995). We tested ω based on actual surveyed channel slopes and cross-section geometry along with a variety of other descriptors including shear stress, dimensionless shear stress (referenced to d_{50} and d_{84} of the bed material), and total stream power that have been used to isolate higher-energy unstable systems from lower-energy stable systems in unconfined settings (Brookes 1988, Chang 1988, Nanson and Croke 1992, Rhoads 1995, Vocal Ferencevic and Ashmore 2011). However, dependence on accurate estimates of channel slope, depth, and/or width made these descriptors impractical for a screening-level assessment that could be performed with the targeted level of effort.

A more pragmatic index was a surrogate for specific stream power following van den Berg (1995), which uses valley slope in place of channel slope as a representation of the potential energy of the valley setting. Valley slope has been demonstrated as a geomorphically-significant parameter by numerous researchers, especially in semi-arid environments (Patton and Schumm, 1975, Schumm *et al*. 1980). It represents an inherent boundary condition over longer temporal scales than channel slope, which is more readily adjustable.

By substituting the standard regime form of channel width, *potential* specific stream power is defined after van den Berg (1995) as:

$$\omega \approx \gamma / a \, S_v \, Q^{0.5} \qquad \text{Eq. 4}$$

where total stream power (γQS) per width is estimated as a function of valley slope (S_v), dominant discharge (Q), and an assumed regime width that varies between sand- and gravel-bed rivers, i.e., width = $aQ^{0.5}$; γ is the specific weight of the water and sediment mixture (assumed 9810 N/m^3); and a is a regression coefficient computed for a particular collection of streams.

Bledsoe and Watson (2001a) further simplified the approach by dropping the coefficients γ and a, to eliminate dependence on variable regime constants across regional settings. Because hydraulic modeling of our study sites indicated that the 10-year flow coincides with the channel-filling better than the 2-year flow (Hawley 2009), their 'power index' (ω_v) is adapted in this study as:

$$\omega_v = S_v \, Q_{10}^{\ 0.5} \qquad \text{Eq. 5}$$

Only fully-adjustable, unconfined, alluvial study sites were used to develop logistic models for braiding and incision risk. Several methods of classifying and stratifying data were examined in the context of the statistical models. From the early stages of the field reconnaissance, the project team recognized important differences in the susceptibility of armored vs. unarmored channels. Accordingly, many of the statistical models that were developed and tested were based on various ways of stratifying the data to reflect differences in bed-material caliber and armoring potential. Moreover, some of the braided channels observed in the field appeared to have achieved some semblance of quasi-equilibrium owing to relatively low levels of specific stream power. Thus, the statistical analyses aimed at discriminating between stable and unstable channel segments required consideration and screening of stable vs. unstable braiding forms. Despite the wide range of options for defining stable vs. unstable channel forms, all models pointed to a tendency for higher specific stream power and shear stress relative to bed-material size to be associated with a greater likelihood of geomorphic instability in unarmored and unconfined valley settings.

To examine susceptibility to lateral adjustments other than braiding, bank data were used to develop regional logistic thresholds for mass wasting. Heights and angles were compiled for each bank that was not artificially reinforced. Non-planar banks were measured in four ways to test various schemes for representing non-planar geometries. Heights and angles most representative for purposes of mass wasting based on failure theory presented by Osman and Thorne (1988) were used in the analyses. Stability of each bank was rated by assessing the extent of mass wasting (absent, broken, complete, and failed), fluvial bank erosion (significant and insignificant), consolidation (moderate/well, poor, and unconsolidated), confinement (hillslope, boulder/bedrock, and unconfined), dominant bank vegetation (extent and type), and artificial reinforcement (embanked, fill, graded, riprap, and none). With the objective of representing the risk of mass-wasting failure, these ratings systematically informed the overall stability rating of stable/unstable geometries.

Heights of moderately- to well-consolidated banks in unconfined channels (i.e., those banks that were not simply connected to the adjacent hillslope) were plotted vs. angle, in which the stratification of stable and unstable banks clearly followed a log-log decay. The shape was analogous to the theoretical Culmann relationship of critical bank height for slab failure via the geotechnical mechanism of mass wasting:

$$H_c = \frac{4c' \sin\alpha \cos\phi'}{\gamma\left(1-\cos\left(\alpha-\phi'\right)\right)} \quad \text{Eq. 6}$$

where H_c is the critical bank height required to generate instability with respect to slab failure via mass wasting, c' is the effective cohesion of bank material (kPa), α is the bank angle (°), ϕ' is the effective friction angle of the bank material (°), and γ is the unit weight of the soil (kN/m^3).

The presence of tension cracks, which can account for up to half of the total height (Terzaghi, 1943, Thorne 1982), can be incorporated via the following relations:

$$H_{cz} = H_c - z \quad \text{Eq. 7}$$

$$z = \frac{2c'}{\gamma}\tan\left(45+\frac{\phi'}{2}\right) \quad \text{Eq. 8}$$

where H_{cz} is the critical bank height required for mass-wasting failure with a tension crack (m) and z is the tension-crack depth (m).

By back-solving for the 50% logistic risk using the Culmann equation adjusted for the presence of tension cracks, regional stress parameters for mass wasting could be estimated. Specific weight was bounded by USDA soil-survey values of 1.50 to 1.81 g/cm^3 (i.e., 14.7 to 17.8 kN/m^3 or 93.6 to 113 lb/ft^3). The friction angle was constrained between 12 and 28° leaving cohesion free to fluctuate 0 to 40 kPa (~800 lb/ft^2) after measured/typical ranges from other regions (Lawler *et al*. 1997, Simon *et al*. 2000). As the presence of pore-water pressure is unknown and the values were not directly measured but fitted within the constraints of measured data, they would be more appropriately termed *operational* stress parameters (Colin Thorne, 2009, Pers. Comm.).

To assess relative severity of potential lateral adjustments, it was necessary to develop a valley width index (VWI) to provide a rapid measure of the relative extent of valley bottom width that is available for erosion by a laterally enlarging or migrating channel. In defining the VWI, we used a 'reference width' to avoid dependence on 'bankfull' width, which can be particularly difficult to identify in semiarid channels. It also avoids taking additional field measurements, thereby saving time. We used the 10-year peak flow relation (Equation 5) to quantify the reference width in the VWI:

$$\text{VWI} = W_v / W_{ref} \quad \text{Eq. 9}$$

where W_v is measured between hillslope grade breaks at the valley floor and W_{ref} is approximated by a regional relationship for top width stable, single-thread unconfined sites at Q_{10}.

Tool Validation

The assessment tool was initially tested on the 83 sub-reaches that were used in its development. These tests confirmed both its congruence with stakeholder goals and its consistency in generating susceptibility ratings that reflect expert judgment. We subsequently conducted initial tests of the tool in its present form by comparing ratings to relative magnitudes of channel adjustment that were estimated using historical analysis at a diverse subset of sites. We estimated the extent of channel enlargement in response to (and independent of) hydromodification at the selected study sites, and whether the scales of adjustment corresponded with susceptibility ratings. This is admittedly circular but nevertheless provides an illustration of method application and an informative initial test of the tool.

Finally, we revisited monumented cross sections at six sites in spring 2011 (four years after the initial cross sections were measured) following the rainy winter of 2010-2011, to determine if channels responded as predicted by the screening tool. The reoccupied sites were selected based on a gradient of screening ratings and risk types in the vertical and lateral dimensions (e.g., braided vs. single thread, gravel/cobble vs. fine-grained, Very High risk vs. Low risk). Annual rainfall in 2011 was approximately 50% higher than the long-term average; however, December through February rainfall was approximately three times the long-term average. We both re-measured cross sections originally surveyed in 2007 and reoccupied photo points from that same period. The magnitude and direction of change (i.e., vertical vs. lateral) was compared to the initial ratings to evaluate the qualitative success of the susceptibility tool's predictions. For the purposes of this comparison, 'enlargement' was defined as the ratio of the post-urbanization cross-sectional area of a channel (opposed to flow) to its former size prior to substantial urban development. Enlargement is computed as:

$$\Delta A\% = (A_{post} - A_{pre}) / A_{pre} \qquad \text{Eq. 10}$$

where $\Delta A\%$ is the relative channel enlargement between the current area occupied by the channel (A_{post}) and the historic or pre-developed channel (A_{pre}), and cross-sectional area as measured from the top of bank (as opposed to a depth at a specific return interval).

Results

Selection of Metrics

Statistical analyses of the field data indicated that susceptibility to vertical and lateral instabilities can be assessed based on a few physically-intuitive metrics that represent the primary controls on channel response to hydromodification. In assessing the utility of various statistical models, we initially examined separate models for quantifying the risk of vertical (incision) and lateral (braiding) responses using the power index, dimensionless shear stress, and various descriptors of stream power; however, these models returned very similar thresholds which were ultimately combined into one 'stability' threshold for reasons of both parsimony and improved statistical power. Of the statistical models tested, 102 were significant at $p < 0.05$, and relatively simple surrogates for flow energy such as the power index performed comparably to more detailed variables such as dimensionless shear stress and specific stream power that require detailed channel surveys. Therefore, the variable and model selection process was focused on these less data-intensive descriptors which discriminated between states of incising, braiding, and mass wasting relatively well with model significance ranging from $p \sim 0.001$ to $p < 0.0001$ (Table 3). Watershed imperviousness was not a significant predictor of channel enlargement or condition.

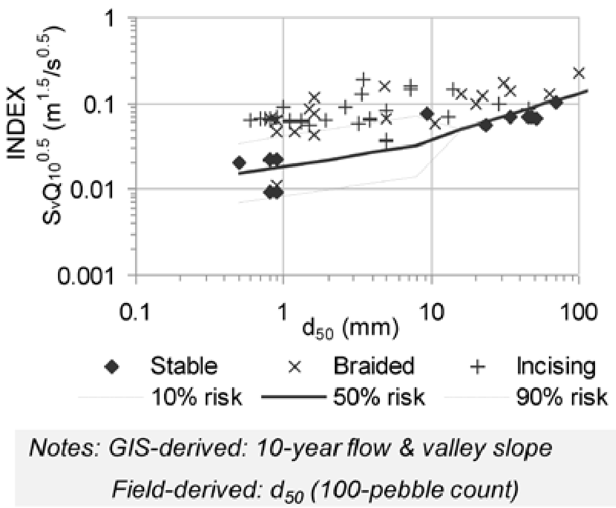
In general, modeling results indicated that two suites of metrics provided robust discrimination between stable and unstable channel forms: 1) the power index, bed-material composition and associated armoring potential, degree of incision (CEM stage), and proximity to a downstream hardpoint; and 2) a bank stability threshold based on bank height and

Table 3. Performance measures of selected logistic regression analyses of geomorphic thresholds of incision, braiding, and mass wasting.

Model	*p*-values			% Correctly Classified	
	Overall Model	Individual Terms		Unstable	Stable
		d_{50}	$S_v Q_{10}^{0.5}$		
Pr(incising or braiding) $0.5 \leq d_{50} \leq 100$ mm	< 0.0001	0.0009	0.0006	(52/54) 96%	(8/13) 62%
Pr(incising or braiding) $d_{50} \geq 16$ mm	< 0.0001	0.36	0.34	(9/9) 100%	(6/6) 100%
Pr(incising or braiding) $d_{50} < 16$ mm	0.0011	0.25	0.005	(44/45) 98%	(2/7) 29%
		Height	Angle		
Pr(mass wasting)	< 0.0001	0.01	0.02	(34/36) 94%	(121/125) 97%

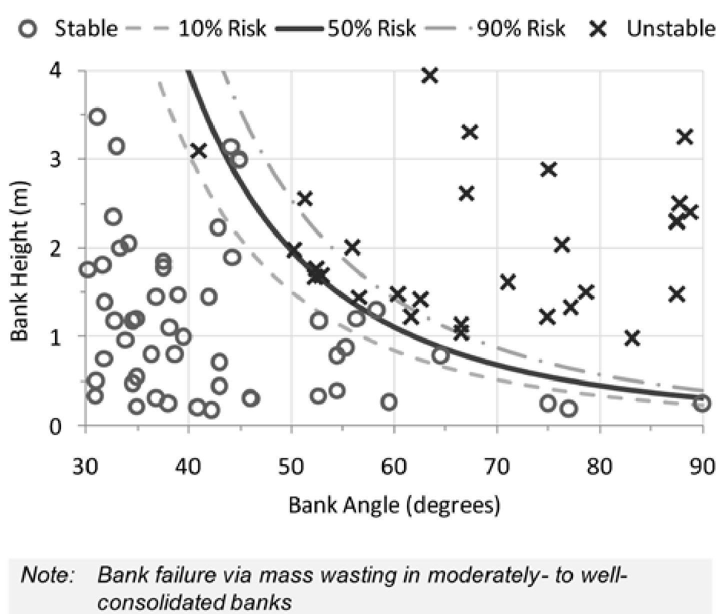
angle of stable vs. banks exhibiting significant mass wasting, consolidation of toe material, and confinement as measured by a VWI. These metrics were subsequently incorporated as central components of the assessment tool and led to the identification of two field-calibrated thresholds of overall channel stability and bank geotechnical stability (Figures 3 and 4). In both instances, statistical analyses suggested distinct breaks between channel stability clusters that could plausibly be represented as probabilistic thresholds. The logistic regression models depicted in Figures 3 and 4 each had >90% classification accuracy in identifying unstable systems, and were deemed important elements of regional assessments of vertical and lateral susceptibilities, respectively. We subsequently embedded these probabilistic models within two distinct decision trees for evaluating channel susceptibility in the vertical and lateral dimensions as described below. The variables used to assess proximity to these thresholds can be rapidly measured and quantified and are, therefore, suitable for use in a screening-level assessment in accordance with the goals of the tool.

The final logistic regression model based on the power index for coarse size fractions yielded complete separation of unstable/stable sites (i.e., 100%

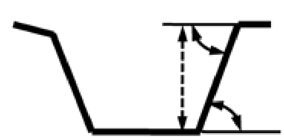


Logistic Regression Model	d_{50} (mm)	50% Risk $S_vQ_{10}^{0.5}$ ($m^{1.5}/s^{0.5}$)
d_{50} ≥ 16 mm	128	0.145
	96	0.125
	80	0.114
	64	0.101
	48	0.087
	32	0.070
	16	0.049
d_{50} < 16 mm	8	0.031
	4	0.026
	2	0.022
	1	0.018
	0.5	0.015

Figure 3. Probability of incising/braiding based on logistic regression of the power index and d_{50}.



Bank Angle	Bank Height (m) (10% Risk of Mass Wasting)
30	7.6
35	4.7
40	3.7
45	2.1
50	1.5
55	1.1
60	0.85
65	0.66
70	0.52
80	0.34
90	0.24



Bank height and angle schematic

Figure 4. Probability of mass-wasting diagram used in the susceptibility assessment tool.

correctly classified; Table 3). This explains why the 90 and 10% risk lines converge to the 50% level for d_{50} >16 mm in Figure 3. The combined size fraction models supported our hypothesis that in unconfined valleys, dynamically-unstable states of incision and braiding tend to occur in settings that are inherently higher in hydraulic energy.

Logistic regression models of mass-wasting failure in streams with unconfined, moderately- to well-consolidated banks also discriminated between stable and unstable states with high accuracy (Table 3). By back-solving the Culmann equation for the 50% risk, *operational* stress parameters for critical bank height were: $\gamma = 1.81$ g/cm^3 (i.e., 17.8 kN/m^3 or 113 lb/ft^3), $\gamma = 21.1^{o}$, and $c = 1.72$ kPa (35.8 lb/ft^2). The VWI was also useful for discriminating channels based on susceptibility of response. We selected a VWI of 2 as a key discriminator in the assessment tool because it best segregated all of the systems assessed as 'confined' during field investigations, i.e., channels that had little space to adjust laterally due to bedrock or hillslope constraints.

Multivariate regression of channel enlargement provided empirical support for the inclusion of proximity to a natural or engineered hard point as another important discriminatory factor in the analysis. The longitudinal distance to a hard point (when scaled by channel width) was statistically significant ($p < 0.05$) in four separate models of enlargement. Because the hard point influence was evident in a continuous manner (i.e., hard point proximity) rather than a discontinuous form (i.e., present/absent), it was also important to consider the spacing of grade controls more than simply their existence. Spacing intervals were segregated based on typical regional valley slopes and potential incision depths, and were consistent with projected enlargement classes based on the multivariate regression models Both natural and artificial grade control were prevalent in the region and field investigations generally indicated that channel responses became progressively larger moving upstream from such a hard point.

Decision Trees for Assessing Lateral and Vertical Susceptibilities

To facilitate hydromodification management decisions, the relative susceptibility of a stream reach to hydromodification effects is assigned one of four categorical screening ratings. The ratings are designed not only to provide an indication of likely hydromodification response, but also to identify logical implications regarding the next phases of data collection and modeling.

The field-based susceptibility assessment is designed to have a flow of logic that builds a weight of evidence toward an overall conclusion (Figure 5). The assessment considers: 1) identifiable risk factors, 2) proximity to geomorphic thresholds, and 3) ratio of disturbing to resisting forces to assign a rating of Low, Medium, High, or Very High for both the lateral and vertical components. In practice, the field screening tool uses combinations of decision trees, checklists, tables, and calculations to assign ratings (details of the indices and field rating systems are provided in the *Field Manual for Assessing Channel Susceptibility*, Southern California Coastal Water Research Project (SCCWRP) Technical Report 606; Bledsoe *et al*. 2010b). Ratings based on likely response in the vertical and lateral directions (i.e., channel deepening and widening) are assigned separately.

The decision trees are also designed to have "early off ramps" that identify channel segments to which susceptibility ratings can be assigned with high confidence with a minimum amount of information. These early off ramp ratings are assigned to end members including minimally-susceptible armored and confined channels and highly-susceptible sand-bed channels that are incising and lack grade control. The probabilistic models of braiding and incision risk and potential for mass wasting are embedded in

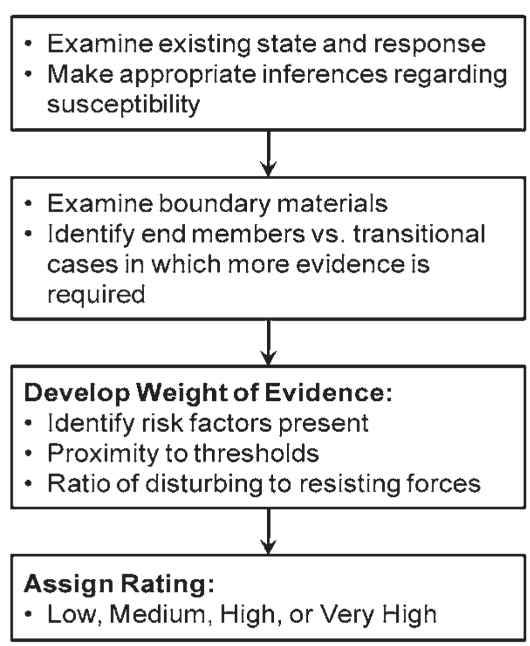


Figure 5. Logic flow for assigning susceptibility ratings with the decision trees.

subsequent levels of the decision trees. After the end member ratings are assigned, the amount of additional information required to arrive at susceptibility ratings for other channel types is commensurate with the degree of uncertainty as described below.

The vertical susceptibility decision tree is used to assess the risk of incision. Vertical stability is typically a prerequisite for lateral stability because a stream that incises can increase bank heights to the point of geotechnical instability and mass wasting. Accordingly, vertical susceptibility is assessed first because it affects the lateral rating in most instances. In the Vertical Susceptibility decision tree, there are three potential states of bed material based on broad classes of armoring potential: 1) Labile Bed – sand-dominated bed, little resistant substrate, 2) Transitional/Intermediate Bed – bed typically characterized by gravel/small cobble, intermediate level of resistance of the substrate and uncertain potential for armoring, or 3) Threshold Bed (Coarse/Armored Bed) – armored with large cobbles or larger bed material or highly-resistant bed substrate (Figure 6). To assign vertical susceptibility ratings to reaches of uncertain armoring potential, two checklists are used to assess the joint influence of grade control and channel substrate conditions on incision potential (Figure 7).

The lateral decision tree is used to assess the risk of widening (Figure 8). In terms of lateral stability, there are five primary states of bank characteristics. In order from most to least susceptible, they are: mass wasting or fluvial erosion/braiding, poorly consolidated or unconsolidated with fine/nonresistant toe material, poorly consolidated or unconsolidated with coarse/resistant toe material, consolidated, fully-armored bedrock/engineered reinforcement, or fully confined by hillslope. Banks fail through a variety of mechanisms; however, one of the most important distinctions is whether they fail in mass (as many particles) or by fluvial detachment of individual particles. We found it valuable to segregate bank types based on the inference of the dominant failure mechanism (as the management approach may vary based on the dominant failure mechanism). Although we recognize that bank vegetation is a key influence on bank processes (Thorne 1990), metrics associated with vegetation were not included because our field investigations indicated that root reinforcement and stabilizing influences were often short-lived in the semi-arid climate of the study region. To facilitate understanding and application by end users, the

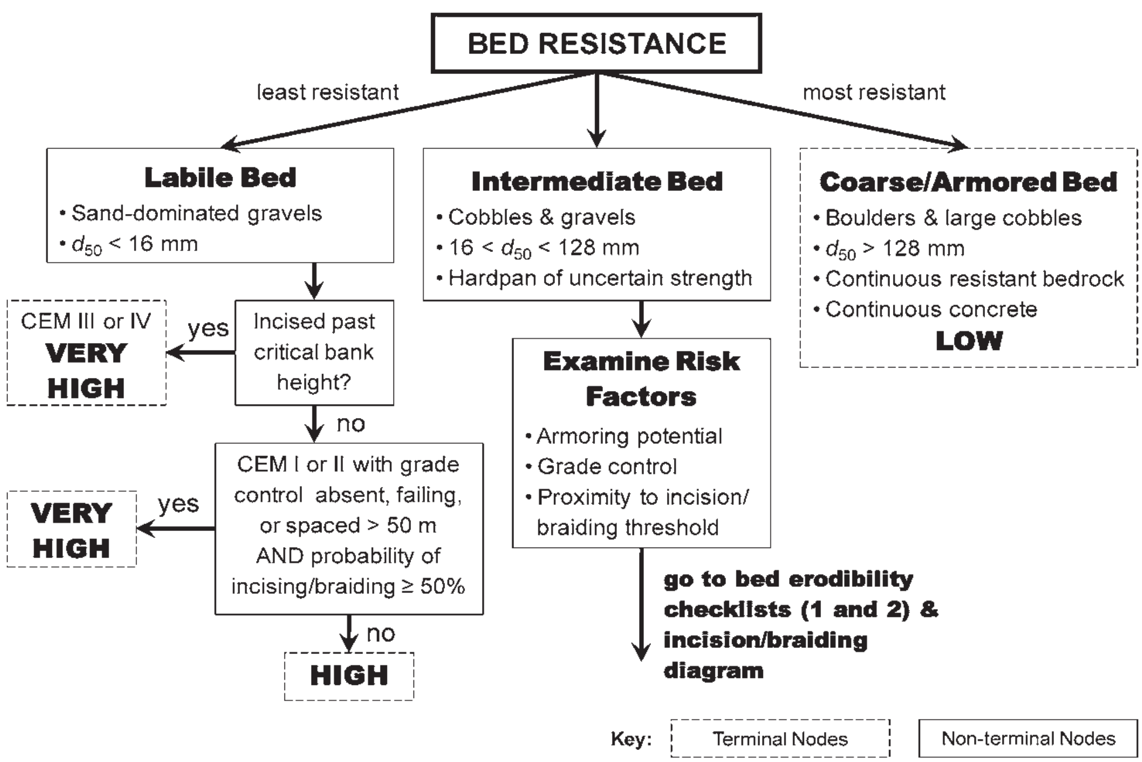


Figure 6. Decision tree for assessing channel susceptibility to vertical adjustment. The bed erodibility checklists for intermediate armoring potential are shown in Figure 7.

Checklist 1: Armoring Potential

☐ A A mix of coarse gravels and cobbles that are tightly packed with < 5% surface material of diameter < 2 mm

☐ B Intermediate to A and C or hardpan of unknown resistance, spatial extent (longitudinal and depth), or unknown armoring potential due to surface veneer covering gravel or coarser layer encountered with probe

☐ C Gravels/cobbles that are loosely packed or > 25% surface material of diameter < 2 mm

Checklist 2: Grade Control

☐ A Grade control is present with spacing < 50 m or $2/S_v$ m

- No evidence of failure/ineffectiveness, e.g., no headcutting (> 30 cm), no active mass wasting (analyst cannot say grade control sufficient if mass-wasting checklist indicates presence of bank failure), no exposed bridge pilings, no culverts/structures undermined
- Hard points in serviceable condition at decadal time scale, e.g., no apparent undermining, flanking, failing grout
- If geologic grade control, rock should be resistant igneous and/or metamorphic; for sedimentary/hardpan to be classified as 'grade control,' it should be of demonstrable strength as indicated by field testing such as hammer test/borings and/or inspected by appropriate stakeholder

☐ B Intermediate to A and C – artificial or geologic grade control present but spaced $2/S_v$ m to $4/S_v$ m or potential evidence of failure or hardpan of uncertain resistance

☐ C Grade control absent, spaced > 100 m or > $4/S_v$ m, or clear evidence of ineffectiveness

Calculate the overall Vertical Rating for Transitional Bed channels using the formula below. Numeric values for responses to Form 3 Checklists and Table 1 as follows: A = 3, B = 6, C = 9.

$$\text{VerticalRating} = \sqrt{\{(\sqrt{\text{armoring} * \text{grade control}}) * \text{screening index score}\}}$$

Vertical Susceptibility based on Vertical Rating:
< 4.5 = LOW; 4.5 to 7 = MEDIUM; and > 7 = HIGH

Notes: Vertical rating incorporates the 'screening index score,' which is determined using Figure 3. < 50% risk for incision/braiding = a score of 'A;' ≥ 50% risk for incision/braiding = a score of 'C.' See Bledsoe et al. (2010b) for more detail.

Figure 7. Bed armoring potential and grade control checklists for assessing channel susceptibility to vertical adjustments.

lateral decision tree can also be presented as a series of questions (Figure 9).

Tool Validation

Initial validation of the assessment tool using historical analyses to reconstruct channel responses to hydromodification suggested that it correctly categorized relative channel susceptibility for the test sites examined. Table 4 shows a gradient of examples from least susceptible to most disturbed. Although the reference cross section (A_{pre}) had to be conservatively inferred from historic aerial photographs and field indicators, the results provide reasonable estimates of relative channel response. For example, since its development beginning in the 1990s, sub-reaches at Acton, a fine-grained unconfined system, have enlarged by approximately 35, 120, 900, and 1,300% (Figure 10). This response occurred in association with watershed impervious cover of ~2.5% in 2001 and ~10% in 2006. However, this and similar cases of dramatic changes in fine-grained systems with relatively small amounts of watershed urbanization (e.g., Hicks, Perris, and Yucaipa), compared to inappreciable channel responses in bedrock systems despite greater extents of watershed development, reinforce the notion that impervious cover alone is not an adequate predictor of the likelihood of channel response.

San Antonio Creek demonstrates the susceptibility of a relatively resistant coarse-gravel/small-cobble

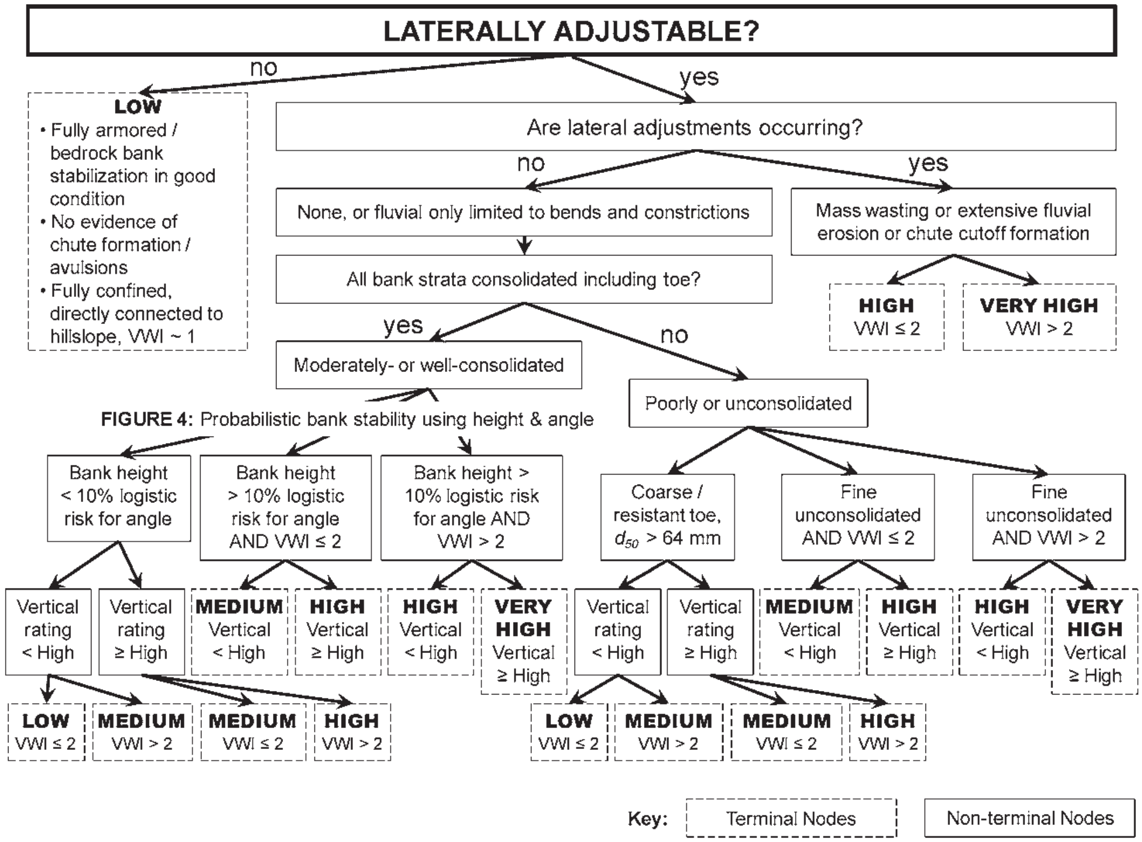


Figure 8. Decision tree for assessing channel susceptibility to lateral adjustment.

Channel fully confined with VWI ~1 – connected hillslopes OR fully-armored/engineered bed and banks in good conditions?	If YES, Then LOW	
If NO, Is there active mass wasting or extensive fluvial erosion (> 50% of bank length)?	If YES, VWI ≤ 2 = HIGH VWI > 2 = VERY HIGH	
If NO, Are both banks consolidated?	If YES, How many risk factors present? Risk Factors: ○ Bank instability *p* > 10% ○ VWI > 2 ○ Vertical rating ≥ HIGH	• All three = VERY HIGH • Two of three = HIGH • One of three = MEDIUM • None = LOW
If NO, Are banks either consolidated or unconsolidated with coarse toe of d_{50} > 64 mm?	If YES, How many risk factors present? Risk Factors: ○ VWI > 2 ○ Vertical rating ≥ HIGH	• Two = HIGH • One = MEDIUM • None = LOW
If NO, At least one bank is unconsolidated with toe of d_{50} < 64 mm	If YES, How many risk factors present? Risk Factors: ○ VWI > 2 ○ Vertical rating ≥ HIGH	• Two = VERY HIGH • One = HIGH • None = MEDIUM

Figure 9. Lateral susceptibility decision tree presented as a series of questions on the presence of risk factors.

Table 4. Susceptibility rating, estimated 'enlargement,' and key geomorphic parameters at selected study sites.

Sub-reach	Susceptibility		Estimated Enlargement	Impervious Area	d_{50} (mm)	Reference (yr)
	Vertical	Lateral				
Escondido_A	Low	Low	~ 0%	14%	128	1947
Topanga_B	Medium	Very High	~ 0 – 50%	1.40%	100	1947 – 1989
SanAntonio_A	High	Very High	~ 0 – 100%	0.20%	64	1947 – 1989
Borrego_B	Very High	Very High	~ 500%	14%	1.6	1952
Acton_C	Very High	Very High	> 1,000%	10.40%	5	~ 1990s

bed system in an unconfined setting. Two cross sections range in d_{50} from 16 to 64 mm and watershed imperviousness is only 0.2%. The incising low-flow channel is set within a braided bandwidth that is severely incised through a poorly-sorted alluvial floodplain (3.5-m bank height relative to the 65-m width). The observed incision and failing banks are consistent with the assessment tool ratings for both vertical and lateral susceptibilities.

Topanga Creek provides another interesting case study. Three distinct sub-reaches are markedly different in terms of grain size and confinement. A confined upstream segment has a median grain size of ca. 500 mm, a mid-segment reach that is unconfined and braided has a median grain size of ca. 100 mm, and a downstream reach is confined with a median grain size of ca. 90 mm. Aerial photography from 1947 through 1989 documents large pulses in sediment supply. The unconfined section exhibited periods of braiding and single-thread form, and an approximate enlargement range of 0 to 50%. The upstream confined/bedrock section (d_{50} ~500 mm) showed nominal effects from the sediment pulses through time, while the low-gradient confined section downstream (d_{50} ~88 mm) documented aggradational periods that occasionally caused multiple flow paths within the relatively narrow valley (i.e., VWI <2). This reach underscores the importance of looking over an appropriate analysis domain at the screening level. For example, a proposed project at the upstream site (composite rating of 'Low') could have undesirable effects in the unconfined braided section just 400 m downstream if mitigation controls were not designed with downstream reaches in consideration.

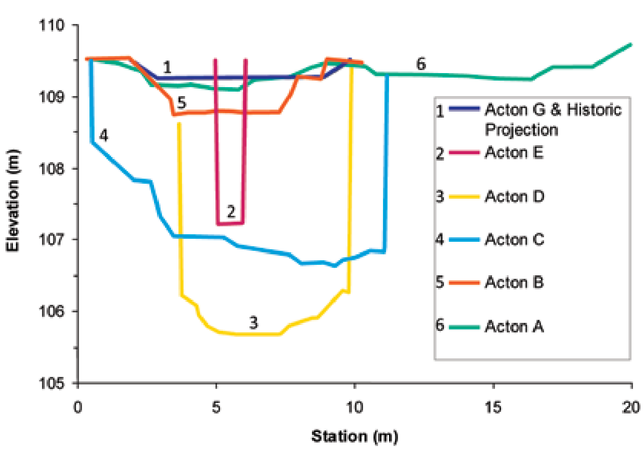


Figure 10. Superimposed cross sections along study reach at Acton, with the upstream-most site (Acton G) as well as the left channel of the downstream-most reach (Acton A) serving as historical reference cross sections, which may have been graded during ca. 1990s development.

Finally, Escondido Creek provides an example of a system that is bounded by bedrock in its bed and banks. This resilient system has shown no appreciable changes in form despite a highly-developed watershed at 14% imperviousness. Although the San Dieguito Reservoir has likely played a role in reducing high flows, this and several other bedrock systems (e.g., Silverado and Santiago) are clear examples of the region's least susceptible channel types.

In the second step in the validation process based on resurveys of seven transects approximately four years after the initial surveys, observed channel responses fell within ranges of what would be expected based on the *a priori* screening tool ratings. For example, a re-occupied coarse, step-pool reach (Santiago NL-B, vertical and lateral Low risks) showed no bank failure or channel incision. The re-surveyed braided site (Santiago A, vertical = Medium and lateral = Very High) showed about 0.5

m of aggradation and no net widening; however, morphology within the 70-m bandwidth was quite dynamic, experiencing a full-scale shift of the channel thalweg from the far left bank to the far right bank. Furthermore, it should be noted that these changes occurred in a stream with an almost totally undeveloped watershed (0.3% imperviousness).

The reoccupation of reaches at Acton (Very High vertical and lateral ratings) depicts channel susceptibility in a lightly-developed watershed but a highly-susceptible geomorphic setting (fine-grained bed material, d_{50} of 4 to 9 mm). Transect D increased in width by 30% (1.7 m) with no vertical change (Figure 11). In contrast, Acton transect B had less susceptible banks and responded in the vertical dimension by incising 0.22 m.

Finally, Agua Hedionda represented the most developed (26% imperviousness) and High risk (fine-grained bed material, d_{50} of 5 mm) setting, rated as having High susceptibility in both the lateral and vertical dimensions, despite having moderately well-vegetated banks. During the high-flow season, this reach widened 60% (4.2 m) and incised 0.2 m. Although the bank vegetation (i.e., 5- to 15-m riparian buffer ranging from shrub to 12- to 24-inch diameter trees) may have reduced the rate of channel response, it seems to have ultimately been overwhelmed by the channel evolution sequence once the degree of incision resulted in chronically-unstable bank geometries such that even well-established root systems could no longer prevent mass-wasting failure. This response reinforced the decision to withhold bank vegetation influence from the tool design as vegetation alone is not capable of fully resisting the effects of urbanization and mitigating channel response in High-risk geomorphic settings.

Discussion

The regionally-calibrated assessment tool offers a sound physical basis for assessing channel susceptibility to hydromodification and a transparent decision-making process that can easily be replicated between individual users. This makes it suitable for regional ambient monitoring and regulatory applications, which require repeatability between users. Results of the logistic regression analysis demonstrate that assessments with simple-to-evaluate field metrics can credibly inform ratings of hydromodification susceptibility that are applicable across heterogeneous stream conditions where streams are varying in both their resistance to erosive forces and their proximity to geomorphic thresholds.

The susceptibility rating derived from this assessment method informs the level of data collection, modeling, and ultimate mitigation efforts that can be expected for a particular stream-segment type and geomorphic setting (Figure 12). This will allow managers to move beyond standard one-size-fits-all flow control strategies to more comprehensive approaches that combine flow control with stream buffer and in-channel mitigation measures. However, jurisdictions would also be able to tailor site-specific mitigation strategies using different suites of modeling tools that correspond to varying degrees of vertical and lateral susceptibilities.

The precise combination of management and mitigation strategies should account for the specific

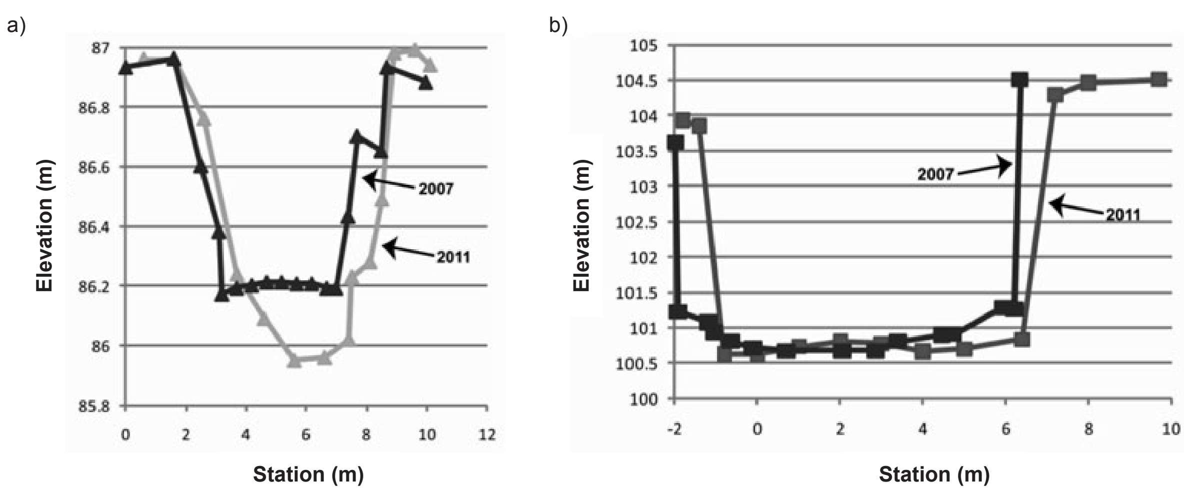


Figure 11. Cross-section surveys from 2007 vs. 2011 showing varying degrees of channel response resulting from differences in channel susceptibility for Acton B (a) and Acton D (b).

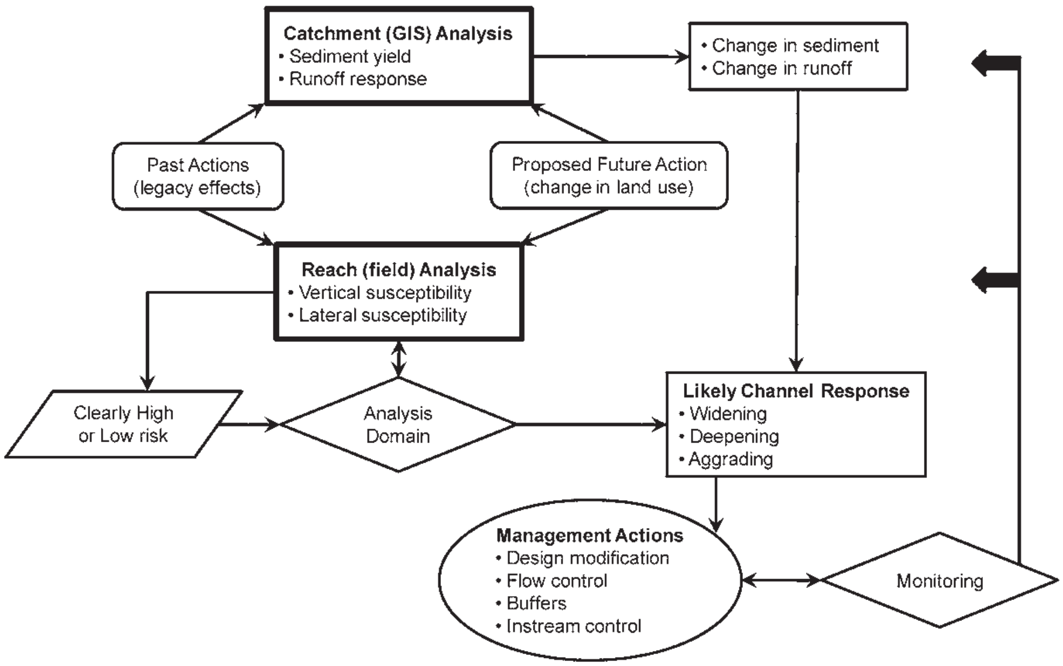


Figure 12. Relationship of catchment and field screening tools to support decisions regarding susceptibility to effects of hydromodification.

channel features that affect its susceptibility to response, which in turn affect the relative ease or difficulty of mitigating or reversing effects. For example, combined vertical and lateral ratings of '*Low*' correspond to a confined/bedrock channel or one that is fully reinforced and in a stable condition. Proposed developments affecting only Low-risk systems could conceivably be subject to the lowest level of analysis, ensuring the minimum mitigation level as determined by the management policy. A '*Medium*' vertical rating corresponds to cobble/boulder systems that have modest amounts of erosive energy relative to their armoring potential. As a hypothetical example, such channels could require a detailed channel survey and a level of modeling sufficient to maintain appropriate shear stresses relative to bed and bank resistance; however, the level of mitigation controls could be intermediate to the maximum and minimum extremes for the High- and Low-risk systems as determined by stakeholders. Finally, a fine-grained channel segment that is near a threshold of incision and/or bank mass wasting with a rating of "*High*" or "*Very High*" will necessarily require a variety of engineering/geomorphic analyses including detailed sediment transport analyses to develop a mitigation strategy that addresses the potential for both vertical and lateral instabilities.

The results of our extensive field surveys support the basic premise of the approach: that channel susceptibility is a key driver of geomorphic response to hydromodification, not the magnitude of urbanization. To date, one of the most common indicators used to assess channel sensitivity to hydromodification has been impervious cover (Hammer 1972, Caraco 2000). It is important to note that the tool does not include a direct evaluation of sediment transport or impervious cover, two factors commonly associated with hydromodification. Although impervious cover has been shown to be a good explanatory variable for channel adjustment due to hydromodification in some instances, it is a poor predictor in others and does not account for specific characteristics of individual channel reaches (Bledsoe and Watson 2001b, Booth and Henshaw 2001) and was not a useful predictor of channel condition at our study sites in univariate analyses. Consequently, it is a poor predictive variable of general channel response, as evidenced by this study where some sites with small increases in impervious cover resulted in dramatic changes in channel cross section, whereas others with large increases resulted in relatively little change (e.g., Acton vs. Escondido; Figure 10). Site-specific factors such as size of bed material and proximity to grade control may mediate effects of basin imperviousness and, therefore, be more predictive of channel condition. The first step of any hydromodification management program should, therefore, be an assessment of channel susceptibility that accounts for such individual channel characteristics in a parsimonious way. Although hydromodification effects reflect changes in the amount, size, and frequency of sediment delivery and transport, direct assessment of these processes is not feasible as part of a rapid field assessment.

To be effective, susceptibility assessments should account for proximity to thresholds of rapid and complex shifts in channel form and processes. The general screening approach is transferable to other areas, but critical geomorphic thresholds must be identified, calibrated, and tested for each region. For example, the southern California thresholds fell conspicuously lower than those from other regions (Bledsoe and Watson 2001a), suggesting that these systems may be relatively sensitive compared to other regions of the United States. This is most likely attributable to the semi-arid climate, flashy-flow regime, and high-sediment loads. Another important distinction between the models developed in this study and previously published thresholds based on classic planform categories (van den Berg 1995, Bledsoe and Watson 2001a) was that these prior efforts segregated 'unstable' forms from stable meandering systems (i.e., sinuosity ≥1.3), whereas most of the 'stable' sites in southern California were relatively straight with a mean sinuosity of 1.15. Finally, the vertical adjustment criterion developed for southern California streams focused on erosional processes, which predominate in this region. However, streams are also susceptible to depositional responses. Additional criteria may need to be developed in situations where aggradation is an important management concern.

The lateral susceptibility thresholds describing bank instability through mass wasting are also region-specific and must be recalibrated before being transferable to other regions. Because cohesion is difficult to assess in the field, we segregated banks by relative degree of consolidation. Failure in banks composed of recently-deposited alluvium with little time to consolidate (i.e., <~10 year, unconsolidated) was generally dominated by the resistance of individual particles. Banks composed of much older fluvial deposits with more time to both acquire more cohesive particles and become more consolidated (i.e., well-consolidated) were controlled by mass failure. Intermediate poorly- and moderately-consolidated bank types were generally found to be controlled by fluvial entrainment and mass wasting, respectively. Although lower than other regions where cohesion values are typically on the order of 10 kPa or greater (Lawler *et al*. 1997), the negligible cohesive strength we back-calculated was consistent with field observations. Broadly speaking, the streams banks we assessed tended to have little geotechnical strength. Unconsolidated banks, and in some instances banks that are moderately- or well-consolidated, frequently lack appreciable cohesion. This is compounded by the semi-arid climate and paucity of bank vegetation (which is exacerbated by steep, sandy banks). Moreover, high sediment loads can lead to central bar deposition that promotes flow deflection into banks and further weakening. These characteristics collectively result in relatively low thresholds for mass wasting compared to many US regions.

Future work to continue refining the channel susceptibility assessment tool will allow its application to a broader set of streams and circumstances. Areas for future refinement include adding categories to the vertical susceptibility evaluation to better account for hardpan and cohesive clay substrates. Areas with deep stagnant pools (often due to the presence of downstream grade control) will also be difficult to assess due to the inability to directly observe the channel bed and toe of the banks. In addition, in many newly urbanizing areas, water is conveyed through swales that are typically highly susceptible to widening under increased flow condition. However, in their current state, there may not be clear bed or bank features. Additional guidance on when the lower bounds of applicability to subtle features should also be included in future iterations of the tool.

Finally, some metrics were not included in the tool, due to end-user constraints, that could have improved predictions of channel susceptibility. For example, we would have preferred to have included a metric that quantifies the current extent of incision and the potential for a positive feedback on incision as shear stress accumulates in the channel (e.g., how many multiples of Q_2 can the channel contain before breaking onto a floodplain?). However, such an analysis is not feasible without increasing the complexity and time demands of the rating process in this particular context. Such practical constraints may not be as limiting in other management contexts and similar tools could include more rigorous, survey-level analysis of channel processes and boundary conditions. Ultimately, tools for assessing channel susceptibility to hydromodification must balance the perceived needs of end users with a level of analysis that is not overly simplistic or too complex. Ongoing monitoring is an essential means of assessing prediction accuracy and refining the tool to achieve the right balance of detail and user friendliness.

Literature Cited

Allen, P.M., J.G. Arnold and W. Skipwith. 2002. Erodibility of urban bedrock and alluvial channels, north Texas. *Journal of the American Water Resources Association* 38:1477-1492.

American Society of Civil Engineers (ASCE). 1998. River width adjustment, II: Modeling. *Journal of Hydraulic Engineering* 124:903-917.

Bagnold, R.A. 1966. An approach to the sediment transport problem from general physics. US Geological Survey Professional Paper 422-I. US Government Print Office. Washington, DC.

Biedenharn, D.S., C.M. Elliot and C.C. Watson. 1997. The WES stream investigation and streambank stabilization handbook. US Army Engineer Waterways Experiment Station. Vicksburg, MS.

Bledsoe, B.P. and C.C. Watson. 2001a. Logistic analysis of channel pattern thresholds: Meandering, braiding, and incising. *Geomorphology* 38:281-300.

Bledsoe, B.P. and C.C. Watson. 2001b. Effects of urbanization on channel instability. *Journal of the American Water Resources Association* 37:255-270.

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* 38:861-870.

Bledsoe, B.P., R.J. Hawley and E.D. Stein. 2008. Stream channel mapping and classification systems: implications for assessing susceptibility to hydromodification effects in southern California. Technical Report 562. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bledsoe, B.P., R.J. Hawley, E.D. Stein and D.B. Booth. 2010a. Hydromodification screening tools: technical basis for development of a field screening tool for assessing channel susceptibility to hydromodification in southern California. Technical Report 607. Southern California Coastal Water Research Project. Costa Mesa, CA.

Bledsoe, B.P., R.J. Hawley, E.D. Stein, and D.B. Booth, 2010b. Hydromodification Screening Tools: Field Manual for Assessing Channel Susceptibility. Technical Report 606, Southern California Coastal Water Research Project. Costa Mesa, CA.

Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. *Water Resources Bulletin* 26:407-417.

Booth, D.B. and P.C. Henshaw. 2001. Rates of channel erosion in small urban streams. pp. 17-38 *in*: M. Wigmosta and S. Burges (eds.), Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas (Water Science and Application Volume 2). American Geophysical Union. Washington, DC.

Booth, D.B. and B.P. Bledsoe. 2009. Streams and urbanization. pp. 93-123 *in*: L.A. Baker (ed.), The Water Environment of Cities. Springer-Verlag. New York, NY.

Brookes, A. 1988. Channelized Rivers: Perspectives for Environmental Management. John Wiley & Sons, Inc. Chichester, United Kingdom.

Bull, W.B. 1979. Threshold of critical power in streams. *Geological Society of America Bulletin* 90:453-464.

Bunte, K. and S.R. Abt. 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. Technical Report RMRS-GTR-74. US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Fort Collins, CO.

Caraco, D. 2000. The dynamics of urban stream channel enlargement. *Watershed Protection Techniques* 3:729-734.

Carson, M.A. 1984. Observations on the meandering-braided transition, Canterbury Plains, New Zealand: Part two. *New Zealand Geographer* 40:89-99.

Chang, H.H. 1988. Fluvial Processes in River Engineering. John Wiley & Sons. New York, NY.

Christensen, R. 1997. Log-linear Models and Logistic Regression. Springer-Verlag. New York, NY.

Downs, P. 1995. Estimating the probability of river channel adjustment. *Earth Surface Processes and Landforms* 20:687-705.

Dunaway, D., S.R. Swanson, J. Wendel and W. Clary. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. *Geomorphology* 9:47-56.

Edgar, D.E. 1973. Geomorphic and hydraulic properties of laboratory rivers. M.S. Thesis, Colorado State University. Fort Collins, CO.

Edgar, D.E. 1976. Geomorphology and hydrology of selected midwestern streams. Ph.D. Dissertation, Purdue University. West Lafayette, IN.

Ferguson, R.I. 1987. Hydraulic and sedimentary controls on channel pattern. pp. 129-158 *in*: K.S. Richards (ed.), River Channels: Environment and Process, Blackwell. Oxford, United Kingdom.

Friedman, J.M., W.R. Osterkamp, M.L. Scott and G.T. Auble. 1998. Downstream effects of dams on channel geometry and bottomland vegetation: regional patterns in the Great Plains. *Wetlands* 18:619-633.

Hammer, T.R. 1972. Stream channel enlargement due to urbanization. *Water Resources Research* 8:1530-1540.

Harrelson, C.C., C.L. Rawlins and J.P. Potyondy. 1994. Stream channel reference sites: an illustrated guide to field technique. Technical Report RM-245. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. Fort Collins, CO.

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. Fort Collins, CO.

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.

Johnson, P.A., G.L. Gleason and R.D. Hey. 1999. Rapid assessment of channel stability in vicinity of road crossings. *Journal of Hydraulic Engineering* 125:645-651.

King County. 1991. Executive proposed basin plan, hylebos and lower Puget Sound. King County Public Works Department, Surface Water Management Division. Seattle, WA.

King County. 1997. Conceptual Alternative Design Report, South 360th Street Regional R/D Facility, Hylebos and Lower Puget Sound Basin Plan. Project Number 0A1685, King County Public Works Department, Surface Water Management Division. Seattle, WA.

King County. 1998a. Des Moines Creek basin plan. King County Public Works Department, Surface Water Management Division. Seattle, WA.

King County. 1998b. Des Moines Creek regional CIP preliminary design report. King County Public Works Department, Surface Water Management Division. Seattle, WA.

Knighton, A.D. 1998. Fluvial Forms and Processes: A New Perspective. John Wiley & Sons. New York, NY.

Lane, E.W. 1957. A study of the shape of channels formed by natural streams flowing in erodible material. Series Number 9. US Army Engineer Division, Missouri River Corps of Engineers, Missouri River Division Sediment. Omaha, NE.

Lawler, D.M., C.R. Thorne and J.M. Hooke. 1997. Bank Erosion and Instability. pp. 137-172 *in*: C.R. Thorne, R.D. Hey and M.D. Newson (eds.), Applied Fluvial Geomorphology for River Engineering and Management. Wiley. Chichester, United Kingdom.

Leopold, L.B. and M.G. Wolman. 1957. River channel patterns: braided, meandering, and straight. US Geological Survey Professional Paper 282-B. US Government Printing Office. Washington, DC.

Menard, S.W. 1995. Applied Logistic Regression Analysis. Sage Publications. Thousand Oaks, CA.

Montgomery, D.R. and L.H. MacDonald. 2002. Diagnostic Approach to Stream Channel Assessment and Monitoring. *Journal of the American Water Resources Association* 38:1-16.

Nanson, G.C. and J.C. Croke. 1992. A genetic classification of floodplains. *Geomorphology* 4:459-486.

Osman, A.M. and C.R. Thorne. 1988. Riverbank stability analysis I: Theory. *Journal of Hydraulic Engineering* 114:134-150.

Ott, R.L. and M. Longnecker. 2001. An Introduction to Statistical Methods and Data Analysis. Duxbury Press. Pacific Grove, CA.

Patton, P.C. and S.A. Schumm. 1975. Gully erosion, northwestern, Colorado: a threshold problem. *Geology* 3:88-90.

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

Richards, K.S. and S.N. Lane. 1997. Prediction of Morphological Changes in Unstable Channels. pp. 269-292 *in*: C.R. Thorne, R.D. Hey, and M.D. Newsom (eds.), Applied Fluvial Geomorphology for River Engineering and Management. Wiley. Chichester, United Kingdom.

Roesner, L.A., B.P. Bledsoe and R.W. Brashear. 2001. Are BMP criteria really environmentally friendly? *Journal of Water Resources Planning and Management* 127:150-154

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. 1979. Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers* 4:485-515.

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

Schumm, S.A., M.T. Bradley and Z.B. Begin. 1980b. Application of geomorphic principles to environmental management in semiarid regions. Submitted to: US Department of the Interior, Office of Water Research and Technology by Colorado State University, Colorado Water Resources. Colorado State University Water Resources Research Institute. Fort Collins, CO.

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

Schumm, S.A. 1991. To Interpret the Earth: Ten Ways to be Wrong. Cambridge University Press. Cambridge, United Kingdom.

Simon, A. 1989. A model of channel response in disturbed alluvial channels. *Earth Surface Processes and Landforms* 14:11-26.

Simon, A. 1995a. Adjustment and recovery of unstable alluvial channels: identification and approaches for engineering management. *Earth Surface Processes and Landforms* 20:611-628.

Simon, A. and P.W. Downs. 1995b. An interdisciplinary approach to evaluation of potential instability in alluvial channels. *Geomorphology* 12:215-232.

Simon, A. and M. Rinaldi. 2000a. Channel instability in the loess area of the midwestern United States. *Journal of the American Water Resources Association* 36:133-150.

Simon, A., A. Curini, S.E. Darby and E.J. Langendoen. 2000b. Bank and near-bank processes in an incised channel. *Geomorphology* 35:193-217.

Terzaghi, K. 1943. Theoretical Soil Mechanics. Wiley. New York, NY.

Thorne, C.R. 1982. Processes and Mechanisms of River Bank Erosion. pp. 227-271 *in*: R.D. Hey, J.C. Bathurst and C.R. Thorne (eds.), Gravel-bed Rivers. Wiley. Chichester, United Kingdom.

Thorne, C.R. 1990. Effects of Vegetation on Riverbank Erosion and Stability. pp. 125-144 *in*: J.B. Thornes (ed.), Vegetation and Erosion. John Wiley & Sons. New York, NY.

Thorne, C.R. 1998. Stream Reconnaissance Handbook. John Wiley & Sons. Chichester, United Kingdom.

Trimble, S.W. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* 278:1442-1444.

United States Environmental Protection Agency (USEPA). 1973. The control of pollution from hydrographic modifications. EPA 430/9-73-017. USEPA. Washington, DC.

USEPA. 2007. National management measures guidance to control nonpoint source pollution from hydromodification. EPA 841-B-07-002. USEPA, Office of Water. Washington, DC.

Van den Berg, J.H. 1995. Prediction of alluvial channel pattern of perennial rivers. *Geomorphology* 12:259-279.

Vocal Ferencevic, M. and P. Ashmore. 2011. Creating and evaluating digital elevation model-based stream-power map as a stream assessment tool. River Research and Applications DOI: 10.1002/rra.1523.

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* 38:151-160.

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