HYDROMODIFICATION SCREENING TOOLS: TECHNICAL BASIS FOR DEVELOPMENT OF A FIELD SCREENING TOOL FOR ASSESSING CHANNEL SUSCEPTIBILITY TO HYROMODIFICATION

SCCWRP
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Colorado State University

Stillwater Sciences

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Hydromodification Screening Tools: Technical Basis for Development of a Field Screening Tool for Assessing Channel Susceptibility to Hydromodification

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EXECUTIVE SUMMARY

Managing the effects of hydromodification (physical response of streams to changes in catchment runoff and sediment yield) has become a key element of most stormwater programs in California. Although straightforward in intent, hydromodification management is difficult in practice. Shifts in the flow of water and sediment, and the resulting imbalance in sediment supply and capacity can lead to changes in channel planform and cross-section via wide variety of mechanisms. Channel response can vary based on factors such as boundary materials, valley shape and slope, presence of in-stream or streamside vegetation, or catchment properties (e.g., slope, land cover, geology).

Management prescriptions should be flexible and variable to account for the heterogeneity of streams; a given strategy will not be universally well-suited to all circumstances. Management decisions regarding a particular stream reach(s) should be informed by an understanding of susceptibility (based on both channel and catchment properties), resources potentially at risk (e.g., habitat, infrastructure, property), and the desired management endpoint (e.g., type of channel desired, priority functions; see Figure ES1).

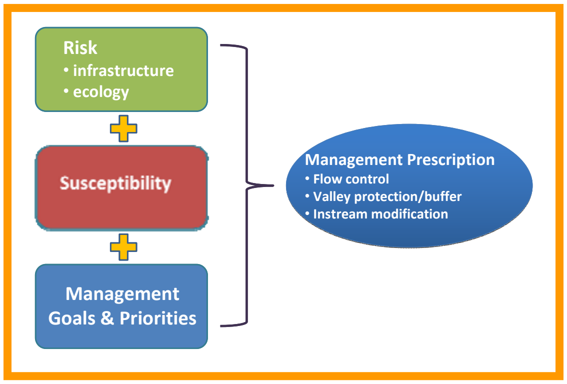


Figure ES1: Decision nodes that influence the management prescription for a particular stream reach.

We have produced a series of documents that outline a process and provide tools aimed at addressing the decision node associated with assessing channel susceptibility. The three corresponding hydromodification screening tool documents are:

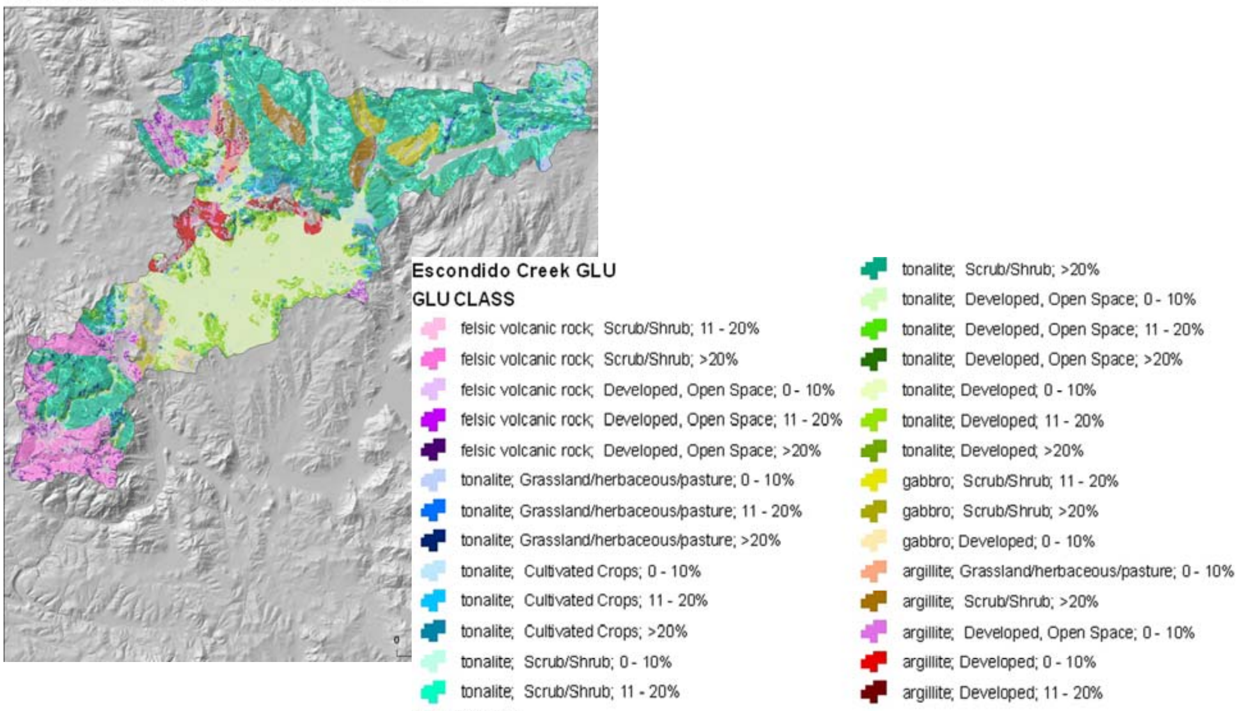
1. *GIS-based catchment analyses of potential changes in runoff and sediment discharge* which outlines a process for evaluating potential change to stream channels resulting from watershed-scale changes in runoff and sediment yield.
2. *Field manual for assessing channel susceptibility* which describes an in-the-field assessment procedure that can be used to evaluate the relative susceptibility of channel reaches to deepening and widening.
3. *Technical basis for development of a regionally calibrated probabilistic channel susceptibility assessment* which provides technical details, analysis, and a summary of field data to support the field-based assessment described in the field manual.

The catchment analyses and the field manual are designed to support each other by assessing channel susceptibility at different scales and in different ways. The GIS-based catchment analyses document is a planning tool that describes a process to predict likely effects of hydromodification based on potential change in water and sediment discharge as a consequence of planned or potential landscape alteration (e.g., urbanization). Data on geology, hillslope, and land cover are compiled for each watershed of interest, overlaid onto background maps, grouped into several discrete categories, and classified independently across the watershed in question.

The classifications are used to generate a series of Geomorphic Landscape Units (GLUs) at a resolution defined by the coarsest of the three data sets (usually 10 to 30 m). Three factors: geology, hillslope, and land cover are used because the data are readily available; these factors are important to controlling sediment yield. The factors are combined into categories of High, Medium, or Low relative sediment production. The current science of sediment yield estimation is not sophisticated enough to allow fully remote (desktop) assignment of these categories. Therefore initial ratings must be verified in the field.

Once the levels of relative sediment production (i.e., Low, Medium, and High) are defined across a watershed under its current configuration of land use, those areas subject to future development are identified, and corresponding sediment-production levels are determined by substituting Developed land cover for the original categories and modifying the relative sediment production as necessary (Figure ES2). Conversely, relative sediment production for currently developed watershed areas can be altered to estimate relict sediment production for an undeveloped land use and used to assess the impact of watershed development on pre-development sediment production. The resultant maps can be used to aid in planning decisions by indicating areas where changes in land use will likely have the largest (or smallest) effect on sediment yield to receiving channels.

ESCONDIDO CREEK PRELIMINARY GLU CLASSES - DRAFT



Source: SWS 2008

Figure ES2: Example of Geomorphic Landscape Units for the Escondido Creek Watershed.

The field assessment procedure is intended to provide a rapid assessment of the relative susceptibility of a specific stream reach to effects of hydromodification. The intrinsic sensitivity of a channel system to hydromodification as determined by the ratio of disturbing to resisting forces, proximity to thresholds of concern, probable rates of response and recovery, and potential for spatial propagation of impacts. A combination of relatively simple, but quantitative, field indicators are used as input parameters for a set of decision trees. The decision trees follow a logical progression and allow users to assign a classification of Low, Medium, High, or Very High susceptibility rating to the reach being assessed. Ratings based on likely response in the vertical and lateral directions (i.e., channel deepening and widening) are assigned separately. The screening rating foreshadows the level of data collection, modeling, and ultimate mitigation efforts that can be expected for a particular stream-segment type and geomorphic setting. The field assessment is novel in that it incorporates the following combination of features:

- Integrated field and office/desktop components
- Separate ratings for channel susceptibility in vertical and lateral dimensions
- Transparent flow of logic via decision trees
- Critical nodes in the decision trees are represented by a mix of probabilistic diagrams and checklists
- Process-based metrics selected after exhaustive literature review and analysis of large field dataset
- Metrics balance process fidelity, measurement simplicity, and intuitive interpretability
- Explicitly assesses proximity to geomorphic thresholds delineated using field data from small watersheds in southern California
- Avoids bankfull determination, channel cross-section survey, and sieve analysis, but requires pebble count in some instances
- Verified predictive accuracy of simplified logistic diagrams relative to more complex methods, such as dimensionless shear-stress analyses and Osman and Thorne (1988) geotechnical stability procedure
- Assesses bank susceptibility to mass wasting; field-calibrated logistic diagram of geotechnical stability vetted by Colin Thorne (personal communication)
- Regionally-calibrated braiding/incision threshold based on surrogates for stream power and boundary resistance
- Incorporates updated alternatives to the US Geological Survey (USGS; Waananen and Crippen 1977) regional equations for peak flow (Hawley and Bledsoe In Review)
- Does not rely on bank vegetation given uncertainty of assessing the future influence of root reinforcement (e.g., rooting depth/bank height)
- Channel evolution model underpinning the field procedure is based on observed responses in southern California using a modification of Schumm *et al.* (1984) five-stage model to represent alternative trajectories

The probabilistic models of braiding, incision, and bank instability risk embedded in the screening tools were calibrated with local data collected in an extensive field campaign. The models help users directly assess proximity to geomorphic thresholds and offer a framework for gauging susceptibility that goes beyond expert judgment. The screening analysis represents the first step toward determining appropriate management measures and should help inform decisions about subsequent more detailed analysis.

The GIS-based catchment-scale analysis and the field screening procedure are intended to be used as a set of tools to inform management decisions (Figure ES3). The catchment-scale analysis provides an overall assessment of likely changes in runoff and sediment discharge that can be used to support larger-scale land use planning decisions and can be applied prospectively or retrospectively. The field screening procedure provides more precise estimates of likely response of individual stream reaches based on direct observation of indicators. The field assessment procedure also provides a method to evaluate the extent of potential upstream and downstream propagation of effects (i.e., the analysis domain). In concept, the catchment-scale analysis would be completed for a watershed of interest before conducting the field analysis. However, this is not required and the two tools can be used independent of each other. It is not presently possible to describe a mechanistic linkage between the magnitude of the *drivers* of hydromodification (i.e., changes in the delivery of water and sediment to downstream channels), the *resistance* of channels to change, and the net expression on channel form. For this reason, the results of the catchment and field analyses must be conducted independently and the results cannot be combined to produce an overall evaluation of channel susceptibility to morphologic change (Figure ES3).

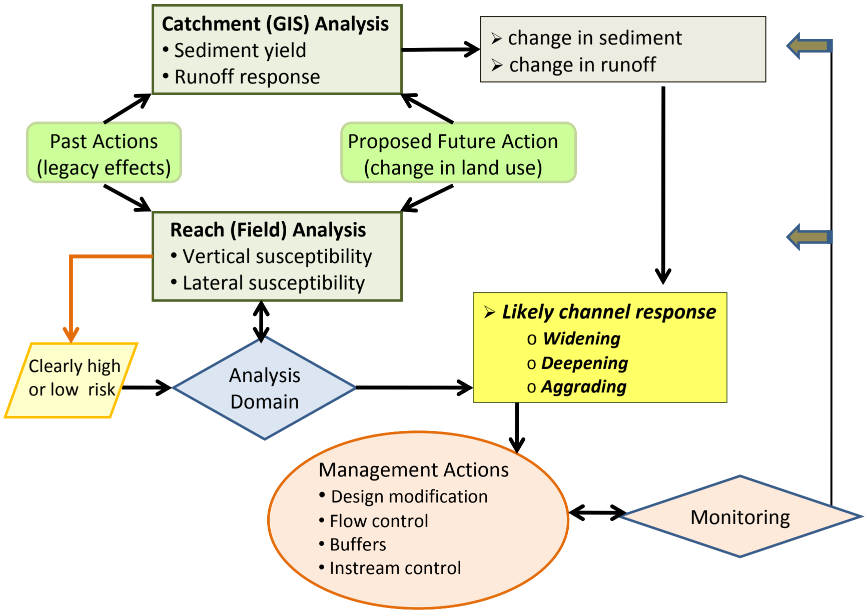


Figure ES3: Relationship of catchment and field screening tools to support decisions regarding susceptibility to effects of hydromodification.

Finally, it is important to note that these tools should be used as part of larger set of considerations in the decision making process (see Figure ES1). For example, the tools do not provide assessments of the ecological or economic affects of hydromodification. Similarly, they do not allow attribution of current conditions to past land use actions. Although the screening tool is designed to have management implications via a decision framework, policy/management decisions must be made by local stakeholders in light of a broader set of considerations.

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INTRODUCTION

Streams in semiarid settings are known to be highly dynamic (Wolman and Gerson 1978; Graf 1981, 1988; Bull 1997), and those of southern California are no exception. The region is characterized by both its geologic heterogeneity and its highly stochastic sediment delivery and hydrologic forcing. Flashy flow regimes, steep topography, and channels composed of a wide range of erodible materials are the norm. Gross sediment loads for the region are relatively high, even in areas where recent tectonic uplift has largely ceased. Fire is also an important influence that frequently creates large (order of magnitude) fluctuations in annual sediment delivery.

Within this dynamic geologic context, there is growing recognition that contemporary land-use changes associated with urbanization are altering channels and accelerating erosion processes in many southern California watersheds. Such changes are referred to as “hydromodification.” Hydromodification can be defined as changes in watershed hydrologic and sedimentation processes associated with changes in land use. In particular, land-use changes that increase the extent and connectedness of impervious areas can amplify surface runoff and produce higher flow magnitudes and durations for equivalent rainfalls relative to undeveloped settings. Some of the effects of hydromodification include altered sediment delivery from the watershed, increased sediment transport within channels, and rapid changes in channel forms (Trimble 1997).

Significant impacts to wetland, riparian, and stream habitats (Allen 1993, Allen and Feddema 1996, Stein and Ambrose 2001), as well as infrastructure and property losses, point to a need for improved hydromodification management strategies and tools.

Accordingly, recent management attention has been directed at the need to address the effects of hydromodification. This effort necessarily involves moving beyond an over-reliance on control structures solely aimed at flood protection (or in some cases water-quality protection) to management practices aimed at protecting channel stability through the application of principles from fluvial geomorphology and sedimentation engineering.

An important early step in managing hydromodification effects is to be able to rate streams in terms of their potential susceptibility of response to planned changes in watershed land use, hydrology, and sediment yield. It is increasingly recognized that not all streams are the same and hence management approaches should not all be the same. Stream management actions aimed at mitigating the effects of hydrologic modifications will be most effective when tailored to different stream types. One-size-fits-all practices based on “single factor” geomorphology (e.g., a simple erosion index) or extrapolation across diverse stream types is not likely to provide cost-effective protection of stream amenities. For example, a channel that naturally contains extensive bedrock control or very resistant boundary materials will be less physically susceptible to urbanization than a fully alluvial stream in relatively erodible material.

Although many existing classification and mapping systems offer insights to assessing channel stability, none were developed for or would exclusively capture the full range of risk types and settings in southern California (Bledsoe *et al*. 2008). Furthermore, existing screening systems are predominantly descriptive in nature, often relying on expert judgment and field indicators to assess current condition with few quantitative components. Quantitative aspects of studies from other regions would likely be affected by local variability due to the unique combination of hydrogeomorphic and anthropogenic factors in southern California. A regionally-calibrated screening tool tailored to local stakeholder needs and designed with their input would have clear benefits to local jurisdictions in their mandate to protect water quality from the effects of hydromodification. Accordingly, a broadly collaborative effort was undertaken to develop such a tool. This "screening tool" is the first element of a multifaceted collaborative project aimed at developing tools for assessing and managing hydromodification in southern California. In a broad sense, three levels of project tools are designed to address the following questions:

1) Screening: Which streams are most susceptible to hydromodification?
2) Modeling: What are the predicted magnitudes of responses in the most susceptible stream systems?
3) Mitigation: What are potential management measures that could be implemented to offset hydromodification effects?

The goal of this document is to provide details of the approach, methodology, scientific basis, and supporting data used to develop the first iteration of a hydromodification effects screening tool. This document provides the technical basis for the companion *Field Manual for Assessing Channel Susceptibility* (Southern California Coastal Water Research Project (SCCWRP) Technical Report 606; Bledsoe *et al*. 2010).

The Natural and Anthropogenic Setting

Despite relatively few studies focused on hydromodification in southern California, there is a growing body of research and experience upon which to build a practical hydromodification screening tool. Indeed, the effects of altered flow and sediment regimes resulting from urbanization have been described across many hydro-geomorphic settings and include increased sediment transport, channel incision, widening, and enlargement (Wolman 1967; Hammer 1972; Booth 1990, 1991; MacRae 1997; Pizzuto *et al*. 2000; Bledsoe and Watson 2001a; Chin 2006). However, consistent with previous work in semiarid environments (Trimble 1997) and specific to the region (Coleman *et al*. 2005), channel responses to urbanization in southern California appear to be acute with relatively rapid rates of spatial propagation. Complex responses from incision-driven channel evolution analogous to the original Channel Evolution Model (CEM; Schumm *et al*. 1984) as well as planform shifts, such as meandering to braided, have cascading effects to both adjacent land and the upstream/downstream stream network. These responses are attributable to the intersection of high-energy fine-grained fluvial systems with dramatic changes in runoff patterns, often associated with human activities.

The hydrogeomorphic setting of southern California gives rise to stream channels that are arguably more dynamic than those of humid and/or lower relief regions. The domain is bounded by the Transverse Ranges to the north and Peninsular Ranges to the east, with a total relief of up to 3,500 m and short-travel distances to the Pacific Ocean on the order of 50 to 100 km. Such steep slopes produce substantial sediment loads, particularly when coupled with regional climatic and lithologic settings. Sediment yields from 115 debris basins in the San Gabriel Mountains had estimated yields ranging from 100 to 7,440 m^3/km^2/year with a mean of 1,600 m^3/km^2/year (Lavé and Burbank 2004). The region's heterogeneous lithologies can generally be described as having a limited amount of coarse material with an abundance of fines. Gradations of regional debris-dam sediments have averaged 50% by volume fine ($d < 0.06$ *mm*), 42% sand, and less than

7% gravels and boulders (*d >2 mm*; Taylor 1981). The climate is characterized as semiarid/Mediterranean, with precipitation and vegetative cover typically increasing with elevation from average annual extremes of 200 to 1,000 mm/year and sparse grasses/chaparral to dense coniferous stands, respectively.

The combination of high-energy streams and erodible materials leads to a predominance of labile single-thread and braided channels with both sand and gravel substrates. Flow regimes are typically ephemeral and extremely flashy with instantaneous peaks that are generally much larger than the respective daily mean. For example, a 10-year instantaneous event would ordinarily correspond to a daily mean flow on the order of a 2- to 3-year event, with the former approaching 20 times the latter.

In addition to variability in seasonal rainfall patterns, the region experiences large fluctuations in inter-year precipitation, which can be subject to decadal and even multi-decadal trends. This sets the stage for an active fire regime, triggering dramatic pulses in sediment production and runoff (Los Angeles County Flood Control District (LACFCD) 1959; Booker *et al*. 1993; Benda and Dunne 1997a,b). With measured inter-year sediment yields varying by more than four orders of magnitude at regional debris basins (Taylor 1981), some researchers have suggested that fire-induced sediment production is the dominant form of contemporary erosion (Lavé and Burbank 2004). Such dynamic ambient conditions lend credence to widespread postulation that periods of substantial aggradation and degradation can be more recurrent than states of equilibrium, and that the concept of equilibrium itself may need to be reconsidered for the region (Wolman and Gerson 1978, Graf 1988, Bull 1997).

Contemporary management practices have done little to mitigate the effects of hydro-modification. 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 that have been implemented are designed for flood control (and in a few cases water quality). Consequently, they have little effect on promoting geomorphic stability. Field observations consistently indicate that it often takes only 5 to 10 years of moderate rainfall following development for channel incision and/or widening to become so severe that channel armoring measures are deemed necessary. These measures have customarily consisted of concrete or riprap bank armoring or channelization. Although effective for flood-control purposes, these control strategies often result in severely depressed ecological or geomorphic function (McIninch and Garman 2001, Fitzpatrick *et al*. 2005).

OVERVIEW OF SCREENING-TOOL DEVELOPMENT

Throughout this project, a technical advisory committee (TAC) composed of regional stakeholders including managers, policymakers, and technical experts provided a wealth of practical guidance on defining the overall vision, goals, technical basis, level of detail, practical constraints, and target audience for the screening tool. TAC input was provided at several critical junctures throughout the entire process from conceptual development through field testing of the penultimate versions of field forms, and played a central role in shaping the screening tool presented herein.

The overall process of screening tool development was iterative and involved the following steps:

- Stakeholder input was used to define states of concern and degrees of severity for defining channel susceptibility classes;
- Stakeholders helped define guiding principles for the design of the screening tool, e.g., structure, balance of detail, and time required;
- Project team and the TAC formed hypotheses regarding key geomorphic processes, boundary conditions, and thresholds that control channel response to hydromodification in the southern California region;
- Project team conducted field surveys across a gradient of stream types (e.g., labile vs. threshold, planforms, and incision stages), hydrogeomorphic settings, and degree of urbanization to test the hypotheses;
- Project team developed inventory of candidate indices and descriptors to consider for inclusion in the tool;
- TAC reviewed and commented on candidate indices;
- Project team conducted statistical modeling of the southern California field dataset to identify geomorphic thresholds and identify associations between intrinsic/extrinsic factors and channel responses;
- Project team selected a minimum set of indices and variables for inclusion in the screening tool based on criteria above, outcomes of statistical modeling, field observations, and expert judgment;
- Project team developed tentative overall structure of decision trees with nodes that are linked with checklists and simple probabilistic models;
- TAC reviewed and commented on the tentative structure of the screening tool;
- Project team streamlined and refined screening tool decision trees based on field testing;
- Members of the TAC participated in field testing and provided input to data requirements (commensurate with the uncertainty of the susceptibility rating), eases of use, and applicability to southern California conditions; and
- Project team finalized the field screening tool.

At the outset of this process, the TAC and project team converged on several guiding principles. First, susceptibility should be hierarchically assessed across watershed, valley, and channel-segment scales (*sensu* Frissell *et al*. 1986 and Montgomery and Buffington 1998). This guidance pointed to a tool that combined desktop Geographical Information System (GIS) based analysis with field reconnaissance. The TAC also recommended a transparent and process-based flow of logic. Accordingly, the project team identified a decision tree as a logical structure for the tool.

The TAC further recommended that the screening tool be risk-based and calibrated with regional data; that is, it would ideally provide a probabilistic framework for assessing the likelihood of accelerating channel adjustment processes and crossing geomorphic thresholds that is based on observations of streams in southern California. Indeed, geomorphic thresholds are real (Osman and Thorne 1988, van den Berg 1995, Bledsoe and Watson 2001b) and of particular concern in stream management. To be effective, susceptibility assessments should account for proximity to thresholds of rapid and complex shifts in channel form and processes. To this end, the Colorado State University (CSU) / SCCWRP project team performed an extensive field campaign across a gradient of stream types and contemporary anthropogenic influences as described below. The data provided by the field campaign was used to calibrate probabilistic models of braiding/incision, and bank instability risk that are embedded in the screening tool as probabilistic nodes in the decision tree framework.

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 screening ratings that are attained 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), incising sand channel near critical bank height (Very High), and alluvial fans (separate management strategies). In striving for a parsimonious tool, the project team considered an extensive set of candidate geomorphic metrics at several spatial scales. The literature review of fluvial classification systems and methods for assessing channel susceptibility (Bledsoe *et al.* 2008) also influenced the type, level, and precision of data collection required in the tool. Development of the screening tool consisted of compiling a set of previously suggested field metrics from the literature and testing those (and other metrics) through analysis at selected southern California field sites. Field forms, definitions, and supporting documentation were also refined through field testing with local managers.

Finally, the TAC and project team restricted the geomorphic settings that the tool would be applicable to by identifying two specific cases that fall outside the scope of this screening tool and warrant alternative management tools:

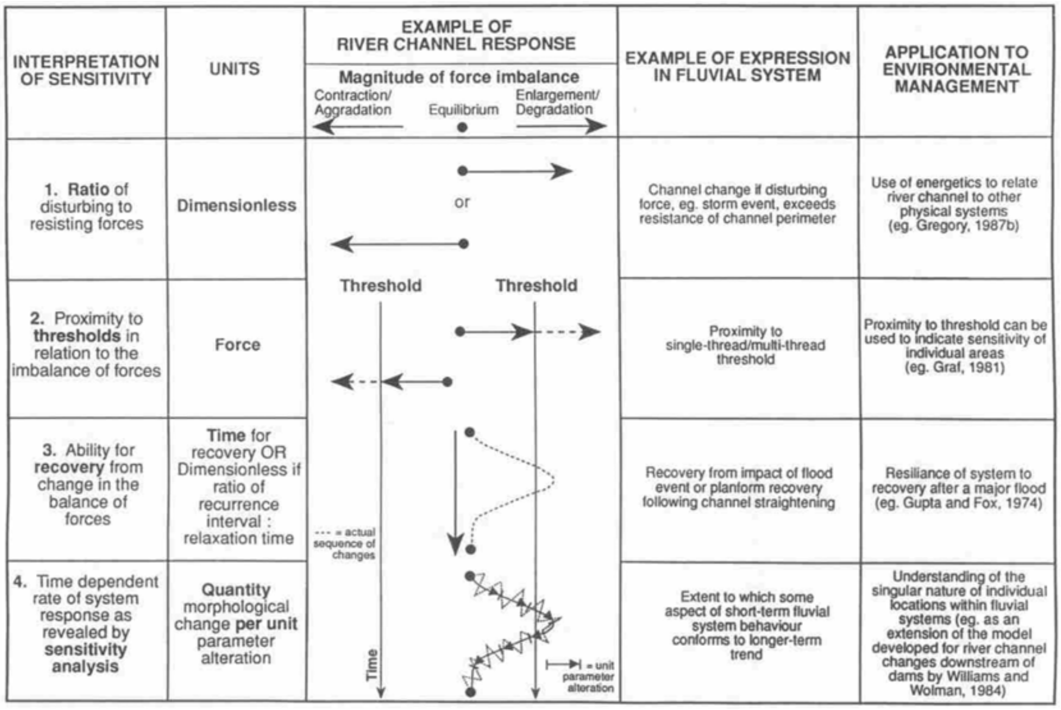
1) Alluvial fans
    - Alluvial fans are clearly very high-risk settings in need of special management requirements and modeling steps.
2) Estuarine confluences
    - Projects discharging directly to the ocean or tidal backwater warrant separate management due to the unique, generally low-risk boundary conditions.

Based on the guidance received from the TAC, the screening tool was developed with the following combination of features:

- Integrated field and office/desktop components;
- Separate ratings for channel susceptibility in vertical and lateral dimensions;
- Transparent flow of logic via decision trees;
- Critical nodes in the decision trees are represented by a mix of probabilistic diagrams and checklists;
- Process-based metrics selected after an exhaustive literature review and analysis of a large field dataset;
- Metrics balance fidelity to process, simplicity of measurement, and interpretability;
- Explicitly assesses proximity to geomorphic thresholds that were identified with field data from small watersheds in southern California;
- Avoids bankfull determinations, channel cross-section surveys, and sieve analyses, but requires a pebble count in some instances;
- Verified prediction accuracy of simplified logistic diagrams against more complex methods such as dimensionless shear-stress analyses, and the Osman and Thorne (1988) geotechnical stability procedure;
- Assesses bank susceptibility to mass wasting with a field-calibrated logistic diagram of geotechnical stability vetted by Colin Thorne;
- Regionally-calibrated braiding/incision threshold based on surrogates for stream power and boundary resistance;
- Incorporates updated alternatives to the US Geological Survey (USGS; Waananen and Crippen 1977) regional equations for peak flow(Hawley and Bledsoe, In Review);
- Does not rely on bank vegetation given uncertainty in future influence / difficulty of assessing root reinforcement, rooting depth/bank height; and
- Channel evolution model underpinning the tool is based on observed responses in southern California that is a modification of the Schumm *et al*. (1984) five-stage model to represent alternative trajectories of channel response.

The overarching goal of the screening tool as defined by the TAC and project team is to rapidly assess the susceptibility of a stream segment to hydromodification in its watershed context. Following Schumm (1985, 1991) and Downs and Gregory (1995; Figure 1), we define susceptibility as:

> *"the intrinsic sensitivity of a channel system to hydromodification as determined by the ratio of disturbing to resisting forces, proximity to thresholds of concern, probable rates of response and recovery, and potential for spatial propagation of impacts."*



INTERPRETATION OF SENSITIVITY	UNITS	EXAMPLE OF RIVER CHANNEL RESPONSE Magnitude of force imbalance	EXAMPLE OF EXPRESSION IN FLUVIAL SYSTEM	APPLICATION TO ENVIRONMENTAL MANAGEMENT
1. **Ratio** of disturbing to resisting forces	**Dimensionless**	or	Channel change if disturbing force, eg. storm event, exceeds resistance of channel perimeter	Use of energetics to relate river channel to other physical systems (eg. Gregory, 1987b)
2. Proximity to **thresholds** in relation to the imbalance of forces	**Force**		Proximity to single-thread/multi-thread threshold	Proximity to threshold can be used to indicate sensitivity of individual areas (eg. Graf, 1981)
3. Ability for **recovery** from change in the balance of forces	**Time** for recovery OR Dimensionless if ratio of recurrence interval : relaxation time		Recovery from impact of flood event or planform recovery following channel straightening	Resiliance of system to recovery after a major flood (eg. Gupta and Fox, 1974)
4. Time dependent rate of system response as revealed by **sensitivity analysis**	**Quantity** morphological change **per unit** parameter alteration		Extent to which some aspect of short-term fluvial system behaviour conforms to longer-term trend	Understanding of the singular nature of individual locations within fluvial systems (eg. as an extension of the model developed for river channel changes downstream of dams by Williams and Wolman, 1984)

Figure 1. Interpretation of sensitivity from Downs and Gregory (1995).

To achieve this goal in accordance with the guiding principles outlined above, the screening tool begins with an office component (*sensu* Vermont Agency of Natural Resources (VTNR; 2004) and Thorne (2002)) that takes advantage of the recent proliferation of GIS and aerial photography technology. Field reconnaissance is also required (*sensu* Downs and Thorne (1996)) with a goal of completing both field and office components in less than one day total. These initial assessments avoid detailed channel surveys but may require a minimum amount of field measurements such as median bed particle size (d_{50}). As such, screening assessments are largely based on quantitative – albeit simplified – metrics, rather than being wholly subjective.

Through combinations of decision trees, checklists, and regionally-calibrated probabilistic thresholds, the user arrives at susceptibility ratings of Low, Medium, High, or Very High for both vertical and lateral channel adjustments. Several photographs provide users with examples at various stages of the screening process. Although qualitative, the ratings are designed to have direct implications for the next phases in the review process by indicating the level of subsequent data collection and modeling that could be necessary.

Screening ratings can also foreshadow the ultimate level of mitigation that may be appropriate, although jurisdictions will likely tailor site-specific mitigation strategies using different suites of modeling tools that correspond to varying degrees of vertical and lateral susceptibility. For example, 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 (*sensu* VTNR (2004)) 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. Combined vertical and lateral ratings of '*Low*' correspond to a confined/bedrock channel or one that is fully reinforced and in good 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 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 to develop a mitigation strategy that addresses the potential for both vertical and lateral instability.

Beyond arriving at a clear and meaningful endpoint via a transparent flow of logic, the tool is designed with the understanding that geomorphic thresholds are real and proximity to such thresholds should be of great concern for informed stream management. Logistic regression analyses of braiding, incision, and bank stability directly and probabilistically assess proximity to geomorphic thresholds, and offer a framework for assessing risk that goes beyond expert judgment. Such objective quantifications of risk make a screening tool more easily transferable between regionally-diverse agencies, while the probabilistic framework adds a desirable level of flexibility such that jurisdictions may stratify screening ratings via locally-acceptable levels of risk (e.g., 10 vs. 50% probability of response). With the identification of geomorphic thresholds as a key aspect of the screening tool, the following chapters of this report are focused on describing:

- The details of the screening tool structure and its congruence with the stakeholder goals outlined above;
- How regional data were used to refine probabilistic nodes for incising, braiding, and mass wasting within that structure; and
- How a preliminary validation of that structure was performed with currently available data.

METHODS

Site Selection

In designing the field data-collection effort supporting the screening tool, the most central gradient and primary stratification for site selection in the study domain was the extent of urbanization. Equally important was to understand system dynamics independent of hydromodification as a reference condition. Consequently, we targeted undeveloped, developing/recently developed, and fully-developed watersheds. This resulted in an array of sites composing channel evolution stages from 'stable' single-thread to incising, widening, and braiding. While most channels of southern California are inherently dynamic, we define 'stable' for the purposes of this tool after Biedenharn *et al.* (1997):

> *"In summary, 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)."*

Interpreting the definition in the context of southern California, we must think in terms of relative scales about 'significant aggradation/degradation.' For example, consider a reach type/process domain (Montgomery, 1999; Montgomery and Buffington, 1997, 1998) of confined, step-pool/bedrock that temporarily aggrades with finer material (i.e., gravels and smaller) into a plane-bed form following a fire. Such a system could still warrant a 'stable' rating if, over a period of gradual flushing, it returned to the pre-fire form (as we have witnessed). There are also regional examples of braided channels that have maintained a relatively constant width for over 50 years. Although not traditionally considered 'stable,' such special cases of braided systems could fall under a broader interpretation of the Biedenharn *et al.* (1997) definition.

Perhaps more appropriately in the context of hydromodification effects, 'stable' could tentatively be defined as a channel that has not been significantly affected by adjacent land uses or reaches upstream/downstream through considerable headcutting, widening, or planform shifts over the engineering time frame. Empirical evidence suggests that active widths and slopes of some channels in southern California have evolved to absorb intrinsic pulses in flow and sediment without such complex adjustments (e.g., a detailed analysis of historic (1947, 1967, 1976, 1980, 1985, and 1989) and present day high-resolution aerial photography, USGS gauge records (1930 to 1979), and field assessments of Topanga Canyon by the project team). Indeed, analysis of time-series (1947 to present) aerial photographs which were available at 30 out of 31 study reaches seemed to indicate a tendency toward relative stability in confined reaches and relative instability in broad, unconfined valley bottoms. Based on discussions with stakeholders including municipal managers, the project team identified a preliminary set of channel segments that balanced the number of rapidly adjusting channels in various stages of incision and/or widening (*sensu* Schumm *et al*. 1984 and Downs and Gregory 1995) with those that have shown only relatively minor responses at the decadal time scale in terms of headcutting, widening, or planform shifts. The set of preliminary sites also spanned a variety of geologic, topographic, and hydroclimatic settings within the study region.

We performed field reconnaissance at more than 50 candidate stream reaches within our targeted domains. The channel attributes examined in the field included both physical and logistical parameters such as accessibility and degrees-of-freedom in potential response to urbanization. For each candidate site we specifically examined:

- 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 patterns;
- Proximity to tributary confluence that would facilitate a survey spanning variability in water and sediment supply; and
- Location and extent of armoring, grade control, and encroachment.

We excluded fully-engineered concrete/riprap-lined channels in good condition due to a lack of adjustability in either form or substrate composition. Following the initial investigations, we performed a 'gap analysis' to ensure a wide distribution of sites across regionally-important gradients such as slope, bed material, channel type/planform, evolution stage, valley setting, drainage-basin size, geopolitical setting, and extent of urbanization. The 'gap analysis' and further communication with regional stormwater managers resulted in the consideration and inclusion of two additional study reaches in San Bernardino County (Yucaipa Creek and Oak Glenn), and two coarse-grained reaches in Ventura County (Stewart Canyon and San Antonio Creek). Ranges and means of selected watershed and geomorphic variables are presented in Table 1.

Table 1. Summary of key gradients across 83 morphologically-distinct sub-reaches used in screening-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	5 - 52	26	%
Sub-Reach	channel slope	0.2 - 15	2.6	%
	top width at 2-year flow	0.2 - 62	11	m
	median grain size	0.125 - 500	26	mm

We focused on small watersheds because most of the larger streams in the region have been substantially altered in form (concrete/riprap lining and channelization) and/or flow (dams/diversions). The spatial distribution of project stream reaches is shown in Figure 2.

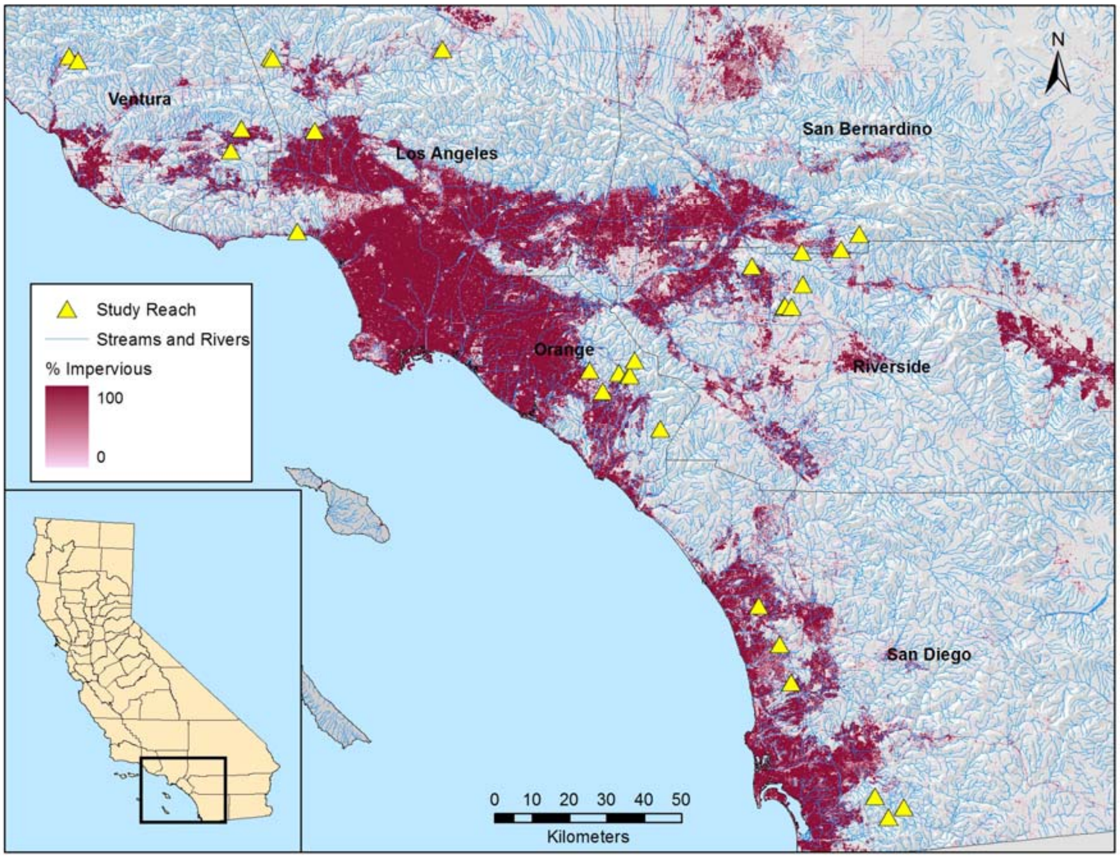


Figure 2. Overview of reaches sampled for screening-tool development.

The final set of 52 candidate locations for conducting field surveys was reduced through the selection-criteria analysis to 31 streams with 83 geomorphically-distinct sub-reaches or 'sites' (Table 2). Photographs and cross sections of each site are depicted in Appendix A, while watershed-, reach-, and cross-section-scale metrics are summarized in Appendix B. An individual stream segment may have several 'sites' due to significant differences in form (incised vs. widening), flow (additional tributaries), or valley setting (confined vs. alluvial valley). While interconnected, we felt the loss of independence was outweighed by the benefits gained in having such paired data to isolate differences such as valley setting or form alone (i.e., 'stable' vs. incising vs. widening, all with the same flow and parent material).

Substituting space for time by capturing differing response stages along a single segment is often necessary to make inferences on projects with fixed start/stop dates such as this. Such observations should be tempered with the understanding that average rates of change decrease as time spans increase (Schumm 1991); therefore, analyses were coupled with audits of historical aerial photography to bolster any space-for-time inferences.

Table 2. Summary of field sites.

Site Name	County	Watershed	Catchment Area (km^2)	% Urban (approximate)	General Bed Material	Planform
Santiago Creek	Orange	Santa Ana River	17.40	Low	Sand/Boulders	Meandering
Hasley Canyon Site 1	Los Angeles	Santa Clara River	4.80	Medium	Sand/Cobbles	Meandering
Hasley Canyon Site 2	Los Angeles	Santa Clara River	4.80	Medium	Sand/Cobbles	Straight
Hicks Canyon	Orange	Newport Bay	3.30	Low	Sand/Cobbles	Meandering
RC Site 7 Avery Canyon @ Gibbel Rd Hemet	Riverside	Santa Ana River	9.52	Low	Sand/Gravel	Meandering
Agua Hedionda @ Melrose	San Diego	Agua Hedionda	27.66	High	Gravel/Boulders	Meandering
Dry Canyon	Ventura	Calleguas	3.15	Medium/High	Sand/Gravel	Meandering
Hovnanian (Aliso)	Los Angeles	Los Angeles River	4.80	Medium	Sand/Gravel	Meandering
San Bernardino Site 1	San Bernardino	Santa Ana River	ND	Low/Medium	Sand/Gravel	Meandering
Dulzura Crk @ Little Cedar Canyon	San Diego	Otay	7.24	Very Low	Gravel/Cobbles	Meandering
Proctor Valley	San Diego	Otay	7.70	Medium	Sand/Gravel	Meandering
RC Site 12 Lk Perris State Park	Riverside	Santa Ana River	0.50	Medium/High	Sand/Gravel	Meandering
Lake Perris Site 2	Riverside	Santa Ana River	0.50	Very Low	Sand/Gravel	Meandering
Lake Perris Site 3	Riverside	Santa Ana River	0.50	Very Low	Sand/Gravel	Meandering
RC Site 14 Contour Ave Nuevo	Riverside	Santa Ana River	14.76	Low	Sand/Gravel	Braided
Alt Perris Lake Site	Riverside	Santa Ana River	ND	Low	Sand	Braided
Dulzura Creek @ CA94	San Diego	Otay	69.66	Very Low	Gravel/Cobbles	Meandering
Acton	Los Angeles	Santa Clara	9.50	High	Sand/Cobbles	Meandering
Borrego Canyon Wash	Orange	San Diego Creek	7.56	Medium/High	Sand/Cobbles	Braided
Topanga Canyon/Creek	Los Angeles	Malibu	37.60	Very Low	Gravel/Boulders	Meandering
Challenger Park	Ventura	Calleguas	5.90	Medium	Sand/Gravel	Meandering
McGonigle-3	San Diego	Penasquitos	ND	Very High	Sand/Cobbles	Meandering
San Juan Creek	Orange	San Juan Creek	58.82	Very Low	Sand/Boulders	Meandering
RC Site 13 Pigeon Pass Valley	Riverside	Santa Ana River	8.42	Medium/High	Sand/Gravel	Meandering
Stewart Canyon	Ventura	Ventura River	4.59	Medium	Boulders	Meandering
Santiago Nat Load	Orange	Santa Ana River	ND	Very Low	Gravel/Boulders	Meandering
Santiago Nat Load	Orange	Santa Ana River	ND	Low	Gravel/Boulders	Straight
San Elijo Canyon (Escondido Creek)	San Diego	San Elijo	ND	High	Gravel/Boulders	Meandering
San Antonio Creek	Ventura	Ventura River	ND	Low	Gravel/Cobbles	Straight
Alt RC-2 Site	Riverside	San Jacinto Valley	ND	Low	Sand/Gravel	Meandering
Yucaipa Creek @ Mesa Grande	San Bernardino	Santa Ana River	ND	Low/Medium	Sand/Gravel	Braided
Oak Glenn	San Bernardino	Santa Ana River	ND	Low	Sand/Gravel	Straight

ND = not determined

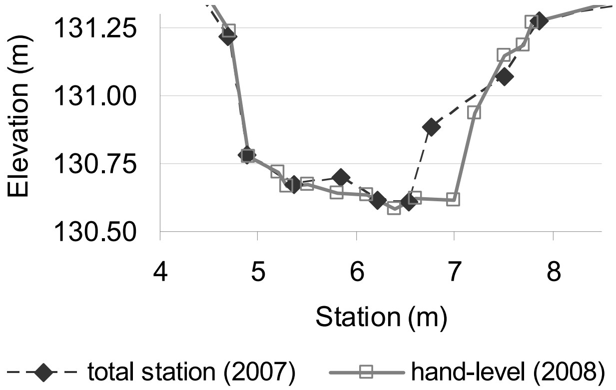
Field and GIS Data Collection

Bed material, cross-sectional and longitudinal channel geometry, valley setting, and watershed data were collected at each unique site. Sites were located at representative cross sections within a study reach away from major fluvial influences such as bends and constrictions. For example, in a pool-riffle channel type, the transect (i.e., site) would be placed at a representative riffle section and oriented perpendicularly to flow direction. 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 (2001a). Unbiased particle selection was secured through equally-spaced sampling frame transects across riffle sections after Bunte and Abt (2001b). Phi template measurements following Potyondy and Bunte (2002) are known to efficiently return more consistent readings than individual b-axis measurements, which is important for a tool that will be applied across diverse agencies and staff.

For sites greater than roughly 20% sand by volume, both sieving and phi-sampling were employed. Volumetric gradations (pebble counts) were composited with distributions by weight (sieve analyses) via a combination of rigid and flexible procedures designed by D. Dust and K. Bunte (Pers. Comm. 2008), and typically converged to similar median particle diameters.

Geometric data collection was primarily guided by Harrelson *et al.* (1994), with two levels of precision for cost optimization. A subset of 13 of the 31 stream reaches (i.e., 34 of 83 sites) was surveyed at a higher level of precision based on their utility for detailed fluvial/sediment-transport modeling in subsequent phases of the project and for long-term monitoring. At these sites, cross sections were set using semi-permanent rebar benchmarks spaced at short intervals (≤5 channel widths) and surveyed with high-precision instruments. Points were translated to Global Positioning System (GPS) coordinates with lateral and vertical accuracies of 3 and 1 cm, respectively.

In contrast, the remaining eighteen ‘synoptic’ stream reaches (i.e., 49 of 83 sites) were surveyed with fewer cross sections and less precision as a tradeoff for collecting data at a larger number of reaches across a wide range of settings. A commercial-grade GPS unit located sites to within *ca.* 1 to 10 m of true position, while cross sections and profiles were surveyed with 2x magnification hand-levels, fiberglass tapes, and pocket rods. To attain reasonable accuracies, shots were kept to distances less than or equal to 5 m with a fixed-height instrument stand for effective stabilization of the hand-level. As a check, three cross-sections with modeling-level precision were resurveyed using the synoptic survey methods at an average vertical error rate of 0.5 to 0.6 mm per lateral meter over 20- to 50-m transects. Figure 3 presents an example of the congruity between the two approaches (see unchanged top of bank locations, left bank, and bottom left portion of main channel). The repeated surveys (October 2007 vs. January 2008) also quantified enlargement due to mass wasting of the right bank following the fires of October 2007.



(a) Comparison of 'modeling' (total station, 2007) and 'synoptic' (hand-level, 2008) surveys looking downstream

(b) Photograph looking upstream capturing interim failure of right bank

Figure 3. Main channel of cross section D at Hicks Canyon.

Finally, although equipment differed between detailed modeling and synoptic sites, longitudinal profiles were surveyed in similar ways. All grade breaks along the channel thalweg were captured including heads and toes of riffles, knickpoints, and other bedform features. Important lateral transitions were also shot such as bends, thalweg crossings, etc. This kept shots to relatively short intervals, which were placed at a maximum of ~15 m with high-precision instruments, and 5 m with screening equipment.

GIS data were acquired from public-domain sources such as the USGS, US 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. Unfortunately, empty fields in some USDA polygons compromised the capacity for conducting analyses with Natural Resources Conservation Service (NRCS) soil types and application of the agency's Curve Number method for estimating flow. Yet most geospatial sources were thorough and complete. Indeed, two fields were calculated from sources spanning different time periods: roadway vectors (2000 vs. 2007) and mean annual precipitation polygons (1900 to 1960 vs. 1961 to 1990). General resolution of these source data was such that their precision was typically on the order of 1% of the measurement (e.g., 10-m National Elevation Dataset (NED) over 1 km of channel).

ArcMap software by Environmental Systems Research Institute (ESRI), including extensions such as 'spatial analyst,' was used to optimize GIS measurements where possible. For tasks such as delineating watersheds and determining flow paths, automated results from NED processing 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. Prior to widespread use in clipping other basin-wide parameters, two separate personnel familiar with the field sites and the associated watersheds provided independent quality assurance/quality control (QA/QC) of watershed boundaries and remedied any discrepancies.

Hydrology, Hydraulics, and Sediment Supply

Stream discharge was estimated using a variety of empirical methods including the NRCS Curve Number, Rational Method, USGS regional equations, and equations developed specifically for this project. The latter equations were developed specifically for small watersheds (1.4 to 270 km^2) within the study domain and incorporate the effects of urbanization. Five similarly performing models were developed using a range of hydrogeomorphic variables; however, for practicality we selected one model for screening tool application based on its superior cross-validation performance (Hawley and Bledsoe, In review). The model was a revision to the USGS format (Waananen and Crippen 1977), with a built-in urbanization factor at lower return intervals using total impervious area:

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

$$Q_{10} = 18.2 * A^{0.87} * P^{0.77} \qquad \textbf{(Eq. 2)}$$

where:

Q_i = instantaneous peak flow rate of return (ft^3/s) over interval i (years);
A = total contributing drainage area (mi^2);
P = mean annual area-averaged precipitation via USGS-delineated shapefile using rainfall (inches) records from 1900 to 1960;
$e^{()}$ = mathematical constant e (i.e., 2.718…) raised to the power of the parenthetic expression; and
Imp = 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 hydraulic-geometry relationships for each site. Expressing hydraulically significant variables such as area, hydraulic radius, and top width as functions of depth (as opposed to functions of flow) creates computational ease and facilitates the recognition of spatial patterns across reaches (Buhman *et al*. 2002). This included power functions for area and hydraulic radius, as well as a predictor of top width that fluctuated across power, linear, logarithmic, or exponential forms.

Normal depth for respective flows was iteratively solved via the Manning (1889) equation and at-a-station hydraulic geometry (hydraulic radius power function). Guided by Chow (1959), values of Manning n were estimated in the field. Compiled hydraulic results were used in development and calibration of the screening tool.

Index Development and Statistical Analysis

A variety of potential indices and descriptors were considered for inclusion in the screening tool. Emphasis was placed on metrics that could be rapidly assessed in the field but nevertheless have a clear and direct physical linkage with channel response. Selection of indices was ultimately based on a perceived tradeoff between the level of effort required to quantify/measure a particular metric and how much it enhances the physical basis and prediction accuracy of the screening tool as suggested by statistical analysis of the field dataset.

In considering a large pool of indices and descriptors for inclusion in the screening tool, the problem of variable reduction was approached in part by: 1) stratifying the variables by the processes that they represent in the vertical and lateral dimensions (e.g., erosive power vs. boundary resistance vs. proximity to threshold); and 2) ranking the various descriptors in terms of their fidelity to the key physical processes, their scale, and their ease of measurement/data requirements. Many of the potential descriptors that could serve as direct surrogates for key processes, such as the amplification of sediment-transport capacity, require various combinations of detailed hydrologic modeling and/or time-intensive surveys of channel geometry that precluded their inclusion given the practical constraints described above.

The descriptors and weighting schemes employed in previously published tools for assessing channel stability were also considered in identifying a set of candidate descriptors to consider in screening tool development. For example, Table 3 illustrates how the channel stability rating schemes of Simon and Downs (1995) and Johnson *et al*. (1999) employ subjective weighting schemes for stability indices that reflect watershed context and different styles of vertical and lateral adjustment.

The screening tool was refined by assessing the degree to which candidate descriptors effectively predict and provide interpretable surrogates for the complex physical processes and boundary conditions that give rise to the myriad of channel forms and responses observed in the field. Candidate descriptors of watershed, geomorphic, hydraulic, and sedimentary characteristics were computed for each site and tested for significance in segregating data into various stability groupings that were consistent with theory and exploitable for the screening tool. Several statistical tools were employed, including multivariate regression using best subset, forward, and backward elimination, as well as logistic regression analysis.

Statistical analyses of predictor variables that could be quantified with an acceptable level of field effort suggested that the primary controls on channel enlargement in the field dataset were valley confinement, median bed material size, distance to grade control scaled by channel width, and an index of erosion potential based on cumulative sediment-transport capacity (Hawley 2009). Accordingly, valley width, median bed material size, armoring potential and distance to grade control were selected as important descriptors for inclusion in the field screening tool.

Table 3. Variables utilized in previously published tools for assessing channel susceptibility.

Simon and Downs (1995)		
Variables[a]		**RW[b]**
Degree of incision	V, L	3
Simon six-stage CEM for incised channels	V, L	3
Primary bed material	V	3
Degree of constriction	C	3
Bed/bank protection	V, L	2
Streambank erosion – mass wasting vs. fluvial	L	1
Streambank instability – % banks failing	L	1
Woody vegetative cover – "riparian"	L	1
Bank accretion	L	1
Hillslope material	C	1
% Hillslope eroding	C	1
Severity of side slope erosion	C	1

Johnson *et al*. (1999)		
Variables[a]		**RW[b]**
Shear stress ratio	V	3
Bed material consolidation and armoring	V	2.4
Vegetative bank protection	L	2.4
Mass wasting or bank failure	L	2.4
High flow angle of approach to bridge	Bridge	2.4
Distance from meander impact point	Bridge	2.4
Percentage of channel constriction	Bridge	2.4
Bank soil texture and coherence	L	1.8
Average bank slope angle	L	1.8
Bar development	L	1.8
Bank cutting	L	1.2
Debris jam potential	Bridge	0.6
Obstructions, flow deflectors, sediment traps	Bridge	0.6

[a] Bridge = specific, intended for bridge crossing analysis; C = watershed/valley context; and L, V = lateral and vertical variables that describe susceptibility to adjustment, respectively.

[b] RW = relative weight values in this column indicate which variables have the most influence on the overall susceptibility score.

General instability (incision, enlargement, and active braiding) was also predicted by various ratios of erosive energy to bed material. Patterns in bank mass wasting as influenced by bank angle and height were also apparent in the field data. In both instances, statistical analyses suggested distinct breaks between channel stability clusters that would be plausibly represented as probabilistic thresholds within the decision trees as described below.

We tested hundreds of models in calibrating the probabilistic decision nodes of the decision trees. 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 to be associated with a greater likelihood of geomorphic instability in unarmored and unconfined valley settings. Nevertheless, further calibration is essential as there is a paucity of stable, unconfined single-thread channels in the dataset, despite the gap analysis described above.

A variety of descriptors including shear stress, dimensionless shear stress, stream power, and specific stream power showed promise in isolating high-energy unstable systems from low-energy stable systems in unconfined settings (Schumm 1977, Simons and Simons 1987, Brookes 1988, Chang 1988, Nanson and Croke 1992, Rhoads 1995), but dependence on accurate estimates of channel slope, depth, and/or width made them impractical for a screening-level assessment. A more pragmatic index was a surrogate for specific stream power after 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 semiarid 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:

$$\omega \approx \gamma/\alpha * S_v * Q_{bf}^{0.5} \qquad \textbf{(Eq. 3)}$$

where:

ω = function of valley slope, estimated bankfull or dominant discharge, and an assumed regime width that varies between sand- and gravel-bed rivers, i.e., width = $\alpha * Q^{0.5}$

α = regression coefficient computed for a particular collection of streams, specific (i.e., unit) stream power = total stream power/width, and total stream power = $\gamma * Q * S$

γ = specific weight of the water and sediment mixture (e.g., often assumed to be that of water = 9810 N/m^3).

Bledsoe and Watson (2001b) further simplified the approach by dropping the coefficients γ and α, to eliminate dependence on variable regime constants across regional settings. Their 'screening index' is adapted as:

$$\omega_v = S_v * Q_{10}^{0.5} \qquad \textbf{(Eq. 4)}$$

where:

ω_v = function of valley slope and estimated mean-annual discharge represented by the 10-year recurrence interval.

By performing logistic regression of the screening index relative to median particle diameter (d_{50}), Bledsoe and Watson (2001b) discerned states of incising, braiding, and stable-meandering (i.e., sinuosity $\geq$1.3) with over 80% accuracy.

Logistic regression offers utility when analyzing binomial distributions (e.g., stable vs. unstable) in that 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 (Menard 1995, Christensen 1997, Ott and Longnecker 2001). Such a continuous probabilistic framework has clear benefits for application in a screening tool that is concerned with categorical states; not only can response thresholds be identified, but the *proximity* to such thresholds can be directly assessed regarding the risk of 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:

$$p = \frac{\exp(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n)}{1 + \exp(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n)} \qquad \textbf{(Eq. 5)}$$

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. Because linear combinations of independent predictor variables can vary between $-\infty$ and $+\infty$, parameter interpretation is performed in the context of the odds ratio (i.e., p/(1 - p)), which in conjunction with a logarithmic transformation results in a dependent variable that will likewise vary between $-\infty$ and $+\infty$. Referred to as the logistic transformation, the log of the odds ratio ($p^{/}$) becomes a function of the standard linear-regression model:

$$p^{/} = \ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n \qquad \textbf{(Eq. 6)}$$

Logistic regression models are generally fit using maximum likelihood techniques via an iterative process that optimizes parameters to maximize the probability of observing the data that were actually observed. The SAS software package (SAS Institute 2004) was used to make the iterative procedure more efficient. Parameterization routines which used both the Fisher's scoring method and Newton-Raphson method were used and converged on identical models to $\geq$3 significant figures.

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 via algebraic transformation of Eq. 6. Model performance was assessed via the χ^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 0. The χ^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. The percentage of observations correctly classified also served as a tangible measure of overall model performance.

Significance of individual predictor variables was assessed using standard errors, confidence intervals, χ^2 statistics, and associated p-values. Potential effects of collinearity were minimized 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. Among others, they included influence plots of Pearson and deviance residuals, the hat matrix diagonal, and observation-withholding schemes such as the standardized difference in parameters (DFBETAS) and change in deviance (DIFDEV). Although influential cases of outlying observations were identified, they do not necessarily imply problems in the model (Menard 1995). Due to the fact that there was no physically based reason for excluding those data, they were retained in the models to present a more realistic range of risk and a better representation of misclassification rates that can be expected in model application.

Only fully-adjustable, unconfined, alluvial study sites were used to develop models for braiding and incision risk. High-energy confined/bedrock systems, including reaches at Proctor, Topanga, San Juan, Stewart, Santiago, Silverado, and Escondido, were prominently sorted by grain size alone and were not included in the final logistic regression analyses due to minimum degrees of freedom. ‘Stable’ sites were considered single-thread channels in unconfined alluvial valleys that were not observably incising, widening, or braiding (e.g., Dulzura and Acton). This included several cases of ‘recovered’ sites; that is, sub-reaches that had undergone evolutionary sequences and returned to some semblance of single-thread quasi-equilibrium (e.g., Borrego and McGonigle). Data at ‘constructed’ sites with either vertical or lateral artificial reinforcement were not used in these analyses.

Sites classified as ‘incising’ and ‘widening’ were those with significant incision (i.e., nearing or exceeding critical bank height) and/or active bank failure. Finally, ‘braided’ sites were broadly defined with the objective of segregating all laterally-dynamic systems with multiple flow paths following Leopold and Wolman (1957). As such, any sub-reach taking a minimum of two actively adjusting flow paths at small to moderate flow events was included. This definition captured systems with a wide range of sediment supplies, flow types, and cases of vegetated bars, which other classification systems may have considered ‘anastamosing’; however, there was little justification to treat them as being statistically different for the purposes of the screening tool, as they all included lateral dynamics/susceptibility.

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 (summarized in Appendix C) 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. For detailed procedures of special cases, see Appendix A. Stability of each bank was rated via a detailed assessment of the extent of mass wasting (absent, broken, complete, and failed), fluvial bank erosion (significant and insignificant), consolidation (moderate/well consolidated, 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 global stability rating of stable/unstable geometries. For example, the height and angle of a failed bank that has slumped to the angle of repose has little utility in identifying the critical dimensions that caused the failure.

As consolidation can be particularly subjective, the intention of the rating scheme was to segregate geotechnical capacity classes for applicability to mass-wasting analyses. A summary of their ratings are as follows:

- Risk of bank failure more attributable to fluvial forces / removal of individual particles:

  - Unconsolidated – bank composed of alluvial material that until recently was the channel bed (< *ca.* 10 years) with failures evident at the angle of repose of sand (*ca.* 30°). Block/ped sample (2.8 cm x 2.8 cm) difficult to attain due to crumbling.
  - Poorly consolidated – bank materials, including cases of historic alluvium, have sufficient settling time to show at least some consolidation. Block/ped sample attainable, but can be crushed between fingers.
- Bank failure can be attributable to mass wasting and/or fluvial erosion:
  - Moderately- to well-consolidated – bank composed of individual particles are difficult to distinguish even with close inspection of the bank with consolidation much greater than that of recent/historic alluvium. Block/ped sample cannot be crushed between fingers.

Because streams in southern California demonstrated relatively little cohesion in general, shallow slips and failures in composite banks were often analyzed as possible mass failures given that failures often result from a combination of weakening, fluvial, and mass failure processes (Hooke 1979, Thorne 1982, Beatty 1984, Lawler 1992, Lawler *et al.* 1997) and pre-failure data were largely lacking. In conclusion, the various approaches are most concisely summarized via the precautionary principle; that is, in cases of uncertainty we erred on the side of being protective given the screening level application of the tool.

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:

$$H_c = \frac{4c^{/}\sin\alpha\cos\phi^{/}}{\gamma\left(1-\cos\left(\alpha-\phi^{/}\right)\right)} \qquad \textbf{(Eq. 7)}$$

where:

H_c = critical bank height required to generate instability with respect to slab failure via mass wasting;
$c^{/}$ = effective cohesion (kPa) of bank material;
α = bank angle (°);
$\phi^{/}$ = effective friction angle (°) of the bank material; and
γ = 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:

$$H_{cz} = H_c - z \qquad \textbf{(Eq. 8)}$$

$$z = \frac{2c^{/}}{\gamma}\tan\left(45+\frac{\phi^{/}}{2}\right) \qquad \textbf{(Eq. 9)}$$

where:

H_{cz} = critical bank height required for mass-wasting failure with a tension crack (m); and
z = 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 between 0 and 40 kPa (~800 lb/ft^2) with respect to measured/typical ranges from other regions (Lawler *et al*. 1997, Simon *et al*. 2000). Because the presence of pore-water pressure is unknown, and values were not directly measured but fitted within the constraints of measured data, these regional estimates would be more appropriately termed *operational* stress parameters (C. Thorne, Pers. Comm., 2009).

To assess relative severity of potential lateral adjustments, it was necessary to develop an index to represent the width of a valley that the channel could occupy if lateral adjustments were initiated. The valley-width index is defined as:

$$VWI = W_{valley} / W_{ref} \qquad \textbf{(Eq. 10)}$$

where:

VWI = function of valley bottom width relative to channel width, W_{valley} is measured between hillslope grade breaks at the valley floor, and W_{ref} is approximated by a regional relationship for top width as a function of Q_{10}, developed using stable single-thread unconfined sites.

RESULTS AND DISCUSSION

Screening-Tool Risk Types

The relative susceptibility of a stream reach to hydromodification effects can be assigned based on four screening ratings (Table 4). The ratings are designed to provide not only an indication of likely hydromodification response, but also to identify logical implications regarding the next phases of data collection and modeling. These ratings may also inform decisions regarding appropriate management or mitigation strategies.

Table 4. Screening ratings and rating definitions for channel susceptibility to hydromodification.

Screening Rating	Rating Definitions
LOW	• Low ratio of disturbing forces to resisting forces
	• Far from geomorphic thresholds of concern (based on explicit quantification of probability if feasible – <1% probability of exceedence)
	• Relatively rapid relaxation time
	• Low potential for positive feedbacks, nonlinear response, sensitivity to initial conditions
	• Very limited or no spatial propagation (*ca*. 10 m)
MEDIUM	• Moderate ratio of disturbing forces to resisting forces
	• Not proximate to geomorphic thresholds of concern (based on explicit quantification of probability if feasible – e.g., <10% probability of exceedence)
	• Moderately rapid relaxation time
	• Low to moderate potential for positive feedbacks, nonlinear response, sensitivity to initial conditions
	• Local spatial propagation, contained within *ca*. 100 m
HIGH	• High ratio of disturbing forces to resisting forces
	• Proximate to geomorphic thresholds of concern (based on explicit quantification of probability if feasible – e.g., >10 to 50% probability of exceedence)
	• Relaxation time may be relatively long given magnitude and spatial extent of change
	• Moderate to high potential for positive feedbacks, nonlinear response, sensitivity to initial conditions
	• Potential spatial propagation – headcutting/base-level change upstream and downstream but contained within *ca*. 100 to 1,000 m domain of control

Table 4. Continued

Screening Rating	Rating Definitions
VERY HIGH	• High ratio of disturbing forces to resisting forces
	• At geomorphic thresholds of concern (based on explicit quantification of probability if feasible – e.g., $\geq$ 50% probability of exceedence)
	• Relaxation time may be relatively long given magnitude and spatial extent of change
	• High potential for positive feedbacks, nonlinear response, sensitivity to initial conditions
	• Potential widespread spatial propagation – headcutting/base-level change upstream and downstream uncontained within *ca*. 1,000 m domain of control
	• Specifically, the VERY HIGH rating is reserved for the following geomorphic thresholds/states (clear and present danger): o **Vertical** ▪ Currently unstable (CEM Type III or IV) with incision past critical bank height for mass wasting and active bank failure ▪ Currently stable (CEM Type I or II) with banks less than critical height, but p $\geq$ 50% for incision or braiding in labile bed (d_{50} < 16 mm) with ineffective/absent grade control o **Lateral** ▪ Currently unstable with active braiding/extensive mass wasting/fluvial erosion (> 50% of banks) in a wide valley ▪ Currently stable consolidated bank in wide valley with High Vertical rating combined with p > 10% for mass wasting ▪ Currently stable unconsolidated banks with fine toe material in wide valley with High Vertical rating

The field screening components are designed to have a flow of logic that builds a weight of evidence toward an overall conclusion (Figure 4). One begins by examining the existing state and response, making inferences regarding susceptibility. Next, they examine the boundary materials, bounded by clear regional end members that correspond to Low and Very High susceptibilities. For intermediate/transitional settings, we then consider: 1) identifiable risk factors, 2) proximity to geomorphic thresholds, and 3) ratio of disturbing to resisting forces. Finally, a rating of Low, Medium, High, or Very High is assigned.

Details of the indices and field rating systems are provided in the *Field Manual for Assessing Channel Susceptibility* (SCCWRP Technical Report 606; Bledsoe *et al*. 2010). The balance of this report provides a summary of the risk-based models produced to support the screening tool and a description of preliminary testing of the screening tool.

Assessing Proximity to Geomorphic Thresholds

Two geomorphic thresholds were identified as central components in the screening tool: 1) a stability criterion based on the screening index vs. d_{50}, and 2) a bank stability threshold based on bank height and angle of stable vs. banks exhibiting significant mass wasting (Figures 5 and 6).

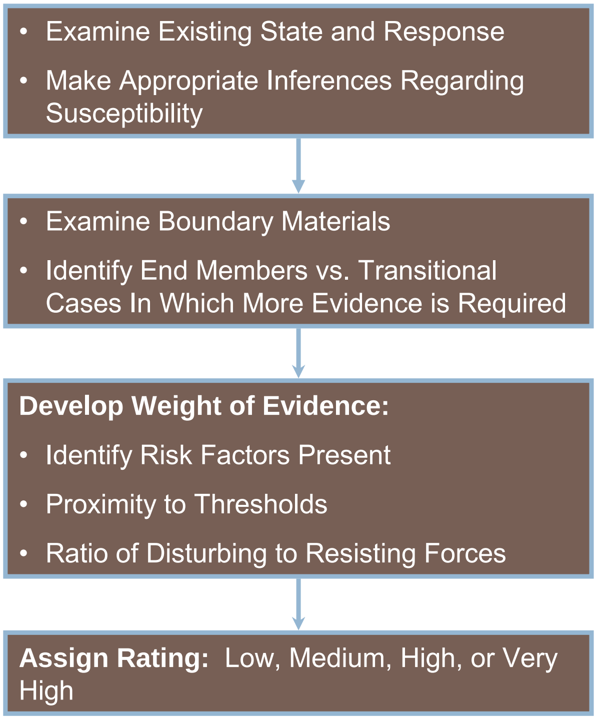
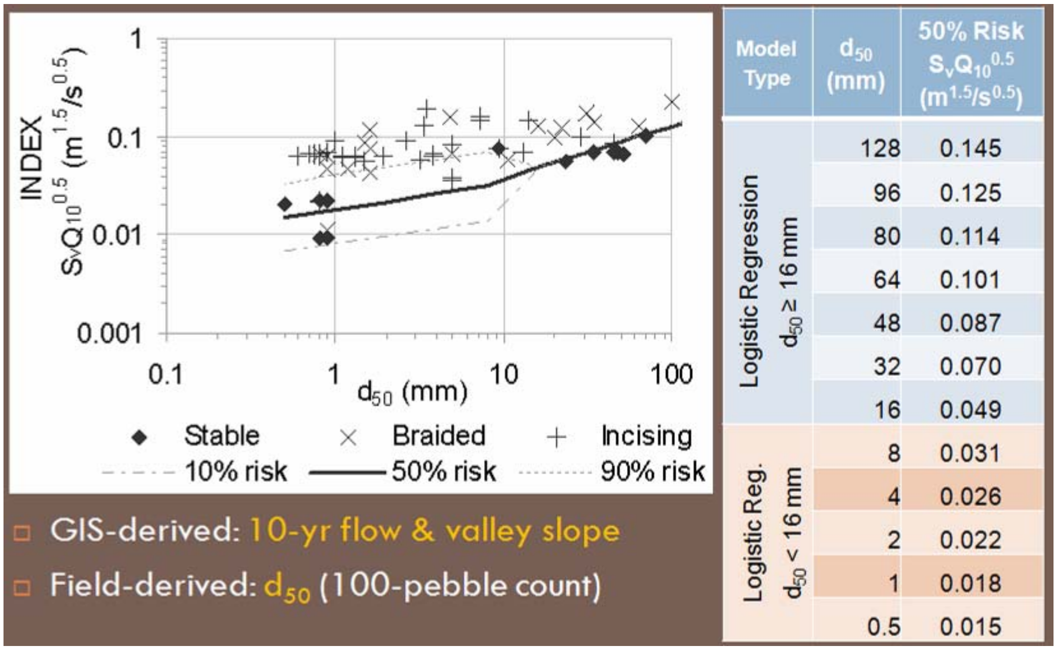
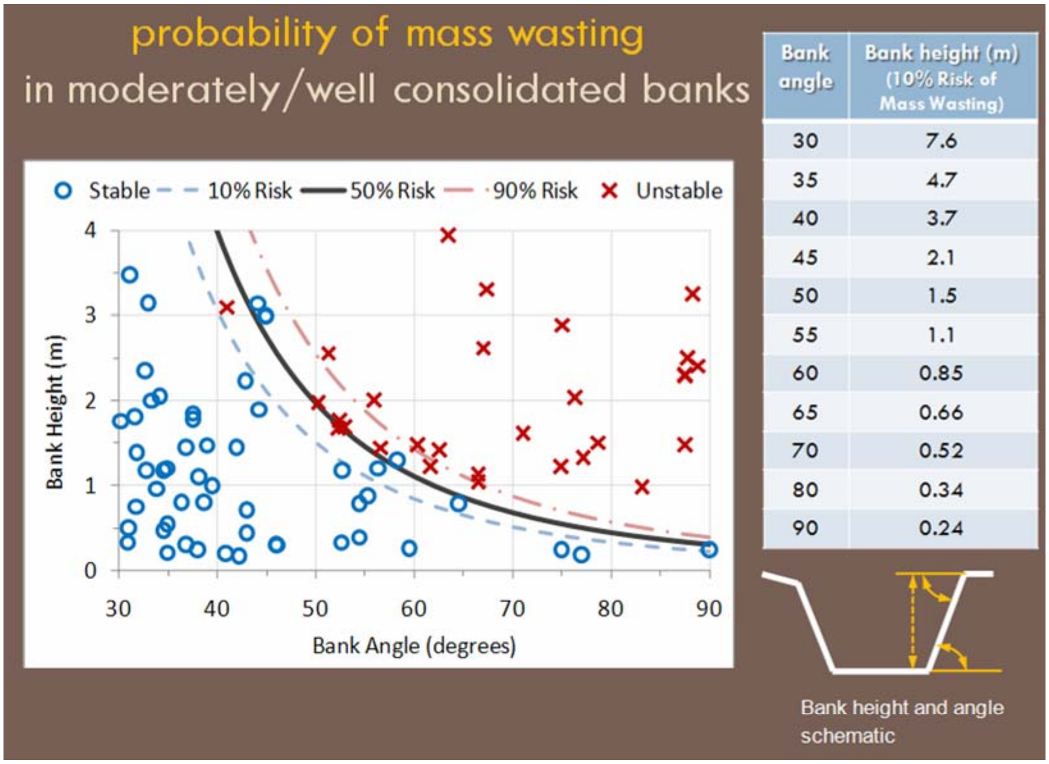


Figure 4. Logical flow of susceptibility decision trees.



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

Figure 5. Probability of incising/braiding based on logistic regression of screening 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

Figure 6. Probability mass wasting diagram.

Logistic regression analyses discriminated between states of incising, braiding, and mass wasting relatively well with model significance ranging p ~ 0.001 to p < 0.0001 (Table 5). Particularly in regards to identifying unstable systems, the models had >90% classification accuracy. The sole case of poor performance was in correctly classifying stable systems as stable; however, from a conservative standpoint this misclassification is the least problematic.

Table 5. Performance measures of 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}	$S_vQ_{10}^{0.5}$		
Pr(incising or braiding) $0.5 \le d_{50} \le 100$ mm	<0.0001	0.0009	0.0006	(52/54) 96%	(8/13) 62%
Pr(incising or braiding) $d_{50} \ge 16$ 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%

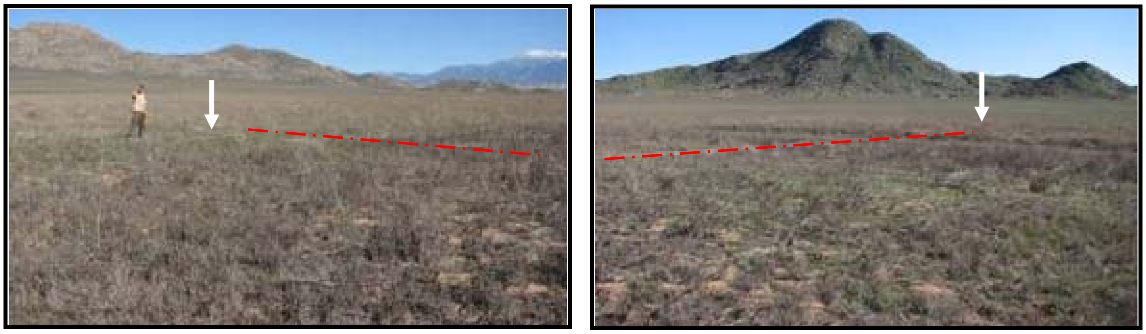
Logistic regression analyses successfully segregated states of incising and braiding relative to stable unconfined single-thread settings with relatively narrow levels of overlap. Although many combinations of variables were tested for significance, using the 'screening index' vs. d_{50} scheme (van den Berg 1995, Bledsoe and Watson 2001b) yielded a similar assortment of stability states with efficacy comparable to that of more data-intensive indices such as dimensionless shear stress or specific stream power based on various flood return intervals (e.g., $\tau_* \sim 0.1$ at Q_2).

The southern California thresholds fell conspicuously lower than those from other regions (Bledsoe and Watson 2001b), suggesting that these systems may be more sensitive than those in other regions of the US. This is most likely attributable to the semiarid climate, flashy flow regime, and high sediment loads. It is notable that the 10-year instantaneous flow would most regularly attenuate to a daily mean flow equal to that of a 2- to 3-year event. That is, it typically takes a 10-year storm to create any sort of a meaningful duration at a 2-year flow magnitude. Another important distinction between the Bledsoe and Watson thresholds and the southern California thresholds was that Bledsoe and Watson segregated unstable forms from stable meandering systems (i.e., sinuosity ≥ 1.3), whereas most of the 'stable' sites in southern California were relatively linear (i.e., mean sinuosity = 1.15).

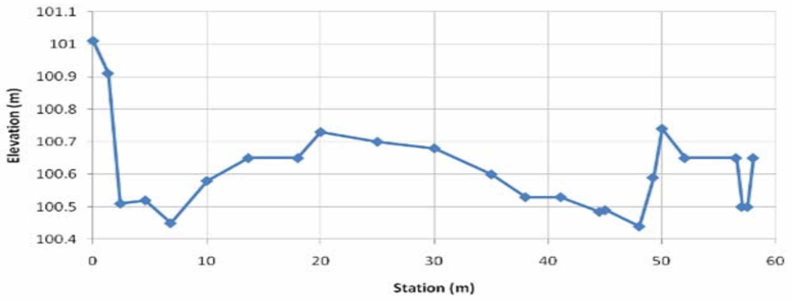
We initially developed separate statistical models for quantifying the risk of vertical (incising) and lateral (braiding) responses using this variable in logistic regression models; however, these models returned very similar thresholds which were ultimately combined into one 'stability' threshold for reasons of both parsimony and improved statistical power (Hawley 2009). Although the response mechanisms are different (vertical vs. lateral), the fact that d_{50} is used as the surrogate measure of resistance, primarily a measure of vertical resistance, offered additional justification for the single threshold. We ran 108 total models of unstable (braided or incising) vs. stable single-thread, unconfined channels using different measures of erosive energy at different return intervals estimated with different hydrologic models (Appendix C). Because a large body of geomorphic literature describes different behavior between coarse and fine systems (e.g., Simons and Simons 1987, Chang 1988, Bledsoe 2002), we developed both combined and separate models, selecting d_{50} of 16 mm as the discriminator between sand-dominated gravels and gravel/cobble armored systems. Out of 108 total models, all but 6 were significant ($p < 0.05$) with the screening index regularly performing similarly or superior to the more rigorous indices of dimensionless shear stress and specific stream power. Indeed, 5 of the 12 models of the screening index for coarse size fractions offered complete segregation of unstable/stable sites (i.e., 100% correctly classified). Although that is beneficial in identifying the threshold, it negatively affects the utility of a logistic model for representing risk levels. This explains why the 90 and 10% risk lines converge to the 50% level for $d_{50} > 16$ mm in Figure 5. It also results in poorer p-values for the individual terms (Table 5). However, the combined size-fraction models offer both an alternative and a weight of evidence for the theoretically supported result that in unconfined valleys, dynamic unstable states of incision and braiding often occur in settings that are inherently higher in hydraulic energy.

Results of logistic regression modeling mass-wasting failure in streams with unconfined, moderately- to well-consolidated banks also had acceptable performance. Appendix C includes logistic results of thresholds for other settings (e.g., poorly/unconsolidated banks or confined hillslopes); however, these models had poorer performance and offered less utility than more consolidated banks. 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), $\phi = 21.1^{\circ}$, and $c = 1.72$ kPa (35.8 lb/ft^2). Although lower than other regions where cohesion values are typically on the order of 10 kPa or greater (Lawler *et al*. 1997), such negligible cohesive strength was consistent with field observations. Broadly speaking, southern California banks have little geotechnical capacity. Unconsolidated banks, and in some instances banks that are moderately- or well-consolidated, frequently lack appreciable cohesion. This is compounded by the semiarid 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 extremely low thresholds for mass wasting relative to many US regions.

Inspection of Figures 5 and 6 offers a rationale as to why 10% mass-wasting risk vs. 50% incision/braiding risk were selected as critical discriminators. The bank data were distributed more equitably over their entire range with little practical difference between the 10 and 50% risk lines. In contrast, the broad range of incising/braiding risk for sites with d_{50} <16 mm favored the 50% risk line as more of a practical screening discriminator. This is statistically supported by the fact that the risk range is predominately influenced (perhaps unduly) by the one unstable outlier (AltPerris_A d_{50} = 0.9 mm), which is a special case rather than the norm. The site has distributary flow paths but there is little alluvial bar activity, with much of the flow potentially sub-surface and/or hyporheic (Figure 7).



(a) photographs looking upstream



(b) cross-section geometry looking downstream

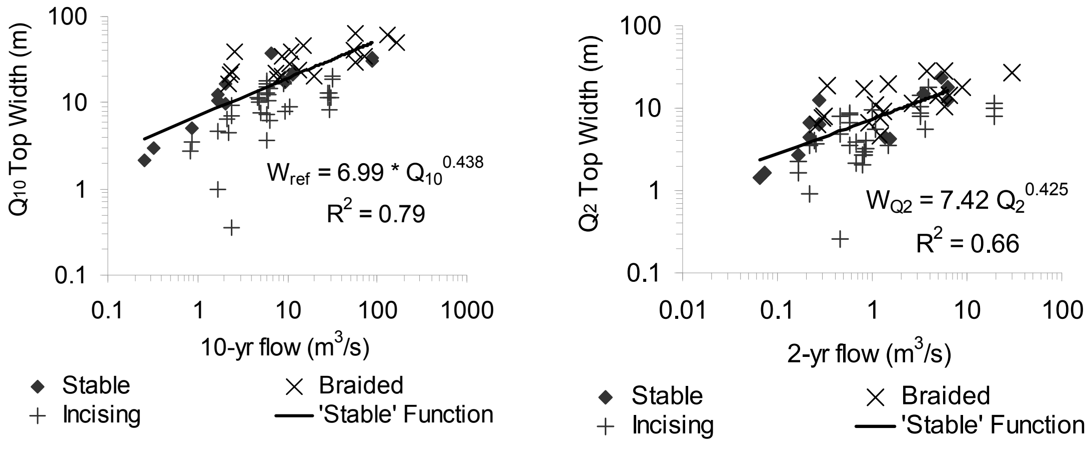
Figure 7. Cross section A at AltPerris.

Cases of braiding in such a low-energy setting are not the primary risk type that the braiding logistic model is intended to screen. Consequently, the 50% risk was judged a more reasonable screening index for braiding and incision, especially given that the two diagrams are used exclusively over the coarse-grain sizes where the thresholds are more apparent. It is recommended that these thresholds be refined through tool application and feedback. In its present form, the screening tool is designed such that jurisdictions may identify risk levels acceptable to local stakeholders. Proximity to a natural or engineered hard point was another important discriminatory factor in the screening analysis. The geomorphic significance of both natural (e.g., bedrock, wood, or sea level) and artificial (e.g., concrete or riprap) grade control is widely recognized (Newbury 2002, Rosgen 2002). It can have a central role in providing vertical and, in consequence, lateral stability. Both natural and artificial grade control were prevalent in the region and field investigations seemed to indicate that channel responses became proportionally larger as one progressed upstream from such a hard point. That is, channel instabilities such as headcut migration seemed to be pivoting around the nearest downstream grade control.

Multivariate regression of channel enlargement provided empirical support for the inclusion of a grade-control screening node, in that the longitudinal distance to a hard point (when scaled by channel width) was statistically significant ($p < 0.05$) in four separate models of enlargement. When used in combination with a surrogate measure for urbanization, such as the proportion of impervious area in the watershed or the cumulative sediment-transport ratio between developed and undeveloped settings, the distance to the downstream hard point and urbanization surrogate could explain 80 to 85% of the variance in channel enlargement (Hawley 2009).

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 control more than simply its existence. Spacing intervals for relative risk types 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 discussed above.

The valley width relative to channel was also able to help discriminate channels based on susceptibility of response. Consequently, we developed 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. In calibrating a simple reference width model with regional data, we expanded upon downstream hydraulic geometry relations in which top width tends to scale with discharge to a coefficient near 0.5 across many hydroclimatic settings (Knighton 1998). Acknowledging that many factors can influence 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), log-transformed linear regression of top width and the 10-year flow in stable unconfined systems resulted in a reasonably-fit power function (Figure 8) that generally stratified braiding (wider) and incising (narrower) systems. Given that flashier and semiarid systems tend to be wider and more variable than humid systems (Wolman and Gerson 1978, Osterkamp 1980), it is not surprising that the coefficient is larger than other published relations in which the higher coefficients (e.g., ~5) tend to correlate to weaker banks (e.g., thinly vegetated (Andrews 1984) or sandy (Simons and Albertson 1963).



(a) 10-year flow (b) 2-year flow

Figure 8. Top width vs. flow in unconfined, unconstructed stable, braided, and incising systems with superimposed power functions fitted to stable sites.

Because the 10-year flow coincides with the channel-filling flow across the region better than the 2-year flow, along with the fact that it is a better-fit model, we incorporated the 10-year relation as the reference width in the screening tool. We selected a VWI of 2 as a key discriminator in the screening tool because it successfully segregated all of the systems assessed as ‘confined’ during field investigations of actual local conditions, i.e., channels which had little room to adjust laterally due to hillslope/bedrock confinement.

Initial Screening Tool Testing

The screening tool was tested on the 83 sub-reaches that were used in its development. We conducted initial tests of the tool in its present form by comparing screening ratings to relative magnitudes of channel adjustment that were estimated using historical analysis. That is, how much have the study sites ‘enlarged’ in response to (and independent of) hydromodification, and do the scales of adjustment correspond with screening ratings? This is admittedly circular, but nevertheless provides an illustration of method application and an informative initial test of the tool.

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 size prior to substantial urban development. Enlargement is computed as:

$$\Delta A\% = (A_{post} - A_{pre}) / A_{pre} \qquad \textbf{(Eq. 11)}$$

where:

$\Delta A\%$ = 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).

Table 6 shows a gradient of examples from least susceptible to most disturbed. Although the reference cross section (Apre) had to be conservatively inferred from historic aerial photographs and field indicators, the results provide reasonable estimates of channel dynamics. For example, since its development in the 1990s, sub-reaches at Acton, a fine-grained unconfined system, have enlarged by approximately 35, 120, 900, and 1,300% (Figure 9). This response occurred in association with watershed impervious cover of only 2 to 3%; levels that might seem nearly inappreciable in other regions. This and similar cases of dramatic changes in fine-grained systems with little urbanization reinforce the notion that these are highly susceptible systems and warrant a 'Very High' screening rating.

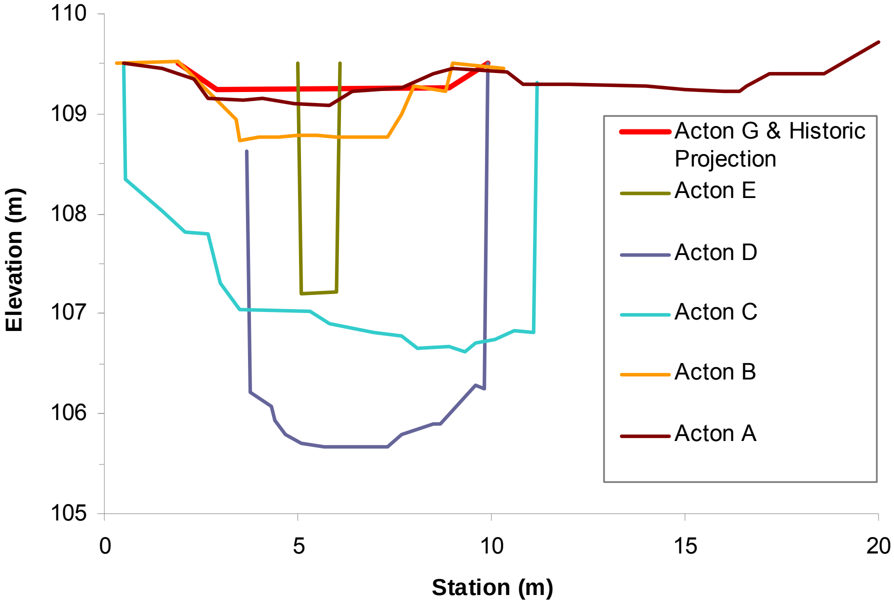
Table 6. Screening rating, estimated 'enlargement,' and key geomorphic parameters at selected study sites.

Sub-reach Name	Vertical Susceptibility	Lateral Susceptibility	Estimated Enlargement	Impervious Area	d_{50} (mm)	Reference (year)
Escondido_A	Low	Low	~0%	14%	128	1947
Topanga_B	Medium	Very High	~0 - 50%	1.4%	100	1947 - 1989
SanAntonio_A	High	Very High	~0 - 100%	0.2%	64	1947 - 1989
Borrego_B	Very High	Very High	~500%	14%	1.6	1952
Acton_C	Very High	Very High	> 1,000%	2.4%	5	~1990s

In contrast to Acton, San Antonio Creek demonstrates the susceptibility of a relatively resistant coarse-gravel/small-cobble 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 screening tool ratings for both vertical and lateral susceptibility.

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 ($d_{50} \sim 500$ mm) showed nominal effects from the sediment pulses through time, while the low-gradient confined section downstream ($d_{50} \sim 88$ 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.

(a) Photograph looking upstream at Acton_D: d_{50} = 9.4 mm with enlargement since development in 1990s approximated at 900%



(b) Superimposed cross sections along study reach at Action with the most upstream 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

Figure 9. Channel dynamics at Acton_D since development in 1990s.

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 (Silverado and Santiago) are clear examples of the region's least susceptible channel types.

SUMMARY AND CONCLUSIONS

Development of the hydromodification screening tool was based on the conclusions that: 1) urbanization markedly affects the flow regimes of streams in southern California, 2) the corresponding imbalances in sediment-transport capacity result in substantial geomorphic instabilities across most stream settings, 3) channels in southern California can be very sensitive to hydromodification and often exhibit very rapid response times and long recovery times, and 4) widely varying degrees of susceptibility to hydromodification are clearly reflected across the field study sites as an interaction between flow energy and the resistance of channel boundaries to lateral and vertical adjustments.

Results of the logistic regression analysis demonstrate that a probability-based assessment can inform development of indices that begin to address stream heterogeneity. The field screening tool should be used in concert with the companion *GIS-based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge* (SCCWRP Technical Report 605; Booth *et al*. 2010) to assign probability ratings that reflect likely response of a stream reach to hydromodification. The screening tools in turn will inform future modeling and management measures that are appropriate for the specific situations at a stream reach of interest and will allow managers to move beyond standard one-size-fits-all flow control strategies. Finally, monitoring plans should be developed to not only assess program performance, but to provide data that can be used to refine and improve these screening tools over time. In this way, all the tools will comprise a comprehensive hydromodification assessment toolkit.

In summary, the screening level analysis supported by this tool represents the first step toward tailoring appropriate management measures to different geomorphic settings and informing decisions about subsequent and more detailed analyses. However, the screening tool is not intended to result in policy decisions, does not assess ecological or economic effects, and does not evaluate current conditions in terms of attribution to historic land-use practices. Although the case studies of channel response described above are consistent with the relative susceptibility ratings provided by the initial version of the screening tool, it is strongly recommended that the overall tool, along with its embedded models and checklists, be refined through application, monitoring, and feedback on user experiences.

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GIS DATA RESOURCES

Cal-Atlas: *2000 and 2007 Roadway Shapefiles*, State of California geospatial clearinghouse, gis.ca.gov.

Google Earth: *Present-day Aerial Photography*, earth.google.com.

National Oceanic and Atmospheric Administration (NOAA): *Precipitation Intensities for 2-year, 24-hour Storm*, http://www.nws.noaa.gov/oh/hdsc/ noaaatlas2.htm (Atlas 2) and hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html (Atlas 14).

United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS): *Soil Surveys, Average Annual Precipitation Shapefile (1961 - 1990)*, http://datagateway.nrcs.usda.gov/.

United States Geological Survey (USGS): *Historical Aerial Photography and Quadrangle Topographic Maps*, *National Elevation Dataset (NED), 2001 Impervious Raster, National Hydrography Dataset (NHD), Average Annual Precipitation Shapefile (1900 - 1960)*, http://seamless.usgs.gov.

APPENDIX A – HYDROMODIFICATION SITE CROSS-SECTIONS, BANKS, AND PHOTOGRAPHS

ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/607_HydromodScreeningTools_TechBasis_AppendixA.pdf

APPENDIX B – HYDROMODIFICATION SITE DATA

ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/607_HydromodScreeningTools_TechBasis_AppendixB.pdf

APPENDIX C - LOGISTIC REGRESSION SUPPLEMENT: DATA, PARAMETER ESTIMATES, AND ADDITIONAL RESULTS

ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/607_HydromodScreeningTools_TechBasis_AppendixC.pdf