HYDROMODIFICATION SCREENING TOOLS: GIS-BASED CATCHMENT ANALYSES OF POTENTIAL CHANGES IN RUNOFF AND SEDIMENT DISCHARGE

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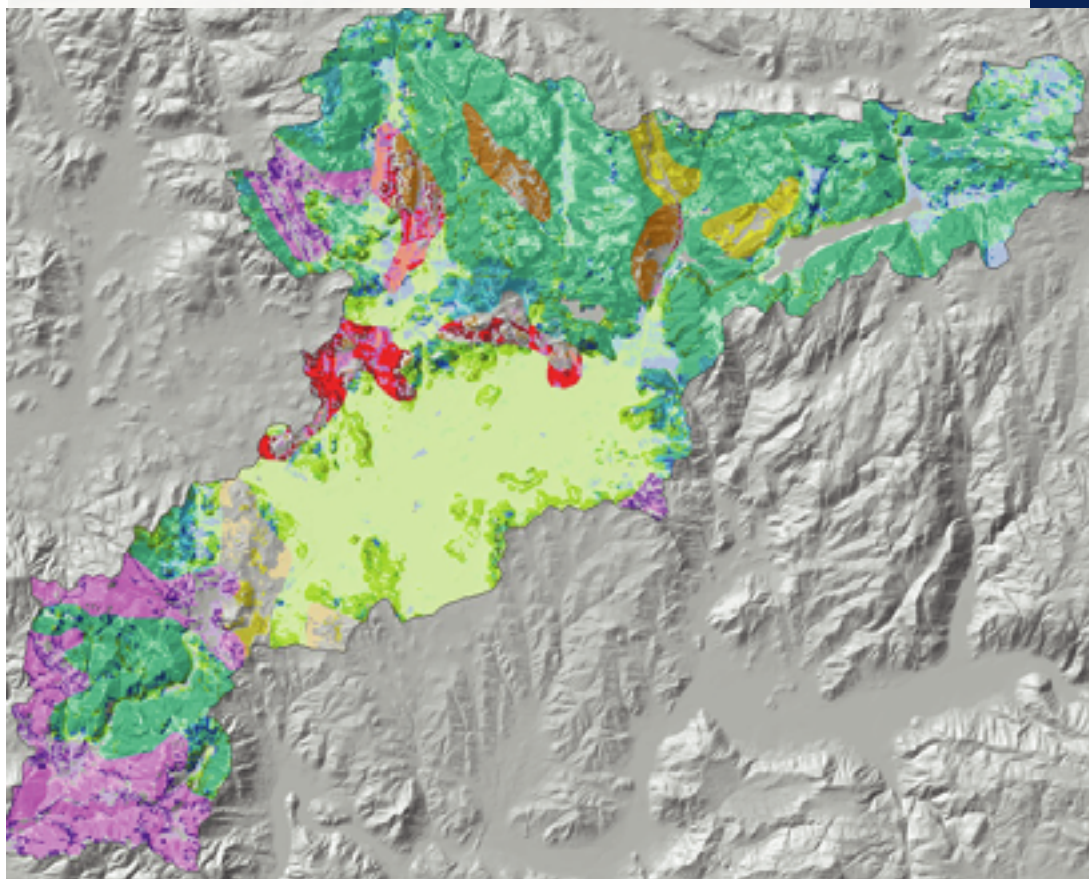
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Hydromodification Screening Tools:
GIS-based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge

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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).
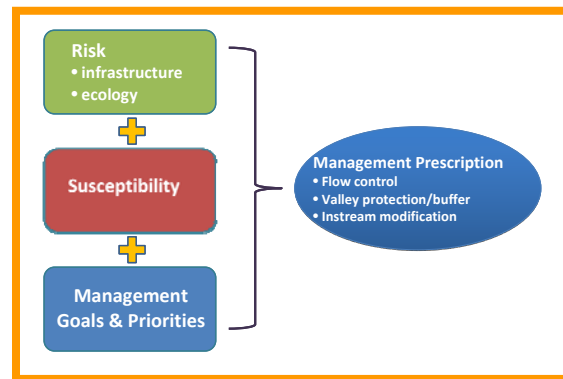

Figure ES1: Decision nodes that influence the management prescription for a particular stream reach.

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.

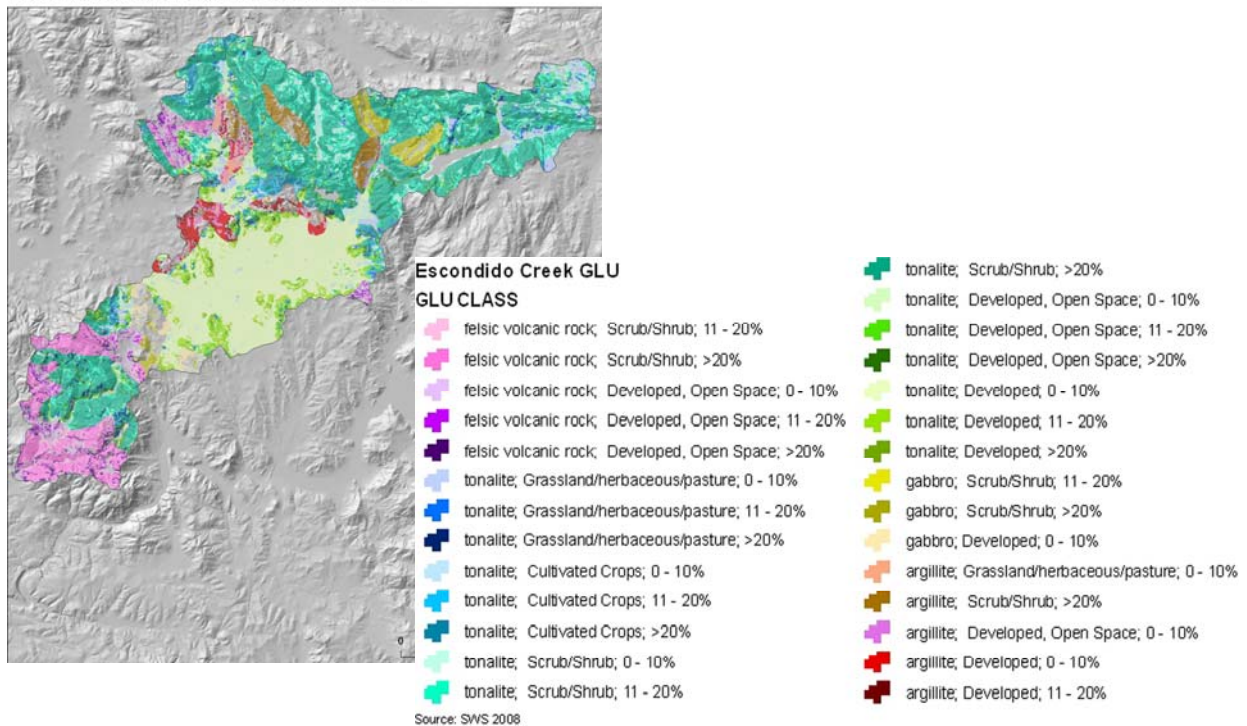ESCONDIDO CREEK PRELIMINARY GLU CLASSES - DRAFT

Escondido Creek GLU

GLU CLASS

- felsic volcanic rock; Scrub/Shrub; 11 - 20%
- felsic volcanic rock; Scrub/Shrub; >20%
- felsic volcanic rock; Developed, Open Space; 0 - 10%
- felsic volcanic rock; Developed, Open Space; 11 - 20%
- felsic volcanic rock; Developed, Open Space; >20%
- tonalite; Grassland/herbaceous/pasture; 0 - 10%
- tonalite; Grassland/herbaceous/pasture; 11 - 20%
- tonalite; Grassland/herbaceous/pasture; >20%
- tonalite; Cultivated Crops; 0 - 10%
- tonalite; Cultivated Crops; 11 - 20%
- tonalite; Cultivated Crops; >20%
- tonalite; Scrub/Shrub; 0 - 10%
- tonalite; Scrub/Shrub; 11 - 20%
- tonalite; Scrub/Shrub; >20%
- tonalite; Developed, Open Space; 0 - 10%
- tonalite; Developed, Open Space; 11 - 20%
- tonalite; Developed, Open Space; >20%
- tonalite; Developed; 0 - 10%
- tonalite; Developed; 11 - 20%
- tonalite; Developed; >20%
- gabbro; Scrub/Shrub; 11 - 20%
- gabbro; Scrub/Shrub; >20%
- gabbro; Developed; 0 - 10%
- argillite; Grassland/herbaceous/pasture; 0 - 10%
- argillite; Scrub/Shrub; >20%
- argillite; Developed, Open Space; 0 - 10%
- argillite; Developed; 0 - 10%
- argillite; Developed; 11 - 20%

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).
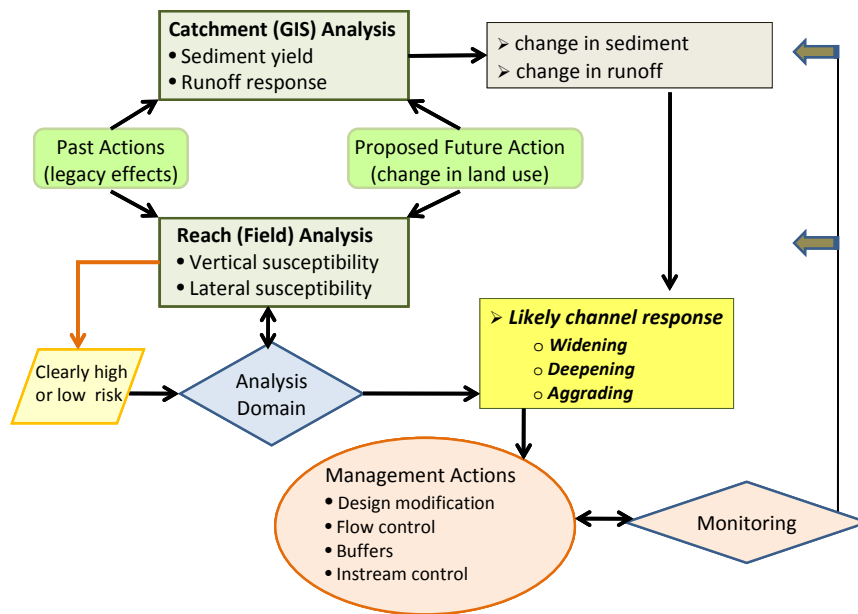

Figure ES3: Relationship of catchment and field screening tools to support decisions regarding susceptibility to effects of hydromodification.

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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BACKGROUND

The magnitude and rate of hydromodification, the physical response of streams to development-induced changes in flow and sediment input, is dependent on the inherent features of potentially affected channels and the characteristics of developed areas that determine the changes to flow and sediment input to those channels. This report describes a method to assess the second of these two elements, namely how to rapidly characterize watershed-scale changes in runoff and sediment yields to stream channels as a result of urban development. In combination with a field-based assessment of channel conditions, the susceptibility of a specific stream reach can be assessed on the basis of both in-channel (i.e., local) and contributing watershed (i.e., landscape-scale) influences (Figure 1).
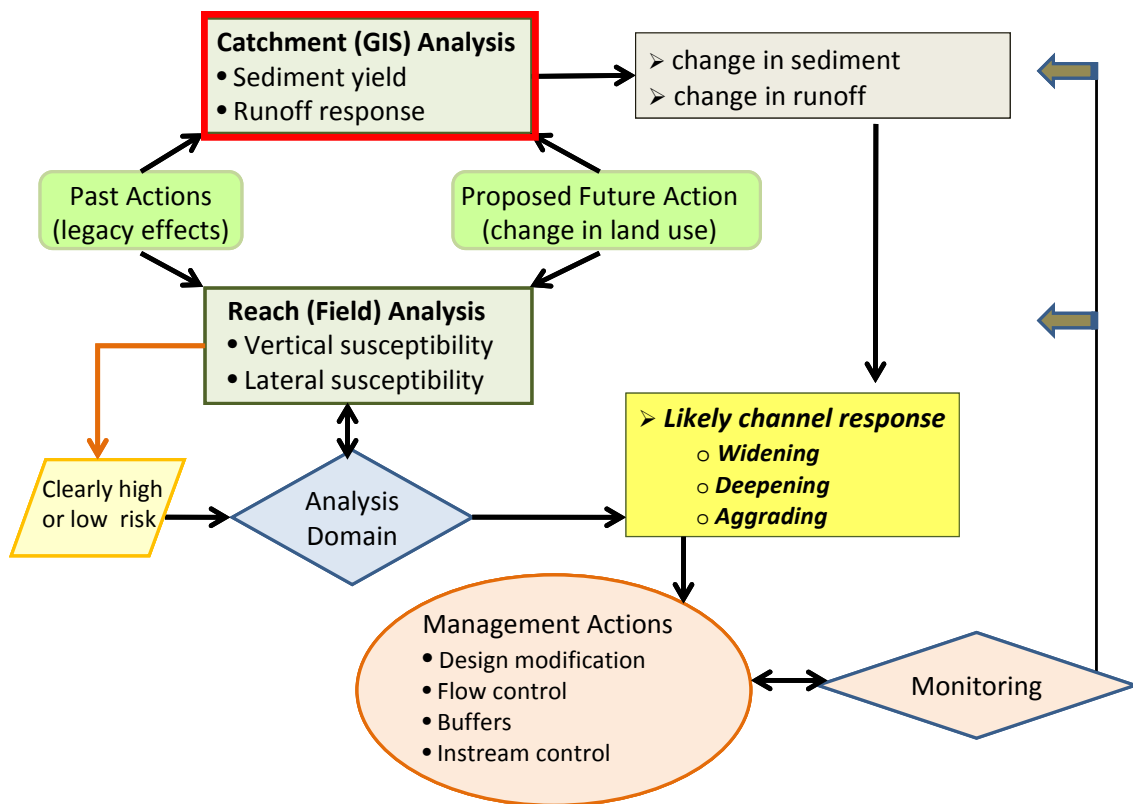
Figure 1. **Conceptual application of GIS- and field-based screening tools, and their inter-relationship in predicting potential effects of hydromodification.**

Assuming erodible boundaries and mobile sediment loads, the condition of stable stream channels reflects a balance between the capacity of the flow to transport sediment and the availability of sediment for transport. Under the broad geomorphic concept of "dynamic equilibrium," this balance is not necessarily achieved at every moment in time or at every point along the stream channel. Over a period of time, however, an observed condition of equilibrium is commonly presumed to express such a water–sediment balance. Conversely, the balance of these components is normally considered to be the defining precondition for maintaining stability in alluvial streams.

From this perspective of geomorphic stability, the **drivers** of channel change are the discharges of water and sediment, for which the importance of their balance in equalized channel formation has been invoked since Lane (1955). Thus, recognizing potential change(s) in these drivers, as a consequence of planned or potential landscape alteration (such as urbanization) is a necessary component of predicting hydromodification and the focus of this report. However, the intrinsic **resistance** of the channel form itself is no less important to determining actual outcomes, and it is the focus of the companion report by Bledsoe *et al.* (2010).

Hydrologic Response Units (HRUs) and Their Simplified Representation in Urban Watersheds

Landscape-scale predictions of water and sediment yields have a long history. For runoff prediction, the wide variety of modern hydrologic models can be traced back over a century to the first invocation of the Rational Runoff equation (Mulvany 1851) and its explicit dependence of runoff on land cover and rainfall intensity. Subsequent models for predicting runoff have typically added soil properties and hillslope gradient to the list of important watershed factors. Grouping common hydrologic attributes across a watershed into a tractable number of Hydrologic Response Units (HRUs: a term first used by England and Holtan 1969) has become a well-established approach for condensing the near-infinite variability of a natural watershed into a tractable number of different elements. The normal procedure for developing HRUs is to identify presumptively similar rainfall–runoff characteristics across a watershed by combining spatially distributed climate, geology, soils, land use, and topographic data into areas that are approximately homogeneous in their hydrologic properties (Green and Cruise 1995, Becker and Braun 1999, Beven 2001, Haverkamp *et al.* 2005). As noted by Beighley *et al.* (2005), this process of merging the landscape into discrete HRUs is a common and effective method for reducing model complexity and data requirements.

Using watershed characteristics to predict runoff is the explicit task of hydrologic models, and there is a host of such models available for application to hydromodification evaluation. For purposes of "screening," however, the goal is simplicity and ease of application even if the precision of the resulting analysis is crude. For any given area of a watershed, the conversion of pre-developed land cover to a developed (and therefore more impervious) land cover is the most prominent change and thus is likely the most important landscape-scale hydrologic driver of downslope (and downstream) physical impacts. Other attributes, although important, are normally of much less significance.

Using imperviousness as a surrogate for the relative magnitude of hydrologic impacts due to development is well-established in the scientific and engineering literature (see Center for

Watershed Protection 2003 for a comprehensive review), and this approach has been recently reaffirmed in National Research Council (2009). Given the ready availability of classified land cover data, the amount of developed land should be a credible index for the overall magnitude of hydrologic alteration, particularly for use in screening applications. It is thus a reasonable substitute in this application for the greater complexity engendered by multi-parameter HRUs or a fully featured hydrologic model.

Although this simplistic approach is recommended here, existing data on stream channel change provide caveats to its uncritical use. For example, a 22-year assessment of stream channel changes across western Washington (Booth and Henshaw 2001) found no significant correlation between imperviousness and the magnitude of channel change across a wide range of suburban and urban watersheds. Data collection for the present study also show no statistical correlation between watershed imperviousness and observed channel instability. These findings do not invalidate the importance of imperviousness in affecting runoff patterns, but they serve as reminders that runoff change is but one of several factors that influence the response of stream channels. In any given setting there are multiple potential drivers of change (e.g., changes to the sediment supply), and their influence will be mediated by the resistance of the downstream channels to geomorphic response.

Geomorphic Landscape Units (GLUs)

Many of the same physical properties that determine the hydrologic response of a watershed also determine the magnitude of sediment production from those same areas. These properties can be grouped into Geomorphic Landscape Units (GLUs: a term without the same degree of prior literature usage as HRUs, but entirely analogous in both definition and application). The closest pre-existing analog is that of "process domains," a conceptual framework based on the hypothesis that "spatial variability in geomorphic processes governs temporal patterns of disturbances that influence ecosystem structure and dynamics" (Montgomery 1999). A GLU-based methodology has been applied to only a few California watersheds to date, but it has seen widespread application and acceptance elsewhere, particularly in the Pacific Northwest. We note that process domains were originally defined by topography, climate, tectonic setting, and geology, but they do not include land use or any explicit effects of human activity or disturbance. Thus they are not entirely appropriate for our current application.

Erosional processes are episodic, resulting in substantial year-to-year variability (Benda and Dunne 1997, Kirchner *et al.* 2001, Gabet and Dunne 2003). Although long-term annual averages cannot predict the sediment load for any given year; nevertheless, these averages can be useful in assessing the long-term consequences of alternative management actions, because different parts of the landscape can be readily identified as to their *relative* sediment-delivery potential.

Prior work in California (Stillwater Sciences 2007, 2008) has identified three factors judged to exert the greatest influence on the variability on sediment-production rates: ***geology types***, ***hillslope gradient***, and ***land cover***. Detailed mapping procedures for GLU analysis are provided in the closing section of this report; here we offer a generalized overview. To begin, data sources for the three factors are readily available and can be compiled in a GIS over the entire watershed in question at a spatial resolution determined by the coarsest dataset (typically 30 m).

Geology types are based on the best available digital geologic maps of the region, with mapped units grouped into a limited number of categories that reflect their inherent primary geologic characteristic (e.g., igneous, sedimentary, or metamorphic unit) and presumed or qualitatively observed erodibility. *Hillslope gradients* are generated directly from digital elevation model (DEM) of the region. Based on observed ranges of relative erosion and slope instability, prior applications have found a useful grouping of the continuous range of hillslope gradients to include just three categories, such as 0 to 10%, 10 to 20%, and steeper than 20% (alternative groupings could be based on natural breaks in the distribution frequency of slope values, but these would likely differ from watershed to watershed). Lastly, *land cover* categories can be based on a classified Landsat image at 30-m resolution. We have found that five grouped categories, identified by an automated classification system, provide a useful level of discrimination. Categories largely correspond to vegetation covers of forest, scrub, and agriculture and/or grassland (which includes bare soil); developed land; and miscellaneous (which includes water bodies and bare rock).

This approach provides a useful, rapid framework to identify a tractable number of categories that can serve the overarching need of a hydromodification screening tool, namely a stratification of the landscape whose relative sediment-delivery attributes can be characterized under alternative land-use conditions. As with measures of hydrologic alteration (e.g., impervious area), however, we note that no simple one-to-one correspondence between the magnitude of altered sediment delivery and the magnitude of channel change should be anticipated. Many different factors are involved, and these various data sets display no simple dominant or additive relationship to each other.

APPLICATION

With the base data assembled, characterization of both runoff and sediment yield (i.e., the top-most box of Figure 1) at the watershed scale is relatively straightforward processes. For runoff, we affirm the common approach of using the change in either developed land or imperviousness as the index of hydrologic change. However, the once-popular concept of a "critical threshold" of imperviousness, below which no channel changes occur, has been widely abandoned in the scientific literature and is not recognized here. Unfortunately, this also eliminates the seemingly promising framework that jurisdictions once used to discriminate whether or not a potential hydrologic change would likely be significant. Although understanding the magnitude of hydrologic change is still relevant to assessing hydromodification effects, a small value clearly does not provide any guarantees of non-impact, presumably because significant sediment delivery changes can still occur and produce dramatic channel changes. For example, Figure 2 illustrates changes in channel morphology and stability associated with an in-stream grade-control structure that blocks sediment passage. Although the change in sediment supply in this example is caused by a physical blockage rather than a change in land cover, the analogy to the relative importance of watershed-scale drivers is clear: channel instability can occur even with no change in hydrology at all.

Figure 2.   Alteration in channel morphology and stability, immediately upstream (left) and downstream (right) of a grade-control structure that blocks sediment passage. The two views are less than 10 m apart in the channel, with no intervening tributary.

Predictions of sediment production using GLUs require that the three sets of contributing data (*geology type*, *hillslope gradient*, and *land cover*) each be grouped into discrete categories and classified independently across the watershed in question. With the typical number of subdivisions for each of these three sets, approximately 30 to 48 different combinations are theoretically possible. In prior applications, nearly every combination of these factors were represented in any given watershed, but the vast majority of the land area is represented by only a few such combinations. Nearly all of these combinations have been observed across multiple southern California watersheds, and those observations suggest the following assignments of relative sediment production (Table 1; see Appendix for map-based example of equivalent

results for the San Antonio Creek watershed, Ventura County, CA, Stillwater Sciences 2007). However, these assignments of relative sediment production are observationally determined, and our current modest range of application precludes universal or automated application without including a subsequent step of field verification.

Table 1. Example of a full set of geomorphic landscape unit (GLU) types from Santa Paula Creek, Ventura County, CA, and assigned relative sediment production (RSP) categories based on observed field conditions (modified from Stillwater Sciences 2007 using a 3-part division of geologic units, 3 slope classes, and 5 land cover classes).

GLU	RSP	GLU	RSP
Unconsolidated Ag/grass/bare 0 - 10%	Low	Shale Misc. 0 - 10%	Medium
Unconsolidated Forest 0 - 10%	Low	Shale Misc. 10 - 20%	Medium
Unconsolidated Forest 10 - 20%	Low	Shale Misc. >20%	Medium
Unconsolidated Scrub 0 - 10%	Low	Shale **Developed** 10 - 20%	Medium
Shale Ag/grass/bare 0 - 10%	Low	Shale **Developed** 10 - 20%	Medium
Shale **Developed** 0 - 10%	Low	Shale Scrub 0 - 10%	Medium
Shale Forest 0 - 10%	Low	Shale Scrub 10 - 20%	Medium
Shale Forest 10 - 20%	Low	Shale Scrub >20%	Medium
Shale Forest >20%	Low	Sandstone Misc. 0 - 10%	Medium
Sandstone Ag/grass/bare 0 - 10%	Low	Sandstone Misc. 10 - 20%	Medium
Sandstone **Developed** 0 - 10%	Low	Sandstone Misc. >20%	Medium
Sandstone Forest 0 - 10%	Low	Sandstone **Developed** 10 - 20%	Medium
Sandstone Forest 10 - 20%	Low	Sandstone **Developed** >20%	Medium
Sandstone Forest >20%	Low	Sandstone Scrub 10 - 20%	Medium
Sandstone Scrub 0 - 10%	Low	Sandstone Scrub >20%	Medium
Unconsolidated **Developed** 0 - 10%	Low		
Unconsolidated Misc. 0 - 10%	Medium	Unconsolidated Ag/grass/bare 10 - 20%	High
Unconsolidated Misc. 10 - 20%	Medium	Unconsolidated Ag/grass/bare >20%	High
Unconsolidated Misc. >20%	Medium	Unconsolidated Scrub >20%	High
Unconsolidated **Developed** 10 - 20%	Medium	Shale Ag/grass/bare 10 - 20%	High
Unconsolidated **Developed** >20%	Medium	Shale Ag/grass/bare >20%	High
Unconsolidated Forest >20%	Medium	Sandstone Ag/grass/bare 10 - 20%	High
Unconsolidated Scrub 10 - 20%	Medium	Sandstone Ag/grass/bare >20%	High

Once these 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 their future sediment production levels are similarly determined, substituting Developed land cover for the original categories and modifying the relative sediment production as necessary. Conversely, relative sediment production for currently developed watershed areas can be altered to relict sediment production for an undeveloped land use and used to assess the impact of watershed development on pre-development sediment production. For nearly all GLUs, a change of preexisting land cover to Developed is accompanied by either no change or a decrease in relative sediment production (see Table 1). Both theory and observation affirm that significant reductions in the delivery of sediment to stream channels can drive channel change. In the context of this screening application, any such predicted reduction in sediment delivery can be used to identify potential hydromodification impacts.

Although prior applications (Stillwater Sciences 2007, 2008) have developed quantitative values associated with the three relative levels of sediment production, those values were determined for specific watersheds, calibrated with nearby sediment accumulation data from debris basins and validated with nearby sediment-load gage data. These conditions cannot be expected uniformly across southern California watersheds, and so translating relative rates into precise numeric values is not presently warranted. However, this prior work has shown that the range of long-term sediment delivery rates probably spans at least two orders of magnitude, and we have used this scaling to calculate the relative change in pre- and post-development sediment production (i.e., Low = 10 to 100 tonnes/km^2/yr and High = 1,000 to 10,000 tonnes/km^2/yr). Also, we note, that it is not presently possible to describe a mechanistic linkage between the magnitude of hydromodification *drivers* (i.e., changes in the delivery of water and sediment to downstream channels), the channel *resistance* to change, and the net expression on channel form. For this reason, hydromodification drivers and channel resistance must be evaluated independently (Figure 1) in the evaluation of channel susceptibility to morphologic change.

VALIDATION OF APPROACH

To test the applicability of the HRU- and GLU-based approaches for determining the impact of watershed development on physical channel conditions, we visited several study watersheds to compare GIS-based predictions with field-based observations. During the spring of 2009, we visited 17 watersheds and examined them from a geomorphic perspective (Figure 3). We viewed previously established channel measurement sites, as well as reaches upstream and downstream, to investigate the local and watershed-scale processes controlling geomorphic conditions at the measurement sites. A direct comparison of GIS-based and field-based channel sensitivity assessment for a study watershed is shown in this report's Appendix.
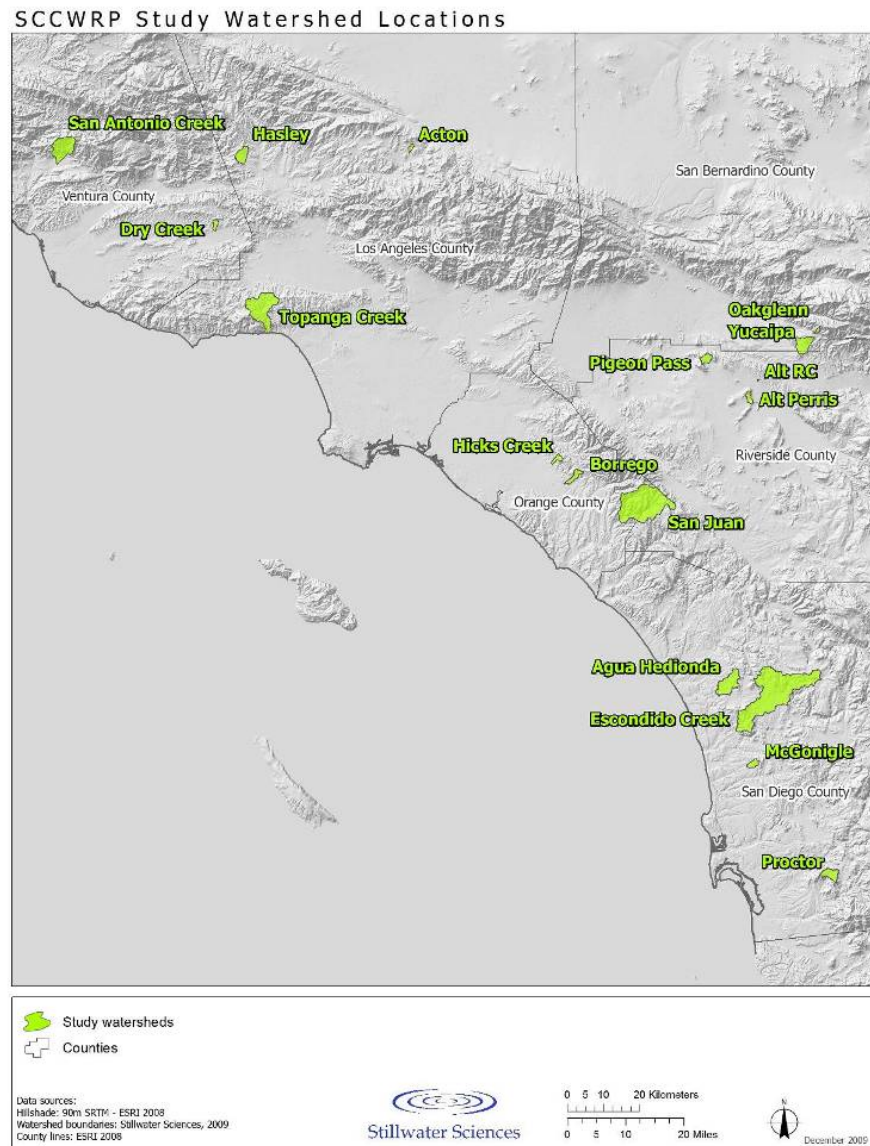

Figure 3. Study watersheds for evaluation of GLU approach.

The study watersheds fell into three development categories:

1) Developed (pre-2001) – watershed was developed at the time of the 2001 National Land Cover Database, and so the development is shown in the GIS layers used for the GIS-based analysis. At these sites we were able to directly relate what the GIS analysis predicts with observed channel conditions:

- Agua Hedionda
- Borrego
- McGonigle
- Pigeon Pass
- Proctor
- San Antonio
- Escondido
- Hicks
- Topanga

2) Developed (post-2001) – watershed is developed now, but the extent of current development is not shown in the GIS land-cover layer (i.e., the development post-dates the 2001 NLCD). So, we were not necessarily able to relate directly what the GIS analysis predicted with on-the-ground channel conditions:

- Acton
- Dry
- Hasley
- Yucaipa

3) Not Developed – watershed is largely undeveloped. If channel instability was observed, it has likely been caused by local or watershed-scale factors other than those related to changes in water or sediment supply as a consequence of urbanization:

- Alt Perris
- Alt RC2
- Oakglenn
- San Juan

Overall, the multiple factors that affect development-induced watershed disturbance (the *drivers* for channel change) can be characterized by how they modify hydrology and sediment delivery to either increase impacts (i.e., factors that contribute to a High impact) of decrease impact (i.e., factors that contribute to a Low impact; Table 2). Note that neither spatial variability nor time-dependent conditions are included in this example, but the influence of either/both may be locally dominant. Also, the effects of past disturbances (i.e., legacy effects) are not included in this example because they are generally not amenable to uniform characterization and likely require site-specific, field-based analysis.

Table 2. Channel change drivers and factors that tend to influence the magnitude of the resulting impact(s) on channel stability.

Driver		Factors for High Impact	Factors for Low Impact
	% Developed	Highly developed, high total impervious area (TIA)	Moderately developed, low total impervious area (TIA)
Hydrology	Development density	Concentrated development	Distributed development
	Degree of upstream stormwater retention	Minimal retention of stormwater run-off	Extensive retention of stormwater run-off
	Upstream relative watershed sediment production	High relative sediment production	Low relative sediment production
Sediment Delivery	Relative watershed sediment production entering downstream of development	Low relative sediment production	High relative sediment production
	Degree of sediment transport blockage (*note: not explicitly included in this GIS-based approach*)	High number of total upstream bridges and culverts and/or close upstream proximity of undersized bridges and culverts	Low number of total upstream bridges and culverts and/or distant upstream proximity of undersized bridges and culverts

For purposes of the validation study, these factors (where known) were combined with an assessment of the impact of development on pre-development relative sediment production. This was achieved by replacing the sediment-production values for Developed land cover in the GIS framework with the corresponding value for Scrub/Shrub land cover with the same slope and geology conditions) to arrive at a qualitative ranking (i.e., Low, Medium, High) of the impact of development on channel conditions for each of the 17 watersheds. The comparison between predicted sediment alteration and field-based observations and channel cross-section measurements of channel stability is given below:

Table 3.   Comparison of GLU-predicted and field-observed channel stability.   Hypothetical = hypothetical downstream channel response to development with percent change in hillslope sediment production shown in parentheses. Observed channel stability CSU/SWS.

Watershed	Area (km²)	Development Status[a]	Hypothetical	Observed
Escondido	156.7	Developed (pre-2001)	Medium (-28%)	Stable
Hicks	3.9	Developed (pre-2001)	Low (<1%)	Moderately Stable
Topanga	50.9	Developed (pre-2001)	Low (-4%)	Stable
Borrego	7.1	Developed (pre-2001)	Low (-10%)	Unstable
Agua Hedionda	27.1	Developed (pre-2001)	High (-65%)	Unstable
Pigeon Pass	6.5	Developed (pre-2001)	Low (-10%)	Moderately Stable
McGonigle	5.1	Developed (pre-2001)	High (-70%)	Stable
San Antonio Creek	31.1	Developed (pre-2001)	Low (<1%)	Moderately Stable (see Appendix)
Proctor	11.2	Developed (pre-2001)	Low (-3%)	Stable
San Juan	105.2	Not Developed	Low (<1%)	Stable
Alt Perris	4.0	Not Developed	Low (<1%)	Stable
Alt RC	0.2	Not Developed	Low (<1%)	Hardened
Oakglenn	1,.4	Not Developed	Low (<1%)	Hardened
Acton	2.0	Developed (post-2001)	Medium	Unstable
Dry Canyon	3.3	Developed (post-2001)	Medium	Unstable
Hasley	11.6	Developed (post-2001)	Medium	Unstable
Yucaipa	16.7	Developed (post-2001)	Low	Stable

[a] Developed (pre-2001) means that the current development was reflected in the land use information used in the GIS analysis; Developed (post-2001) means that the current development was not reflected in the land use information we used in the GIS analysis.

Given the multiplicity of factors that determine channel stability (both natural and man-made), the uneven performance of this metric and the lack of any obvious systematic errors in its prediction of channel stability is not surprising. Other studies of multi-determinant systems also commonly report complex interrelationships that are not amenable to simple step-wise or regression analyses (for examples that also address channel stability, see Gregory *et al.* 2008 or Moret *et al.* 2005). The challenge is thus to incorporate the value of single-factor indices, such as these assessments of change in sediment reduction or runoff, into a more complex system. This analysis is not yet at the point of specifying management or regulatory thresholds under an

automated application. It does, however, suggest that the following screening steps should accompany and complement those intended to determine channel resistance:

1. Characterize the relative change in hydrology following planned development, using the change in watershed imperviousness (or developed land cover) as a surrogate.

2. Characterize the relative change in sediment production following development, using the procedure outlined above.

3. Evaluate the degree of relative risk solely arising from changes in sediment and/or water delivery. The challenge in implementing this step is that presently we have insufficient basis to defensibly identify either low-risk or high-risk conditions using these metrics. For example, channels that are close to a threshold for geomorphic change may display significant morphological changes under nothing more than natural year-to-year variability in flow or sediment load.

    a. Acknowledging this caveat, we nonetheless anticipate that changes of less than 10% in either driver are unlikely to instigate, on their own, significant channel changes. This value is a conservative estimate of the year-to-year variability in either discharge or sediment flux that can be accommodated by a channel system in a state of dynamic equilibrium. It does not "guarantee," however, that channel change may not occur—either in response to yet modest alterations in water or sediment delivery, or because of other urbanization impacts (e.g., point discharge of runoff or the trapping of the upstream sediment flux; see Booth 1990) that are not represented with this analysis.

    b. In contrast, recognizing a condition of undisputed "high risk" must await broader collection of regionally relevant data. We note that >60% reductions in predicted sediment production have resulted in both minimal (McGonigle) and dramatic (Agua Hedionda) channel changes, indicating that "more data" may never provide absolute guidance. At present, we suggest using predicted watershed changes of 50% or more in either runoff (as indexed by change in impervious area) or sediment production as provisional criteria for requiring a more detailed evaluation of both the drivers and the resisting factors for channel change, regardless of other screening-level assessments. Clearly, however, only more experience with the application of such "thresholds," and the actual channel conditions that accompany them, will provide a defensible basis for setting numeric standards.

4. Local in-channel drivers (e.g., bedrock constrictions, small-head dams, weirs) can be extremely important to downstream sediment continuity and channel stability, but they may not be readily discernable from coarse-scale spatial datasets. As with other determinants of channel resistance, field inspection of channel conditions prior to development is an inescapable component of identifying important in-channel elements that may influence the impacts of development on future channel stability.

DETAILED MAPPING PROCEDURES FOR GLU ANALYSIS

The previous sections provided a general overview of the GLU approach. Below we offer detailed procedures for application of this approach in a GIS framework. A GLU layer is derived by overlaying hillslope, land cover, and geology, and then assigning a particular sediment-production rate to each of the resulting categories. These rates are normally categorical (i.e., Low, Medium, and High); however, if data are available, rates could be expressed as numerical values.

To maintain a useful level of standardization between GLU maps across target watersheds within a region, we favor publicly available datasets as the source of our primary GIS analysis layers. These datasets include:

- USGS National Elevation Dataset (NED): 1 arc-second and 1/3 arc-second in ArcGrid format (http://seamless.usgs.gov/products/3arc.php)

- 2001 National Land Cover Database (NLCD 2001): 30-meter pixel IMG grid (http://www.mrlc.gov/nlcd_multizone_map.php)

- 1977 Jennings Geology: 1:750,000 vector ArcInfo coverage (http://www.consrv.ca.gov/CGS/information/publications/pub_index/Pages/statewide_references.aspx)

These datasets represent statewide conditions and provide relatively coarse, but seamless, data without respect to political or watershed boundaries. However, for many areas, equally continuous coverage at much better resolution is available and preferable.

Data Types and Acquisition

Data pre-processing

Before a GLU layer can be generated, a few pre-processing steps need to be followed. The first step is to define the area of analysis. For hydromodification application these areas are watersheds, and therefore the topographic boundary of the landscape draining to the point(s) of interest becomes the area of analysis.

To delineate a particular watershed, we use the National Watershed Boundary Dataset as our primary source (in California these are maintained and distributed by CalWater). CalWater offers a free vector dataset (shapefile) with basin and sub-basin delineations organized by the commonly used 8-digit HUCs from the USGS Hydrologic Unit Maps. After the watershed of interest has been extracted, we conduct a careful examination of its boundaries against a 10-m DEM hillshade. In cases where the boundaries seem inadequate, we turn to the DEM to improve the watershed delineation using ArcInfo Hydrology routines. After the area of analysis has been sufficiently well-defined, the analysis layers are 'clipped' to its boundaries and reprojected to a common coordinate system. An example, shown for the Escondido Creek watershed (San Diego County) on an orthophoto base, is given in Figure 4.

Figure 4. Processing the data layer.

Slope classes

The next step is to refine and classify the attributes of the analysis layers that will be used to create the GLU maps. The hillslope DEM is analyzed to produce a grid of slope values, which are subsequently classified into discrete categories. In applications to date, the following category percentages have been commonly used to categorize hillslope gradients: 0 - 10, 11 - 20, and >20%.
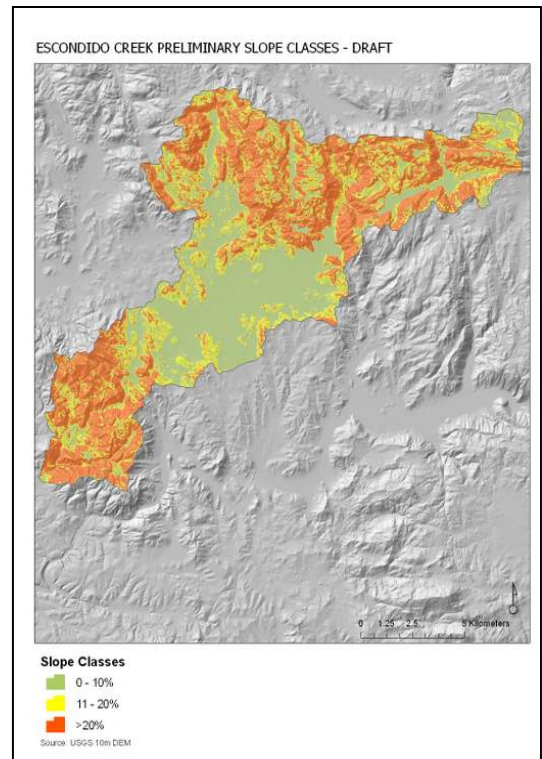

Figure 5. DEM map with preliminary slope classes.

There are no hard-and-fast rules for choosing particular slope breaks, but these have shown a good correlation between broad categories of observed intensity of hillslope erosion in the southern California watersheds in which they have been applied. Although uniformly flat (or uniformly steep) watersheds might display little spatial discrimination using these particular categories; however, maintaining a common framework across the entire region is likely to advance the application of this methodology more effectively than developing unique, watershed-specific categories (even those where the slope categories are chosen on the basis of more 'natural' divisions in the local distribution of values).

Land cover classes

Following a similar philosophy that favors simplicity and cross-watershed uniformity, the land-cover grid categories generally include:

- Agricultural/Grass
- Developed
- Forest
- Scrub/Shrub
- Other (water, bare rock)

Figure 6. DEM map with preliminary land cover classes.

Geology classes

Finally, the geology layer is categorized based on rock types or mechanical competence, the predominant sediment size generated upon erosion, and their associated erodibility. The attribution (and thus the naming) of the geology classes can vary by region, but as an example these categories might be:

- Crystalline (or other specific rock types)
- Fine-grained sedimentary, weak (i.e., easily eroded)
- Coarse-grained sedimentary, weak
- Fine-grained sedimentary, competent
- Coarse-grained sedimentary, competent

ESCONDIDO CREEK PRELIMINARY GEOLOGY CLASSES - DRAFT
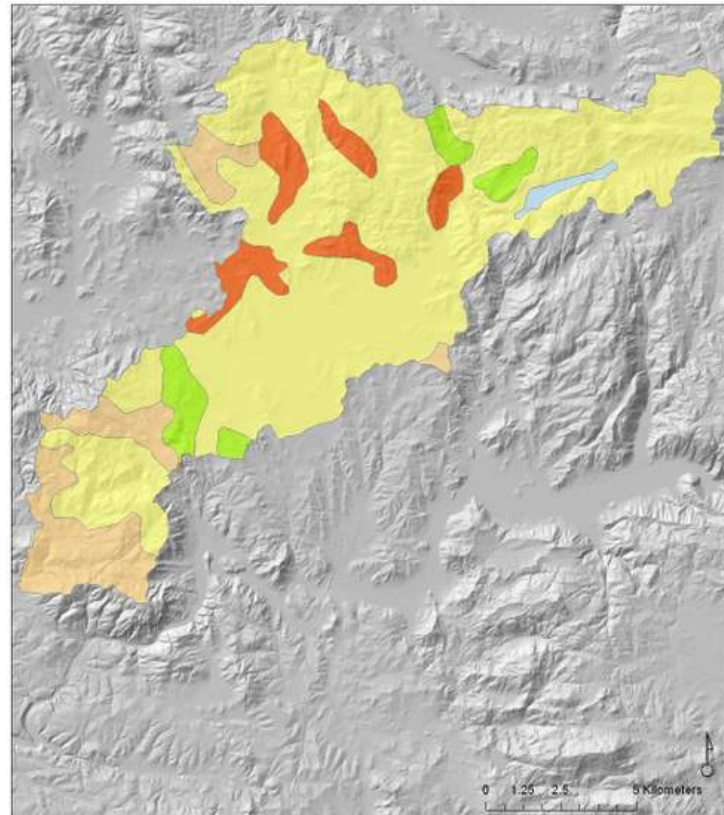
Geology Type (Age, Rocktype 1, Rocktype 2)

- Holocene, water,
- Late Jurassic to Early Cretaceous, felsic volcanic rock, intermediate volcanic rock
- Middle Jurassic to Late Cretaceous, tonalite, quartz diorite
- Paleozoic(?) to Late Jurassic, argillite, graywacke
- Triassic to Cretaceous, gabbro, diorite

Figure 7. DEM map with preliminary geology class types.

The 'geology' categorization is the least well-defined across southern California, because literally thousands of distinct rock types are present here and they have not all been evaluated in applications of this method to date. A common-sense approach will undoubtedly be sufficient for many mapped units in most watersheds (e.g., a named sandstone unit is likely to generate coarse-grained sediment; a named shale unit will not) but, at present, there is less available guidance on how to infer relative erodibility than exists for hillslope gradient or land cover. This shortcoming is anticipated to improve as more areas are evaluated across the region, but some level of geologic acumen will normally be necessary to apply this method in any new locale.

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After the analysis categories have been defined, an attribute column is added to each dataset to store that information.

Lastly, the raster datasets (i.e., hillslope and land cover) are converted to vector format for the final GLU analysis. Although GLU mapping can be done in both raster and vector formats, we have found that keeping the analysis in vector format (which keeps the final GLU layer in shapefile format) achieves the benefits of compressibility, easy distribution, and compatibility of shapefiles.
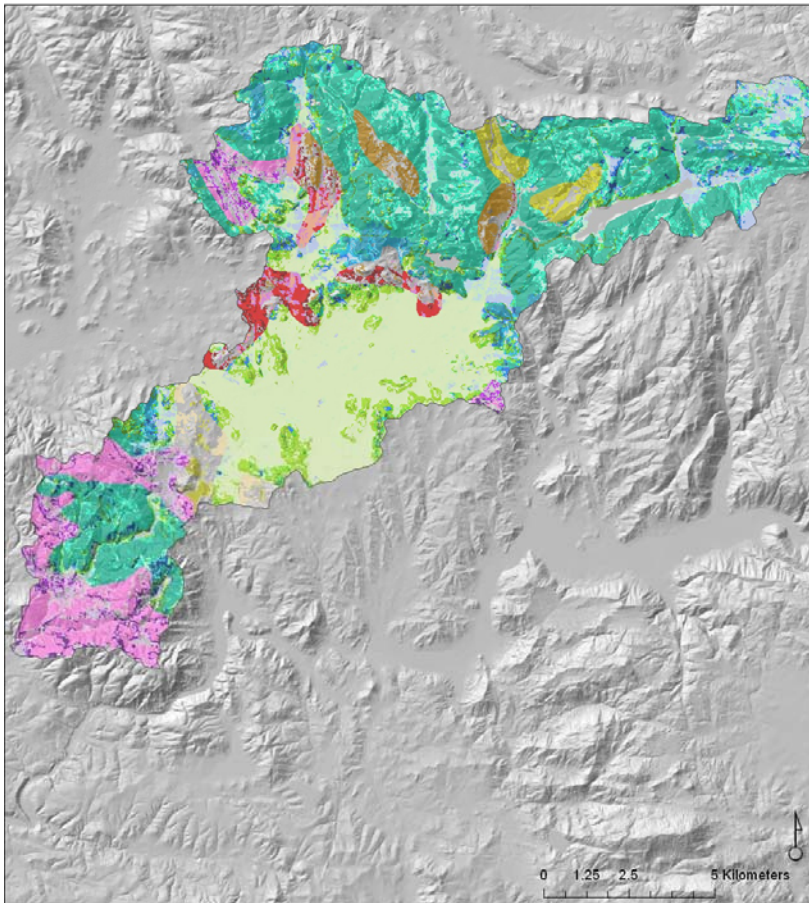
GLU Processing

When all the individual datasets have been completed, generating a GLU layer is reasonably straightforward. With a simple overlay, the primary layers are merged into a single polygon dataset that keeps track of every unique combination of *geology type*, *hillslope gradient*, and *land cover*. An additional attribute field (GLU_Type) is created in this final GLU layer to differentiate each possible combination (see Table 4 below). Note that there is no rating or ranking of these GLU categories at this stage. Each category simply represents a unique combination of slope, land cover, and geology attributes; subsequently, relative sediment production must be determined by observation, not addition of fields. Specifically, the GLU_Type field is a concatenation of each of the analysis layers GLU category, resulting in GLU types similar to those in Table 4 and graphically represented in Figure 8.

Table 4. Example of common percentages for GLU_Type attributes.

GLU_TYPE
Volcanic rocks; Ag/Grass; 0-10%
Volcanic rocks; Developed; 10-20%
Volcanic rocks; Scrub/Shrub; 10-20%
Tonalite; Ag/Grass; 10-20%
Tonalite; Ag/Grass; >20%
Tonalite; Developed; 0-10%
Argillite; Ag/Grass; >20%
Argillite; Forest; >20%
Argillite; Scrub/Shrub; 10-20%

Escondido Creek GLU
GLU CLASS

- felsic volcanic rock; Scrub/Shrub; 11 - 20%
- felsic volcanic rock; Scrub/Shrub; >20%
- felsic volcanic rock; Developed, Open Space; 0 - 10%
- felsic volcanic rock; Developed, Open Space; 11 - 20%
- felsic volcanic rock; Developed, Open Space; >20%
- tonalite; Grassland/herbaceous/pasture; 0 - 10%
- tonalite; Grassland/herbaceous/pasture; 11 - 20%
- tonalite; Grassland/herbaceous/pasture; >20%
- tonalite; Cultivated Crops; 0 - 10%
- tonalite; Cultivated Crops; 11 - 20%
- tonalite; Cultivated Crops; >20%
- tonalite; Scrub/Shrub; 0 - 10%
- tonalite; Scrub/Shrub; 11 - 20%

- tonalite; Scrub/Shrub; >20%
- tonalite; Developed, Open Space; 0 - 10%
- tonalite; Developed, Open Space; 11 - 20%
- tonalite; Developed, Open Space; >20%
- tonalite; Developed; 0 - 10%
- tonalite; Developed; 11 - 20%
- tonalite; Developed; >20%
- gabbro; Scrub/Shrub; 11 - 20%
- gabbro; Scrub/Shrub; >20%
- gabbro; Developed; 0 - 10%
- argillite; Grassland/herbaceous/pasture; 0 - 10%
- argillite; Scrub/Shrub; >20%
- argillite; Developed, Open Space; 0 - 10%
- argillite; Developed; 0 - 10%
- argillite; Developed; 11 - 20%

Source: SWS 2008

Figure 8. DEM map with preliminary GLU layer and attribute percentages.

GLU Post-processing and Analysis

The combination and geoprocessing of these datasets, which are intrinsically different in format (and in many cases different in scale), is typically not free of errors or redundancy. Apart from the obvious considerations of error associated with scale (where the coarsest dataset must dictate the final scale of the analysis) and the outliers resulting from the residual artifacts produced by the manipulation of raster and vector layers, there are commonly a number of spatially insignificant GLU types that are generated in the process. In subsequent analyses, we run basic spatial statistics on each GLU type to determine their dominance in a given watershed. Calculating the percent total of each GLU type proves to be an efficient way of identifying those GLU classes whose representation will be insignificant in any final results. These generally can be omitted from subsequent analysis.

The final step is to assign each GLU type to a High, Medium or Low category based on its relative sediment production rate as observed in the field or inferred from literature information. Examples of areas from each category are provided on the next page (Figure 9). Currently, these assignments are based on field observations; although it might be anticipated that various combinations of the three factors will yield a particular outcome based on prior experience, we presently lack sufficiently widespread application to provide such a list *a priori* or to recommend its application in a new locality. Even with long-standing application, some level of field verification will always be appropriate.

Figure 9. Examples of Low, Moderate, and High sediment production and delivery areas in the Santa Paula Creek watershed (Ventura County).

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APPENDIX: SAN ANTONIO CREEK EAMPLE

The following is a summary of the GIS-based and field-based assessment of the sensitivity of San Antonio Creek to hydromodication.

GIS-based analysis:
- The 'pre-developed' watershed Relative Sediment Production (determined by changing 'developed' GLU sediment production values to sediment production values for an undeveloped land use) is very similar to the current watershed Relative Sediment Production, indicating that the channel is not inherently receiving less sediment due to watershed development.
- Areas of 'H' Relative Sediment Production are interspersed with areas of 'L' Relative Sediment Production throughout the middle portion of the watershed.
- Development density is fairly low and concentrated towards the downstream end of the contributing watershed, so we anticipate relatively low hillslope sediment trapping potential by urban infrastructure.
- Only a few stream road crossings, so we anticipate relatively low in-channel sediment trapping potential.
- **From these data, we conclude that the San Antonio Creek study site has a "Low" sensitivity to current watershed development and is unlikely to express recent development-related changes in morphology.**

Field-based observations (see attached field photos and topographic data)
- Channel is alluvial and is transporting coarse sediment
- Channel has vegetated bars that appear stable
- Cross-sections show a 'stable' channel form (i.e., not incising, and displaying developed bankfull channel and stable banks)
- **From these data, concluded that the San Antonio Creek study site has had a relatively "Low" response to upstream development, expressing a "Low" sensitivity to current watershed development.**

GLU ANALYSIS:

SAN ANTONIO CREEK GEOMORPHIC LANDSCAPE UNITS
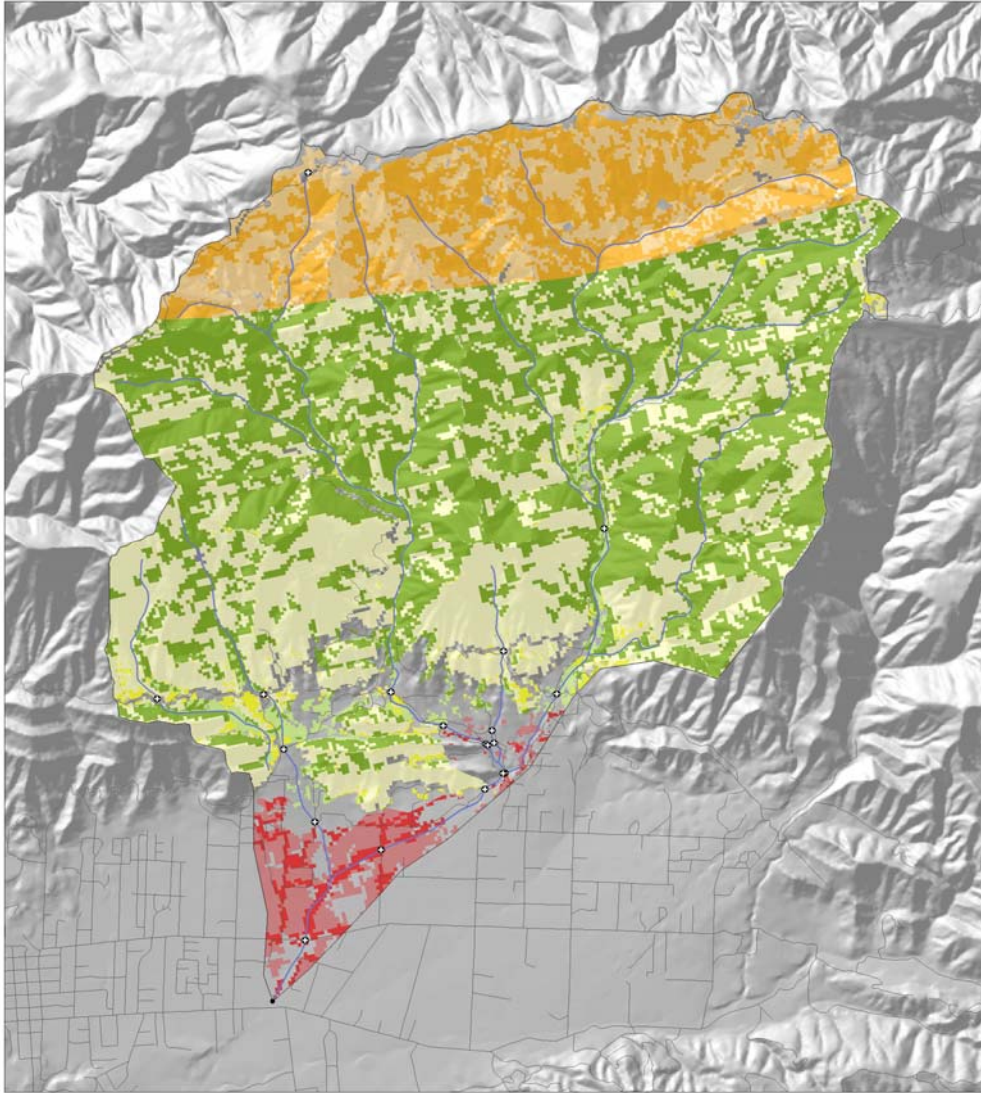
GEOMORPHIC LANDSCAPE UNITS
Geology; Landcover; Hillslope

- alluvium; Cultivated Crops; 0 - 10%
- alluvium; Developed, Open Space; 0 - 10%
- mudstone; Scrub/Shrub; 11 - 20%
- mudstone; Scrub/Shrub; >20%
- mudstone; Forest; 11 - 20%
- mudstone; Forest; >20%
- sandstone; Scrub/Shrub; >20%
- sandstone; Forest; >20%

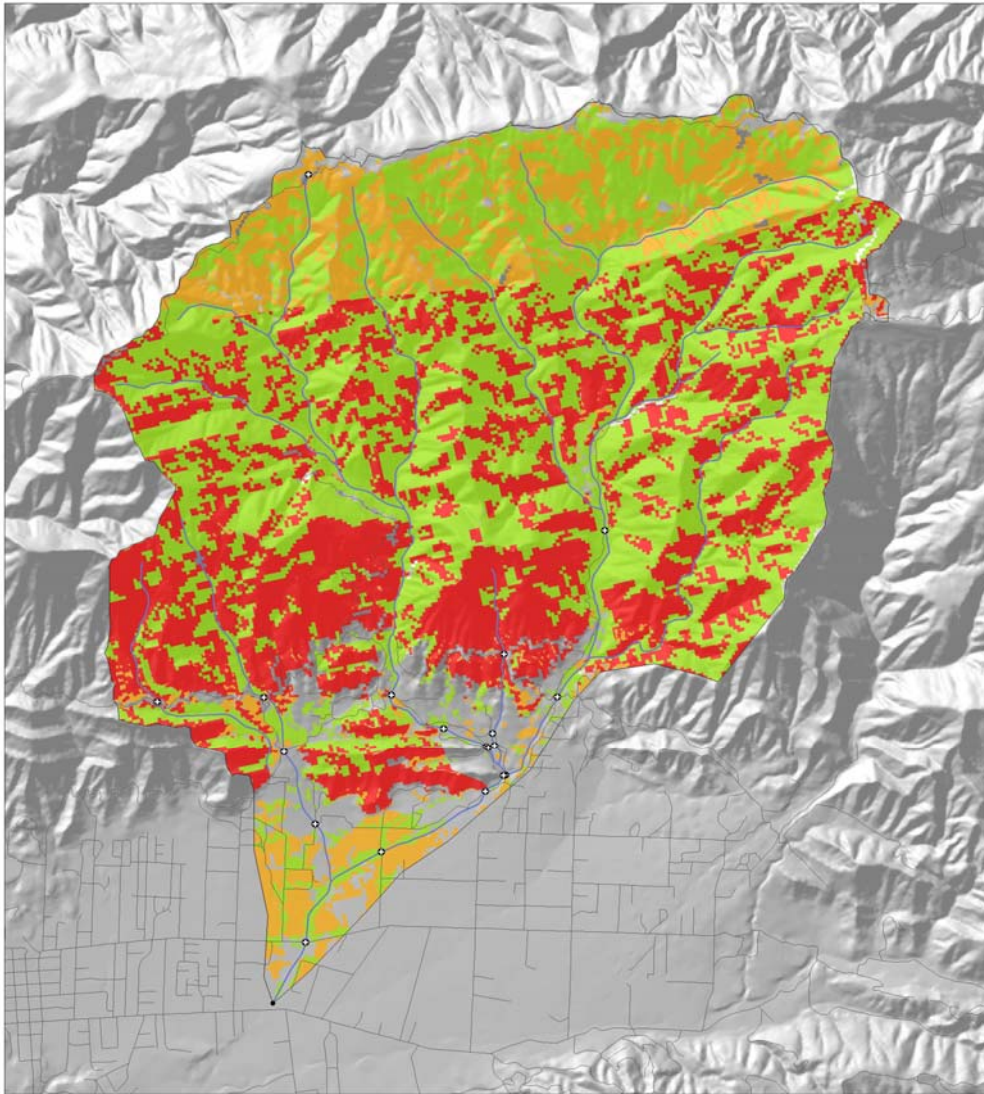The GLU classes shown amount to 96.5% of the total watershed area

MAP LEGEND

- • GPS survey points
- ⊕ Stream Crossings
- Roads
- Streams

Data sources:
Geomorphic Landscape Units: Stillwater Sciences, 2009
Hillshade: USGS 10m DEM
Streams: NHD - 1:100,000
Stream Crossings: Stillwater Sciences, 2009
GPS Survey Points: SCCWRP/CSU 2007
Hillshade: USGS 10m DEM
Streams: NHD - 1:100,000
Roads: ESRI 2000

Stillwater Sciences

0   0.25   0.5   1 Kilometers
0 0.125 0.25   0.5 Miles
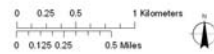
SAN ANTONIO CREEK RELATIVE SEDIMENTATION PRODUCTION RATES

Relative Sediment Production Rates

■ High
■ Medium
■ Low

Rates shown amount to 96.5% of the total watershed area

MAP LEGEND

• GPS survey points
◉ Stream Crossings
⋀⋀ Roads
〜〜 Streams

Data sources:
Relative Sedimentation Production Rates: Stillwater Sciences, 2009
Hillshade: USGS 10m DEM
Streams: NHD - 1:100,000
Stream Crossings: Stillwater Sciences, 2009
GPS Survey Points: SCCWRP/CSU 2007
Hillshade: USGS 10m DEM
Streams: NHD - 1:100,000
Roads: ESRI 2008

Stillwater Sciences

0 0.25 0.5   1 Kilometers
0 0.125 0.25   0.5 Miles

OBSERVATIONS:

LB   U-MW-UC

RB   STABLE-UC

Looking from right bank of SanAntoni_A a[t] nickpoint just upstream from SanAntoni_B

Looking upstream from near SanAntoni_A, toward left bank of SanAntoni_B

These sites are less than 30 meters apart. Therefore, the outer banks are only counted once (see SanAntoni_B next page). Only the within the additional incision within the main channel are counted for SanAntoni_A.

SanAntoni_A

LB = 0.9m, 49^0
RB = 0.8m
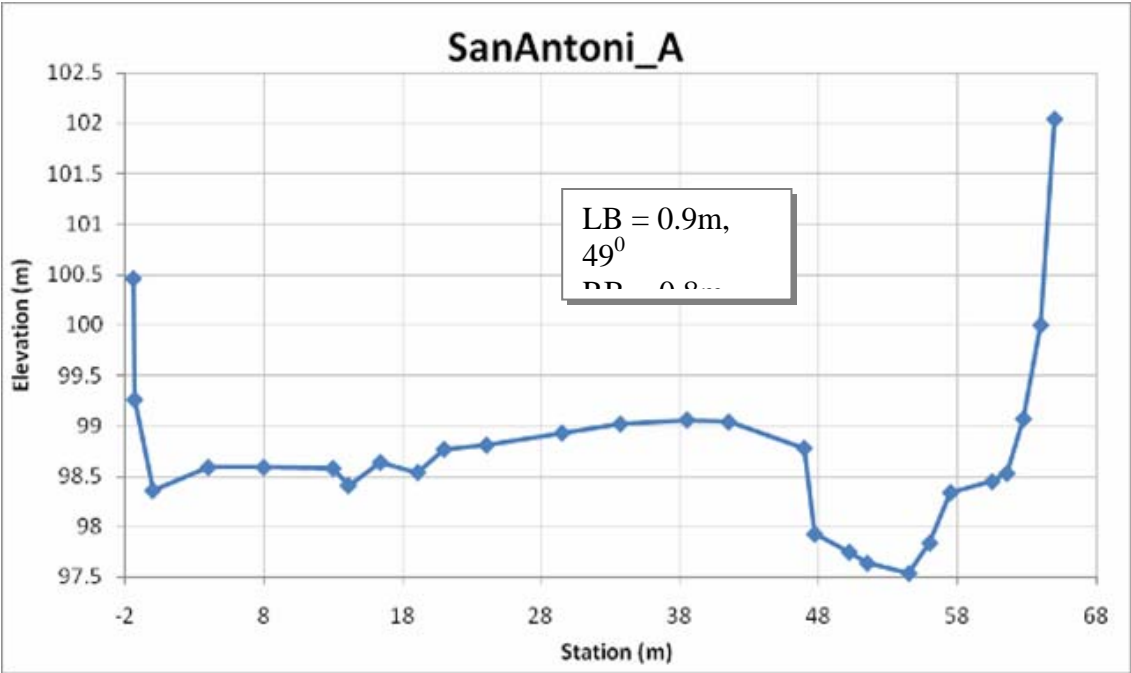
LB   U-MW-PC (upper) & STABLE-UC (lower)

RB   U-MW-PC (upper) & STABLE-UC (lower)

LB = 2.1m, 85^0 & 0.3m, 18^0