STREAM CHANNEL CLASSIFICATION AND MAPPING SYSTEMS: IMPLICATIONS FOR ASSESSING SUSCEPTIBILITY TO HYDROMODIFICATION EFFECTS IN SOUTHERN CALIFORNIA

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INTRODUCTION

Land-use alterations associated with urbanization and agriculture often intensify the potential for stream channel erosion and sedimentation through increases in runoff volumes and rates resulting from diminished watershed storage capacity, infiltration, and vegetative cover. Changes in the magnitude, relative proportions, and timing of sediment and water delivery have been documented as early as 1966 to induce channel adjustments and increase flood frequencies (Leopold 1968, 1972). In summarizing over 100 studies on the effects of urbanization on rivers, Chin (2006) concluded that urbanization has globally altered balances of water and sediment, and the respective river morphologies. Following the initial phase of sediment mobilization during construction, channels typically experience periods of sedimentation followed by enlargement.

Such shifts in the flow of water and sediment, and the resulting imbalance in sediment supply and capacity, also modify physical habitat and ecological potential via a wide variety of mechanisms. Altered channel morphology and bed material, hydraulic environments, and the magnitude, frequency, and timing of sediment-transport events adversely affect aquatic life and their life cycles (Trimble 1997, Waters 1995, Konrad *et al.* 2005, Merritt and Cooper 2000). The effects of these modified runoff and sediment yields are often further exacerbated by direct channel disturbances that increase energy of flow, decrease channel roughness, and reduce erosional resistance (Jacobson *et al.* 2001).

Geomorphic responses to changes in the hydrologic and sediment regimes are difficult to evaluate in a precise or quantitative manner for several reasons. Geologic and human disturbances histories can vary markedly within and among hydroclimatic regions and they impose a specific context in which a channel responds to contemporary hydrologic change (Knox 1977, Fitzpatrick and Knox 2000). Examples include the massive forest clearing and sediment erosion in the 19th century that have modified channel morphology in the southeastern Piedmont (Trimble 1974, Costa 1975), the extensive channelization and drainage of channels in the central United States (US; Rhoads and Herricks 1996), tie drives and removal of debris dams in the Pacific Northwest (Collins and Montgomery 2001, Montgomery *et al.* 2003), extensive damming (Grant et al. 2003), and the episodic arroyo cutting and extended "memory" of fluvial systems in the southwest (Graf 1983, Yu and Wolman 1987).

Channel enlargement, bank instability, degradation of physical habitat, and numerous other geomorphic responses have been associated with increases in peak flow in various hydroclimatic regions (Hammer 1972, Arnold *et al.* 1982, Booth 1990, Booth and Henshaw 2001, Jacobson *et al.* 2001). Existing literature also indicates that the increases in flow variability and flashiness are likely associated with decreased bank stability. Amplified flow variability can significantly increase the risk of bank instability via rapid wetting and drawdown (Thorne *et al.* 1998), and relatively small but frequent flows can promote prolonged periods of bank retreat, channel migration, and high yields of fine-grained sediment (Simon *et al.* 2000). Sediments produced via bank instability can initiate extensive bar formation and braiding, as well as alter substrate size, embeddedness, and bed stability (Carson 1986, Waters 1995, Jackson and Beschta 1984, Wilcock and Kenworthy 2002).

Although qualitative response models, based on water and sediment supply, are useful for predicting the general direction of geomorphic responses (Lane 1955, Schumm 1969, Grant *et al.* 2003), predicting the magnitude of morphologic adjustments and physical-habitat changes is extremely challenging because of historical contingencies, the large number of interrelated variables that can simultaneously respond to natural or imposed perturbations, and the continual evolution of fluvial forms and response with changing water and sediment discharges (Brewer and Lewin 1998, Hey 1997, Schumm 1977, Richards and Lane 1997).

Many stream channels are still adjusting to historical legacies that produce ongoing, lagged geomorphic responses (Trimble 1977, 1995). Moreover, any present-day geomorphic responses to contemporaneous imbalances in sediment and water budgets can be subject to thresholds and non-linearities (Schumm 1991). Several other factors also influence channel response to recent land alteration. For example, whether a channel incises or widens can depend on local variations in boundary materials, as with contrasts in cemented till and weakly consolidated outwash in the Pacific Northwest (Booth 1990, King County 1991, 1997, 1998a,b). Riparian vegetation may also influence channel adjustment and migration (Thorne 1990, Dunaway *et al*. 1994, Friedman *et al*. 1998). Because these and other factors exhibit heterogeneity across the landscape, the response of a local stream reach to watershed-scale hydrologic alteration can be complex and difficult to predict (Richards and Lane 1997, Jacobson *et al*. 2001).

Within the constraints set by extreme antecedent events, streams in arid/semiarid climates are perhaps most vulnerable to morphologic adjustment because of the prevalence of channels that actively transport bedload sediment (i.e., live-bed channels), historical incision, and lack of stabilizing vegetation. Bull (1997) remarked that in cases of discontinuous ephemeral streams, change (i.e., periods of aggradation or degradation) is relatively constant while equilibrium is brief. Conventional theories developed for humid-temperate environments, such as dominant/channel forming discharge, hydraulic geometry relationships, and the concept of equilibrium must be reconsidered in arid/semiarid environments (Graf 1988a). It is well known that streams in arid regions can exhibit radical morphologic responses to urbanization (Trimble 1997). Adjustments can also be relatively subtle and spatially discontinuous, however, because of the influence of urban infrastructure (e.g., culverts and pipelines acting as grade control; Chin and Gregory (2001)). Responses undoubtedly depend on stormwater controls, vegetation colonization, and many other extrinsic factors. Recent associative studies of watershed impervious area versus channel enlargement suggest that urban streams in the southwestern US may detectably enlarge at lower levels of watershed urbanization than streams in the eastern US (Coleman *et al*. 2005). Such studies are at least partially confounded, however, by watershed-specific patterns of impervious connectivity and drainage infrastructure, stream boundary materials, temporal lags, and legacy effects (Bledsoe and Watson 2001a, Jacobson et al. 2001).

In general, the effects of urbanization on perennial streams in humid regions have received much more attention than impacts to arid systems (Rhoads 1986, Chin and Gregory 2001). Findings from perennial streams cannot be directly extrapolated to arid systems where extreme events tend to be more geomorphically effective in ephemeral channels because of the extended memory and long recovery times (Wolman and Gerson 1978), sporadic movement and storage of sediment (Graf 1981), and spatially discontinuous adjustments in channel form due to relatively abrupt changes in fluvial processes (Rhoads 1988).

Fluvial systems in southern California, the ultimate focus of this review, are highly dynamic. Set along the boundary of the Pacific and North American plates, the geology of the region is quite complex, with active faulting and a largely heterogeneous lithology. Frequent fires and infrequent, but highly destructive, extreme storms combine to produce relatively high sediment yields as compared to much of the contiguous US. The bulk of the study domain lies along the NW-SE transform plate boundary of the San Andreas Fault (SAF) where activity is expressed as continuous motion or "stick-slip" (i.e., earthquakes) rather than tectonic uplift. However, the northern portion of the study domain in Ventura County is set along the E-W portion of the SAF. Because the primary plate motion is in the NW-SE direction, the SAF in Ventura County is largely characterized by tectonic uplift as the Pacific plate subducts underneath the North American plate, "pushing up" the latter. Published rates of contemporary uplift in Ventura County along the E-W section of the SAF range between 0.5 and 5 mm per year (Stillwater Sciences 2007).

Direct translation of uplift into gross erosion rates is not possible due to the episodic nature of erosion, storage within basins, the effects of topography and vegetation, and the large influence of disturbance events (e.g., fires). For the Ventura County region along the E-W SAF, Stillwater Sciences (2007; see http://www.santaclarariverparkway.org/wkb/scrbiblio/stillwater2005) estimated an erosion rate of 0.5 to 1 mm per year due to tectonic uplift. When factoring in geology, slope, and land cover, they determined landscape lowering rates of 0.7 to 2.2 mm per year, with gross loads of fine sediment between 1,700 and 5,800 tons per km^2 per year. Interestingly, they found a 2- to 16-fold increase in sediment production when evaluating the post-fire scenario.

These characteristics have two major implications for southern California streams. First, gross sediment loads for the region are relatively high, even in areas where tectonic uplift has largely ceased. Second, the frequent fire regime creates large (order of magnitude) fluctuations in the delivery of sediment. Therefore, one can expect that these systems regularly experience periods of overloading (aggradation) and flushing (degradation), which is consistent with previous studies (e.g., Bull, 1997).

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 processes associated with change in land use, often accompanied by increased imperviousness, which result in increased surface runoff and higher flow magnitudes and durations for equivalent rainfalls relative to the undeveloped setting. Some of the effects of hydromodification include an altered sediment delivery from the watershed, increased sediment transport within channels, and changes in channel forms.

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. Rapid urbanization, legacy effects from past land-uses, and lags in channel response create challenges for the regulatory and management community in addressing proximate and cumulative effects of hydromodification. 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 lands use, hydrology, and sediment yield. Past research in fluvial geomorphology and river mechanics provides a rich source of conceptual, qualitative, and quantitative tools relevant to arid/semiarid streams.

As a first step toward assessing the potential utility or modification of existing tools and previous research for managing hydromodification in southern CA, we performed a literature review of existing geomorphic mapping and classification schemes. The classification systems included in this summary are pertinent to assessing relative susceptibility to hydromodification effects and channel stability in southern California. For the purposes of this review, we define stream stability following 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)."* Although decadal time scales have practical limits for long-term planning, they are valuable in that water and sediment discharge are both primary independent variables (Schumm and Lichty 1965, Schumm 1991). Channel responses to changes in these variables occur at spatial scales that range from drainage networks to reaches to streambed patches. We focus primarily on the reach scale (e.g., on the order of $10^1 – 10^2$ m or 10 - 20 bankfull channel widths), where geomorphic adjustments to altered water and sediment regimes have immediate consequences for stream ecosystems via changes in channel morphology, habitat structure, and disturbance dynamics (Poff *et al.* 2006).

Classification and Mapping Systems Relevant to Hydromodification Management

In the following sections, we summarize nine general types of classification and mapping systems identified in a review of published research on the geomorphic response and susceptibility of streams to changes in water and sediment delivery. The review of these methods will be used to inform development of hydromodification management tools for southern California streams.

Planform Classifications and Predictors

A growing consensus of fluvial geomorphologists and sedimentologists acknowledge that alluvial channel patterns form a continuum rather than discrete types (Ferguson 1987, Knighton and Nanson 1993). Conceptual models of the continuum generally portray a spectrum from no lateral activity (straight and inactive sinuous channels) through localized lateral activity (actively meandering channels) to widespread lateral activity (braided channels). This sequence is associated with increasing discharge and slope, increasing width-to-depth ratio, and replacement of secondary circulation in bends by other forms of flow convergence or divergence (Ferguson 1987). Increasing slope and discharge correspond in broad terms to greater flow strength, shear stress, specific power, and bed-load transport capacity. Knighton and Nanson (1993) defined the continuum in terms of three variables: 1) flow strength, 2) bank erodibility, and 3) relative sediment supply.

Although many natural channels have forms that are intermediate to purely straight, meandering, or braided patterns, several investigators have reported abrupt transitions between straight, meandering, and braided forms in experimental flumes and the field. In contrast to the idea of a gradual continuum of channel forms, an imposed increase in flow strength may result in sudden morphologic responses that suggest the existence of geomorphic thresholds (Schumm 1977; Bull 1979; Harvey and Watson 1986; Graf 1988a,b; Knighton 1998). When compared to equilibrium approaches, the threshold concept places more emphasis on when and where change occurs in fluvial systems and the reasons for change (Bull 1979). Despite the recognition of a continuum of channel forms, the conceptual framework of geomorphic thresholds is central to the analysis of stream and river response to disturbance.

In the latter half of the 20th century, geomorphologists and engineers have attempted to predict the planform of rivers based on the slope and some measure of discharge or drainage area. The concept of a threshold discharge–slope (Q-S) combination that discriminates braided rivers from meandering ones has become a fundamental tenet in the doctrine of fluvial geomorphology (Carson 1984). The Q-S discriminator, which is essentially a measure of stream power, was first suggested by Lane (1957) and Leopold and Wolman (1957). Although such an approach omits sediment size and supply, many other investigators have provided support for the notion of a threshold between meandering and braiding types and have used this approach to interpret a variety of field and flume data (Schumm and Khan 1972, Chitale 1973, Osterkamp 1978, Begin 1981, Richardson *et al*. 1990).

Critical examination of the early work on meandering to braiding thresholds has subsequently revealed several limitations of the original approach. Critical stream power for braiding appears to vary with bed-material size, i.e., the critical slope for braiding at a given discharge is higher for gravel than for sand-bed channels (Carson 1984, Ferguson 1987). The traditional threshold of Leopold and Wolman (1957) is too high for sand-bed channels and too low for gravel-bed channels, because it is based on a combination of the two.

Other concerns associated with the original stream-power approach arise from bias in the slope and discharge parameters and the widely varied influence of bank materials (van den Berg 1995). Channel slope and bankfull discharge are not necessarily independent of planform. Braided channels are inherently steeper than meandering channels for a given valley slope due to very low sinuosity. Braided

channels may also have larger bankfull cross sections as a consequence of braiding. Some investigators have also suggested that bank resistance is a relevant factor in the analysis of channel planform (Carson 1984, Ferguson 1987, Bridge 1993).

Several theoretical approaches to defining the transition from meandering to braiding have also been developed. These techniques were not developed as predictive tools, however, because they rely on parameters such as width, depth, and Froude number that are usually not available for *a priori* predictions of channel form. The theoretical approaches do seem to suggest that braiding generally occurs at channel width-to-depth ratios in excess of 50:1 (Fredsøe 1978). Bridge (1993) provides an excellent review and summary of the various empirical and theoretical thresholds that have been proposed for the transition from braiding to meandering (Table 1).

In another attempt to reconcile some of the issues associated with the original empirical approaches, van den Berg (1995) devised a simple parameter representing potential specific stream power that enables discrimination of braided and high sinuosity meandering rivers ($P > 1.3$) in unconfined alluvium. Using a data set of 126 streams and rivers, he arrived at a discriminant function of the form:

$$\omega \cong \frac{\gamma}{\alpha} \; S_{valley} \; Q_{bf}^{0.5} = 900 \, D_{50}^{0.42} \tag{1}$$

> where: ω = function of valley slope, estimated bankfull discharge, and an assumed regime width that varies between sand-bed and gravel-bed rivers.
> i.e., width = $\alpha * Q^{0.5}$
>
> where: α = regression coefficient computed for a particular collection of streams
> and specific (i.e., unit) stream power = total stream power / width
> and total stream power = $\gamma * Q * S$
>
> where: γ = the specific weight of the water and sediment mixture (e.g., often assumed to be that of water only = 9810 N/m^3)

The discriminate function applies to both sand- and gravel-bed rivers with median bed material ranging from 0.1 to 100 mm. This approach essentially replaces bed slope with valley slope. The resulting specific stream power represents the maximum potential specific stream power for a particular valley slope. Potential specific stream power and median particle size (D_{50}) are expressed in W/m^2 and meters, respectively.

Table 1. Summary of meandering-braiding discriminators (after Bridge (1993)).

Equation*	Comments	Author
$S = 0.0007 Q_m^{-0.25}$	Meandering Sand-bed Channels	Lane (1957)
$S = 0.0041 Q_m^{-0.25}$	Braided Sand-bed Channels	Lane (1957)
$S = 0.0125 Q_{bf}^{-0.44}$	Meandering → Braided	Leopold and Wolman (1957)
$S = 0.000196 D^{1.14} Q_{bf}^{0.44}$	Meandering → Braided	Henderson (1961, 1966)
$S = 1.4 Q_{maf}^{-1}$	Meandering → Braided	Antropovsky (1972)
$S = 0.0009 Q_m^{-0.25}$	Mainly Meandering Sand-bed Rivers in Kansas	Osterkamp (1978)
$S = 0.0017 Q_m^{-0.25}$	Braided Sand-bed Rivers in Kansas	Osterkamp (1978)
$S = a Q_m^{-0.25}$	Meandering → Braided	Osterkamp (1978)
$S = 0.0016 Q_m^{-.33}$	Meandering → Braided	Begin (1981)
$S = 0.07 Q_{2f}^{-0.44}$	Sinuosity > 1.25 and Meandering → Braided for Gravel-bed Rivers	Bray (1982)
$S = 0.042 Q^{-0.49} D_{50}^{0.09}$ $S = 0.042 Q^{-0.49} D_{90}^{0.27}$	Meandering → Braided for Gravel-bed Rivers **	Ferguson (1984, 1987)
$S = 0.0049 Q^{-0.21} D_{50}^{0.52}$	Meandering → Braided using Parker's Theory and Hydraulic Geometry **	
$S = a Q^{-0.5} D_{50}^{0.5}$	Meandering → Braided	Chang (1985)
Sum $P = 1 + 5.52(QS_v)^{0.38} D_{84}^{-0.44}$	Gravel-bed Rivers	Robertson-Rintoul and Richards (1993)
Sum $P = 1 + 2.64(QS_v)^{0.4} D_{84}^{-0.14}$	Sand-bed Rivers	Bridge (1993)
$S^{0.2} w/d = 10$ to 20	Meandering → Braided Weak Dependence on f and Q	Fukuoka (1989)
$w/d = 50$	Meandering → Braided Weak Dependence on f and Q	Fredsøe (1978)
$S/Fr^2 (w/d)^2 f(\Theta) =$ constant	Meandering → Braided	Struiksma and Klaassen (1988)
$S/Fr = d/w$	Meandering → Braided	Parker (1976)
$2(wS/d)^{0.5} = Fr$	Meandering → Braided	Hayashi and Ozaki (1980)
$\gamma SQ/w = 50$ to 60 W/m^2	Meandering → Braided	Nanson and Croke (1992)

* using SI units   ** D in mm   ***d = depth

The high relief, readily erodible soil/weak rock, and semiarid climate result in a relatively high occurrence of braided planforms in southern California. Although not inherently undesirable, they present different management and design challenges. The geomorphic thresholds identified by van den Berg (1995) for meandering and braiding offer an appealing framework by incorporating both stream (and valley) energy and resistance. By including the median grain size (D_{50}), the thresholds are put into context relative to general bed resistance. That is to say, stream-power thresholds for gravel and cobble systems are different from sand systems.

Energy-based Classifications of Overall Channel Stability

Many researchers have explored relationships between the extent of urbanized or impervious area and the magnitude of channel instability or channel cross-section enlargement. Hammer (1972) attributed channel enlargement to sewered streets and other impervious area such as parking lots. MacRae has expanded the approach of relating channel enlargement ratios to total impervious watershed area in many different North American regions (MacRae and Rowney 1992; MacRae 1993, 1997). Coleman *et al*. (2005) applied the approach in southern California, noting an exponential relationship similar to that observed in other regions in terms of channel enlargement relative to the percent of impervious area. Although impervious area is a reasonable starting point, it is clear that channel response is dependent on several other factors, such as, proximity to a downstream hard point, valley materials, and current evolutionary stage.

In a related series of papers, Chang (1979a,b; 1980; 1985; 1986; 1988) developed an approach for predicting equilibrium slopes, widths, and depths for sand-bed channels of varying grain sizes and inflowing sediment loads. The approach is rooted in the hypothesis of minimum total stream power (Bettess and White 1987), that is, the hypothesis that channels adjust their form to achieve an extreme state of minimum energy expenditure for the given boundary conditions. The approach represents a comprehensive attempt to include the significant effects of bed material and sediment load on sand-bed channel form. Some investigators have taken issue with the fact that Chang's regions do not correspond to the sequence observed in nature as stream power increases (Bridge 1993). Nevertheless, two interesting results may be postulated from Chang's work: first, the shift from lower to upper regime in sand-bed channels may markedly affect how the channel adjusts (e.g., widening versus incising), and second, braiding should occur at a width-to-depth ratio of about 50:1, which is in close agreement with other theoretical predictions. Although the exact slopes of Chang's discriminators vary, these relationships are generally of the form:

$$S \approx aQ^{-0.5}D^{0.5} \tag{2}$$

With the values of *a* approximately 0.00039 and 0.0076, and using units of m^3/s for flow (Q) and units of mm for grain size (D), Chang (1988) separated single thread, straight braided, and braided point-bar/wide-bend streams, respectively. However, he suggested that the transition to streams that he categorized as highly braided steep streams (e.g., width-to-depth ratio greater than 100:1 and slopes greater than approximately 0.5%) could not be specifically located by this analysis.

Interestingly, the form of equations above is similar to the relationship developed by Hack (1957) in a classic study of longitudinal profiles of gravel-bed streams in Virginia and Maryland. Hack proposed the relationship:

$$S = a\left(\frac{D_{50}}{A}\right)^b \qquad (3)$$

where: S = bed slope; and
A = drainage area which is used a surrogate for discharge.

Hack found that the value of b was approximately 0.4 for bed slopes surveyed in the field and 0.6 for slopes taken from topographic maps. Hack also suggested that median bed material taken alone was an inadequate predictor of channel slope. Only when slopes were scaled by drainage area (as an ostensible surrogate of discharge) was a significant relationship obtained. Hack's relationship has subsequently been tested in other geologic settings with strikingly similar results (Penning-Rowsell and Townshend 1978, Schröder, 1991). The form of equations above suggest that the ratio of specific stream power (approximated as $SQ^{0.5}$ or $SA^{0.4}$ when using drainage area as a surrogate for discharge) to $D_{50}{}^b$ (where b may be approximately 0.4 to 0.5 for both sand- and gravel-bed channels) is a simple but useful surrogate for the ratio of erosive energy versus boundary materials.

In accordance with Hack's work, several workers have developed stream-power surrogates using combinations of slope and drainage area. These surrogates have proven useful in predicting channel, form and response in various contexts:

- Patton and Schumm (1975) investigated slope-drainage thresholds for gully erosion in northwestern Colorado, which provided insights into the development of the original Channel Evolution Model (CEM, further described in Section 2.5).

- Schumm *et al*. (1984) used the "area-gradient index" (the product of slope and drainage area) as surrogate for stream power to interpret the incision response of sand-bed streams in northern Mississippi.

- Following Schumm *et al*. (1984), the U.S. Army Corps of Engineeers (USACE 1990) subsequently developed "slope-area" relationships for stable versus unstable channels for the Demonstration Erosion Control (DEC) Project in the Yazoo River basin, Mississippi.

- Bledsoe *et al*. (2002) subsequently demonstrated that slope-area relationships that discriminate between stable and incising sand-bed streams can be directly related to thresholds of stream power and sediment-transport capacity.

Basic flow attributes such as velocity, depth, average boundary shear stress, energy slope, etc. may be used as descriptors of varying hydraulic and sedimentation processes across the continuum of channel forms. As mentioned previously, a parameter that is closely related to all of these basic hydraulic descriptors is the power expended per unit area of stream bed, which is defined as specific stream power (sometimes referred to as unit stream power). More than any other single parameter, specific stream power (ω) has been suggested as a comprehensive descriptor of overall hydraulic conditions and

sedimentation processes in stream channels (Bagnold 1966; Schumm and Khan 1972; Bull 1979; Edgar 1973, 1976; Nanson and Croke 1992; Brookes 1988; Rhoads 1995). Specific stream power is defined as:

$$\omega = \frac{\gamma QS}{w} \tag{4}$$

where: γ = specific weight of the water and sediment mixture (often assumed to be that of water only);

Q = flowrate being evaluated (e.g., dominant discharge in many cases);
S = slope; and
W = channel width.

In many instances, channel width data are not readily available. In analyses of channel morphology and response, a regime width is sometimes used as a surrogate for actual width. The empirical relationship between channel width and the square root of dominant discharge is well documented for a wide variety of environments (Knighton 1998) and closely adheres to the form:

$$w = \alpha Q^{0.5} \tag{5}$$

where: α = regression coefficient computed for a particular collection of streams.

Substituting for width, the relation for approximating specific stream power is:

$$\omega \approx \frac{\gamma}{\alpha} \sqrt{Q} \, S \tag{6}$$

Previous research suggests that specific stream power is a simple but robust measure of flow strength and erosive power. Therefore, it seems likely that meaningful thresholds for channel instability might be found in terms of excess specific stream power relative to bed-material characteristics (Carson 1984). Several studies have attempted to identify relationships between overall channel instability and thresholds of specific stream power:

- Booth (1990), in documenting stream incision following urbanization in the Pacific Northwest, explored erosion potential as a function of unit stream power and identified a "moderately well-defined" specific stream power threshold of 80 W/m^2.

- Brookes (1987a,b) found that low-gradient, single-thread rivers that had been channelized in Denmark and Wales re-attained quasi-equilibrium at specific stream power values less than ~35 W/m^2.

- A threshold of 30 to 35 W/m^2 was identified as separating quasi-equilibrium and incising sand-bed streams surveyed as part of the DEC Project in Mississippi. Interestingly, this level of specific stream power corresponds to the transition from lower to upper regime sand-bed behavior according to the Brownlie (1981) depth and sediment-transport predictors.

- Molnar and Ramirez (1998) also used stream power concepts to map reaches of an incised sand-bed system in the Goodwin Creek watershed of northern Mississippi that appeared to be unstable.

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In a study of 270 streams and rivers across many hydroclimatic regions (including semiarid), Bledsoe and Watson (2001b) employed logistic regression to develop risk-based (probability) models for states of braiding, incising, and meandering by using a "mobility index" based on slope, median annual flood (Q), and median bed-material size (d_{50}). By dropping the γ and α terms in Equation 6 above, this index is a surrogate for specific stream power relative to the channel boundary materials. The logistic regression analyses of stable and unstable channel forms suggested that simple indices describing the ratio of erosive energy to boundary material resistance can be robust predictors of channel planform and stability in some geomorphic contexts. The logistic models generally predicted the occurrence of unstable sand and gravel channel forms with more than 80% accuracy. In many cases, the predictive accuracy of logistic models utilizing the mobility index as the only independent variable exceeded 95%. A benefit of this approach is that explicit probability statements may be attached to diagrams depicting channel stability. This provides users with a useful and realistic assessment of risk when compared to the discrete thresholds of traditional approaches.

General Stability Assessment Procedures

We found no existing field assessment protocols for evaluating channel stability developed specifically for arid climates. Nevertheless, many previously proposed stability metrics are potentially useful for arid/semiarid regions, such as southern California. Pfankuch (1978) developed a field stability assessment method for assessing second- to fourth-order (per Strahler, 1952) mountain streams of the northwestern US, which included 15 field indicators with four possible ratings (excellent, good, fair, and poor). Although qualitative, several of the indicators have been used in schemes beyond the Pacific Northwest, and have been explicitly central to more recent methodologies such as the Johnson *et al.* (1999) rapid assessment at road crossings and the Rosgen (2007) protocol. Some of the key elements from Pfankuch (1978), which could be of value for a southern California classification system include:

- bank slope/angle;

- bank vegetation/protection;

- bank mass wasting/failure;

- obstructions, flow deflectors, or debris jams; and

- bed-armoring or bed-material consolidation.

Lewin *et al.* (1988) incorporated both floodplain and channel characteristics into their channel instability scheme based on field indicators. It coupled field indicators with a prediction of instability direction and probable sequence, similar to other sequential models like the incised channel evolution model (CEM) described in detail below. Characteristics such as valley terraces, abandoned multichannel systems on the floodplain, bank erosion, and floodplain soil stratification all inform current thinking regarding channel classification.

Simon and Downs (1995) developed an assessment technique for alluvial channels that is based on 12 metrics. Their approach incorporated the Simon (1989) modification of the original Schumm *et al.* (1984) CEM. Like Pfankuch (1978), Simon and Downs (1995) included a large number of individual metrics, but the approach differed in that it individualizes the scores specific to the index at hand using

relative weighting scheme based on expert judgment. Seven indices are focused on assessing stability at bridges; however, the remaining indices could be of value for a general classification of channel stability:

- bed material;
- bed protection;
- CEM stage;
- bank erosion; and
- vegetative cover.

Johnson *et al.* (1999) synthesized primarily the Pfankuch (1978) and Simon and Downs (1995) approaches into an assessment designed for rapid application to gravel-bed streams in the vicinity of road crossings. In addition to the previously mentioned metrics, they also included:

- bank soil texture and coherence;

- bar development (after Lagasse *et al.* (1995)); and

- shear stress ratio, τ_e (after Olsen *et al.* (1997)), defined as:

$$\tau_e = \tau_0/\tau_c \tag{7}$$

where: τ_0 = the average boundary shear stress
τ_c = the critical shear stress at which bed material particles begin to move

Bank texture was included to quantify the relative resistance of the banks. Bar development along a gradient from raw substrate to fully mature with vegetation proved to be a useful index of stability. Finally, the bankfull shear stress ratio, applicable on streams less than 2% in slope as proposed by Olsen *et al.* (1997), provides a quantitative metric explicitly describing erosive vs. resisting forces. The authors also discussed the possibility of using specific stream power, citing the Brookes (1988) threshold of 35 W/m^2. However, the published stream-power threshold developed for the United Kingdom did not include the influence of bed-material size. As such, they elected to use the shear stress ratio.

Henshaw and Booth (2000) developed an assessment method which they applied to streams along a gradient of urbanization in the Pacific Northwest. Although they found no consistent relationship between the extent of watershed urbanization and channel response, several useful findings have been explored:

- the importance of proximate grade control in mitigating the potential channel response;

- the usefulness of repeated surveys and photographs at the same cross section; and

- application of the Olsen *et al.* (1997) Relative Bed Stability (RBS) index, where RBS is defined as:

$$RBS = \tau_{c84}/\tau_{bf} \qquad\qquad (8)$$

where: τ_{c84} = the shear stress required to mobilize the 84th percentile particle (D_{84})

τ_{bf} = the bed shear stress at bankfull flow

The RBS index is of interest because it begins to factor in the range of bed-material sizes rather than just the d_{50}.

Sand vs. Gravel Behavior/Threshold vs. Live-bed Contrasts

Geormorphologists and engineers agree that sand and gravel/cobble systems behave differently in many important ways. Simons and Simons (1987) provided a summary that serves as an excellent frame of reference (Table 2).

Table 2. Generalized relative differences in sand-bed and gravel/cobble-bed streams (modified from Simons and Simons (1987)).

Parameter	Sand bed	Gravel/Cobble bed
Bed material transport	Continuous	Episodic
Variation in sediment-transport	(Velocity) [5]	(Velocity) [3]
Armoring	Ineffective	Significant
Bed forms and changes in bed roughness/configuration	Rapidly adjusting across flow events	Not rapidly adjustable/formed by relatively infrequent events
Scour depth	Deep	Shallow
Variation in scour depth	Rapid	Slow
Slope and stream power	Lower	Higher
Channel response to changed hydrology	Rapid	Slower
Sensitivity to changed sediment loads	High	Lower
Variation in bed-material size	Small	Large
Bankfull dimensionless shear stress	≈ 1 - 10+	≈ 0.03 - 0.06

In particular, sand and gravel systems are quite varied in their transport of sediment and their sensitivity to sediment supply. On the former, sand-bed channels typically have live beds, which transport sediment continuously even at relatively low flows. Conversely, gravel/cobble-bed channels generally transport the bulk of their bed sediment load more episodically, requiring higher flow events for bed mobility (i.e., threshold behavior; Simons and Simons 1987).

To compare the sensitivity of equilibrium channel slopes to inflowing sediment load, Bledsoe (2002a) used Copeland's method for stable channel design to demonstrate an order of magnitude difference in stable slopes for a sand-bed channel resulting from variations in inflowing sediment loads commonly encountered in single-thread channels. In contrast, the same variations in inflowing sediment for a gravel-bed channel resulted in stable slopes that differed very little. Such sensitivity of sand-bed streams

to the inflowing sediment load is also supported by qualitatively comparing the phase diagrams of Parker (1990) to those of Chang (1988) for gravel and sand, respectively.

As such, sand-bed streams without vertical control are much more sensitive to perturbations in flow and sediment regimes than coarse-grain (gravel/cobble) threshold channels. This has clear implications in their respective management regarding hydromodification (i.e., sand systems being relatively more susceptible than coarser systems). This also has direct implications for the issue of sediment trapping by stormwater practices in watersheds draining to sand-bed streams, as well as general loss of sediment supply following the conversion from undeveloped sparsely-vegetated to developed well-vegetated via irrigation. Finally, the transition from sand-bed to gravel-bed behavior along drainage networks can be quite abrupt (Sambrook Smith and Ferguson 1995). If sharp thresholds are ubiquitous across a region, it may be possible to identify channel segments that are relatively susceptible to the effects of hydromodification using GIS, remotely-sensed data and watershed-scale mapping.

Channel Evolution Models of Incising Channels

A widely referenced contribution to assessing channel stability was the Channel Evolution Model (CEM) presented by Schumm *et al.* (1984). In documenting a sequence of five stages of channel instability and the ultimate return to quasi-equilibrium, it was possible for investigators to have a relative sense of how unstable a reach was and how unstable it may become based on a well-documented series of five response stages:

1. CEM Type I – stable;

2. CEM Type II – incising (degradation);

3. CEM Type III – incision depth exceeds critical height for bank failure and widening (bank failure primarily due to geotechnically unstable banks, that is, mass wasting);

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

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

In observing dredged and channelized rivers of western Tennessee, Simon (1989) described a similar, six-stage CEM. Bledsoe *et al.* (2002) quantified changes in slope, sediment load, and specific stream power as channels evolve through the five stages of the original CEM, noting consistent decreases in all three metrics as a channel proceeds from a state of incision to a state of quasi-equilibrium.

Watson *et al*. (2002) expanded the conceptual framework of the CEM to include a dimensionless stability diagram (Figure 1).
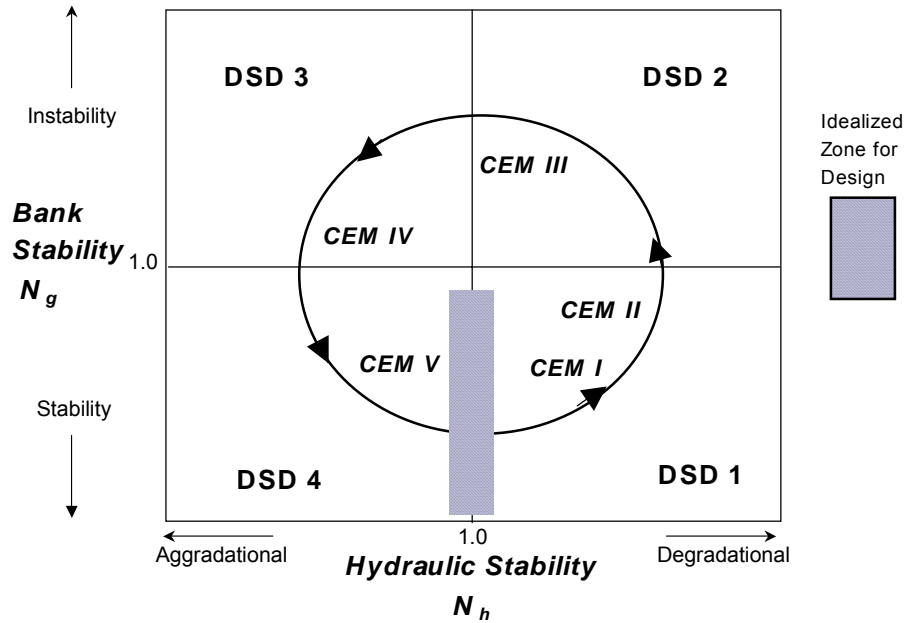
Figure 1. Dimensionless stability diagram based on the Channel Evolution Model for incised sand-bed streams (Watson *et al*. 2002).

In this diagram, the parameters of the CEM are summarized using two dimensionless stability numbers: N_g is a measure of bank stability and N_h is a measure of sediment continuity. N_g is defined as the ratio between the existing bank height and angle (h) and the critical bank height at the same bank angle (h_c). Bank stability is attained when N_g is less than unity ($N_g < 1$). Therefore, N_g provides a rational basis for evaluating the consequences of further bed degradation. The hydraulic stability number (N_h) is defined as the ratio of the actual sediment-transport capacity to the equilibrium sediment supply for the existing channel geometry and flow regime. Sediment continuity yields $N_h = 1.0$ for a stable reach. Hydraulic stability in the channel is attained when $N_h = 1$. If N_h is < 1, the channel will aggrade; if N_h is > 1, it will degrade. The dimensionless stability numbers (N_g and N_h) can be related to the channel evolution modes, as shown in Figure 1.

As the channel evolves from a state of disequilibrium to a state of dynamic equilibrium through the five reach types of the CEM, the channel condition will progress through the four stability diagram quadrants in a counter-clockwise direction. Each quadrant of the stability diagram is characterized by geotechnical and hydraulic stability number pairs, and stream reaches that plot in each quadrant have common characteristics with respect to stability, flood control, and measures that may be implemented to achieve a project goal. In general, using the dimensionless stability diagram to depict a shift from actual to desired sediment supply, and to directly examine potential for bank instability facilitates planning and engineering design for rehabilitation of incised channels. Whereas the CEM provides an understanding of only the existing natural sequence of channel evolution, the combined models provide complementary views of channel processes from engineering and geomorphic perspectives.

CEMs Combining Vertical and Lateral Adjustment Trajectories

The CEM described above is focused exclusively on incising channels in which the initial bank-failure mechanism is primarily geotechnical and not driven by fluvial detachment. However channel response may involve lateral adjustment through both mass wasting and fluvial detachment. Therefore, review of other classifications that describe both vertical and lateral adjustment trajectories is warranted. In a largely descriptive study, Brice (1981) categorized channel responses into degrading, aggrading, widening, and shifting. The study also provided a detailed classification of planform patterns spanning equiwidth single-thread channels to braided channels, with intermediate forms exhibiting varying degrees of chute and central bar formation.

Brookes (1988) focused on channelized streams and outlined a scheme that included degrading, armoring, sinuosity, bar development, and bank erosion. Downs (1995) classified nine morphological adjustment possibilities based in part on the conceptual framework provided by the Brice (1981) and Brookes (1988) studies. The resulting classification encompasses many stages of active fluvial morphologic adjustment types, including depositional, migration, enlargement, undercutting, recovering, and compound phases; however, it does not fully detail specific response sequences.

Rosgen and Silvey (1996) presented eight evolutionary scenarios that they have observed in response to 'improper management' such as removal of riparian vegetation. Although the response scenarios described are in sequential form, the causal mechanisms behind the sequences are unclear. Even so, the State of Vermont has recently released a very detailed geomorphic assessment protocol linked to the original Rosgen stream classification and descriptions of potential response trajectories using the Rosgen system. The basic premise of the approach is that stream susceptibility primarily depends on two factors: existing Rosgen stream type and the current "condition" as compared to a reference range of variability. Channels that are capacity-limited, incised, braided and/or already degraded are generally rated as being more sensitive to additional disturbances (Table 3). In this scheme, factors such as entrenchment and slope are deemed more important than differentiating between sand versus gravel boundary materials as types 3, 4, and 5 (cobbles, gravels, and sand) are generally included in the same risk category for a given stream type.

In general, channel form-based approaches such as the VT procedure are not well-suited to the dynamic fluvial systems of southern California for several reasons. First, changes in the key physical drivers of flow and sediment regime are not explicitly addressed. Second, fundamental differences in the response potential of sand versus coarse bedded streams with armoring potential are not reflected in assessments of relative sensitivity. Third, thresholds and transition probabilities between stream forms of interest to stakeholders in southern California are not included. Fourth, the rationale for assessing stream types to the various categories of sensitivity is not clearly articulated. Fifth, as pointed out by Juracek and Fitzpatrick (2003), the Rosgen channel form-based classification is dependent upon identifying true equilibrium conditions and locating the bankfull elevation, both of which are particularly challenging in southern California.

Table 3. State of Vermont stream sensitivity ratings based on existing stream type and condition (from Vermont Agency of Natural Resources (2004)).

Existing Stream Type	In Regime – Reference or Good Condition	Major Adjustment – Fair Condition	Stream Type Departure or Poor Condition
A1, A2, B1, B2	Very Low	Very Low	Low
C1, C2	Very Low	Low	Moderate
G1, G2	Low	Moderate	High
F1, F2	Low	Moderate	High
B3, B4, B5	Moderate	High	High
B3c, C3, E3	Moderate	High	High
C4, C5, B4c, B5c, E4, E5	High	Very High	Very High
A3, A4, A5, G3, F3	High	Very High	Extreme
G4, G5, F4, F5	Very High	Very High	Extreme
D3, D4, D5	Extreme	Extreme	Extreme

Equilibrium Models of Supply vs. Transport-capacity / Qualitative Response

Another type of classification framework is the qualitative response model. In many instances, there is great value in predicting the probable direction of channel change, despite much greater uncertainty regarding the magnitude of change (Richards and Lane 1997). These models provide a probable direction of change in equilibrium channels given different alterations in inflowing water and/or sediment loads. Indeed, sediment supply is widely recognized as a critical control of channel form and stability. The pioneering works of Gilbert and Stone (1917), Mackin (1948), and Lane (1955) describe a balance between the erosive forces of flow and slope relative to the resistive forces of grain size and sediment supply in equilibrium channels. Usually referred to as "Lane's balance," the proportionality of $QS \sim d_{50}Q_s$ is still widely cited and used as a framework in qualitatively understanding the probable response direction of streams and rivers.

Schumm (1969, 1977) added width, depth, and planform characteristics to the Lane relationship and developed qualitative responses to several system-wide changes such as urbanization, water diversions, land conversion from forest to agriculture, etc. The Schumm/Lane qualitative response is expanded below (Table 4), and provides probable responses to various responses to changes in inflowing water and sediment.

Table 4. Qualitative framework applied in predicting and understanding the physical response of streams to changes in water and sediment flows. Parallel changes reflect relatively high uncertainty in response direction (indicated by "?").

Change	Slope	D_{50}	Depth	Width	Description of Probable Responses
Q_w^+, Q_s^o Q_w^{++}, Q_s^+	-	+	+	+	Erosion and instability, tendency toward incision or braiding depending on boundary materials, coarser substrate, decreased total roughness, increased flow disturbance and scour depths
Q_w^-, Q_s^o Q_w^{--}, Q_s^-	+	-	-	-	Aggradation, finer substrate, reduced channel area and habitat volume
Q_w^o, Q_s^+ Q_w^+, Q_s^{++}	+	-	-	+	Aggradation and instability, finer substrate, increased scour depths and risk of braiding
Q_w^o, Q_s^- Q_w^-, Q_s^{--}	-	+	+	-	Erosion and instability, tendency toward incision or increased meandering, coarser substrate
Q_w^+, Q_s^-	-	+	+	?	Erosion and instability, tendency toward incision (braiding is possible with extreme bank erosion), coarser substrate, decreased debris retention and total roughness, increased disturbance and channel homogenization
Q_w^+, Q_s^+	?	?	?	+	Processes/disturbance increased in intensity, widening, unstable, and unpredictable
Q_w^-, Q_s^+	+	-	-	?	Aggradation, finer substrate
Q_w^-, Q_s^-	?	?	?	-	Processes decreased in intensity, tendency toward meandering/ narrowing, increased roughness

In accordance with previously developed qualitative models of directional response, Montgomery and Buffington (1998) argue that capacity-limited channels (e.g., pool-riffle and dune-ripple bedform channels that have a higher sediment supply than capacity to transport) are more susceptible to watershed disturbance and changes in sediment and water regimes. Montgomery and MacDonald (2002) further developed these ideas in a diagnostic framework that *"assesses reach-level channel conditions as a function of location in the channel network, regional and local biogeomorphic context, controlling influences such as sediment supply and transport capacity, riparian vegetation, the supply of in-channel flow obstructions, and disturbance history."* The diagnostic framework includes a qualitative assessment of the relative susceptibility of widely recognized channel types to increases in the frequency and magnitude of flows, as well as chronic increases in coarse- vs. fine-sediment supplies. This work further emphasizes the principal that streams differ in their resilience and capacity to absorb the effects of urbanization. A channel that naturally contains extensive bedrock control or very resistant boundary materials, for example, will be less physically susceptible to urbanization than a fully alluvial stream in relatively erodible material. This suggests that stream management activities aimed at mitigating the effects of hydromodification will be most effective when tailored to different stream types. One-size-fits-

all practices based on single-factor geomorphology or extrapolation across regions and stream types are not likely to protect stream amenities, nor be cost-effective.

There have been a number of attempts to explicitly quantify the above proportionalities describing channel equilibrium, with the earliest examples focused on a single formative discharge (e.g., Rubey 1952, Henderson 1966). In the 1990s, researchers at the University of Washington in collaboration with King County, Washington, developed tools for managing the full range of geomorphically effective stormwater flows in developing watersheds (Booth and Jackson, 1997). In contrast to the traditional focus on a few individual design events, this approach employs continuous hydrologic simulation over time scales of ca. three decades to quantify the effects of urbanization on the magnitude, frequency, and duration of flows. As such, the cumulative sediment-transport potential or "capacity" side of the balance is explicitly quantified. This approach continues to be refined by King County (e.g., King County 2008a,b).

Following these advances, a recent California investigation of hydromodification, the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP 2004) developed a policy focused on matching the pre- and post-development hydrographs for flows above the critical erosive flow determined on a site-by-site basis. Although it is too early to evaluate the effectiveness of this policy, the approach provides valuable insights in that it is specific to the California setting and takes into account the cumulative erosion potential of all flows and durations that create sediment-transport, rather than simply a single flow rate.

The sediment "supply" side of the balance is not quantitatively addressed in the King County nor the SCVURPPP approaches. Assessing both cumulative capacity and supply over the full spectrum of discharges introduces a substantially greater level of complexity into the analysis. Perhaps the best example of a technique for quantifying the decadal scale equilibrium between the sediment-transport capacity of a flow regime and inflowing sediment loads are the magnitude-frequency or effective-discharge techniques recommended by Soar and Thorne (2001) for stream restoration design. In this approach, a capacity:supply ratio (CSR) of long term transport capacity vs. sediment supply is computed using continuous-flow series and sediment-transport models. Channel segments CSRs within roughly 10% of unity are recommended for stream restoration design. The approach does not readily lend itself to hydromodification analyses, however, because estimates of inflowing-sediment load are based on identifying an upstream supply reach that appears to be in equilibrium with watershed-sediment delivery, a moving target in urbanizing watersheds. Although significant progress has been made in quantifying sediment-water imbalances based on the early work of Gilbert, Lane, and Schumm, the shortcomings of existing techniques underscore the need for further development and integration of tools that can accurately estimate relative changes in both the sediment-transport potential of continuous-flow regimes and changes in sediment delivery in urbanizing watersheds.

Bank Instability Classifications

Bank failure, instability, and erosion rates are frequently used as measures of overall channel stability. Bank-stability classifications and assessment procedures are also useful elements of geomorphic analyses focusing on channel response potential and evolutionary stage.

- Thorne and Lewin (1979), Thorne and Tovey (1981), Thorne *et al.* (1981), and Thorne (1982) provided some of the earlier defining works in bank stability and processes, identifying shear, beam, and tensile-failure mechanisms.

- As described above, Watson *et al.* (1988a,b) employed dimensionless geotechnical-stability numbers as a method for assessing bank stability, in concert with dimensionless hydraulic-

stability numbers for assessing bed stability. This was done under the framework of the original CEM of Schumm *et al.* (1984), adding a quantitative way to assess the current CEM phase. Watson *et al.* (2002) applied the dimensionless-stability number approach into understanding appropriate rehabilitation alternatives for the channel state at hand. Watson *et al.* (1998) provides a broad evaluation of erosion-control projects, also useful for selection of appropriate mitigation measures in unstable systems.

- The Bank Erosion Hazard Index (BEHI) developed by Rosgen and Silvey (1996) has been widely used and referenced by government organizations including the Environmental Protection Agency (EPA). It is largely qualitative, building off Pfankuch (1978).

- Several workers have described field-based methods for identifying unstable combinations of bank height and angle in relatively homogeneous sediments (e.g., Watson *et al.* (2002)). Such approaches can also be linked to an incised CEM. A. Simon and co-workers have described a variety of empirical and mechanistic models for assessing the stability of banks composed of heterogeneous materials and influenced by vegetative root reinforcement (e.g., Simon and Collison (2002), Simon *et al.* (1999), Simon and Darby (1999), and Simon *et al.* (2006)).

Hierarchical Approaches to Mapping Using Aerial Photographs/Geographic Information System

Since the work of Frissell *et al.* (1986), scientists have increasingly viewed streams as hierarchical systems. Accordingly, there is a growing effort to identify and map geomorphic settings, process domains, channel types, and system attributes at basin and regional scales. For example, researchers in the Pacific Northwest are using Geographic Information System (GIS) estimation of slope and stream type to assess salmon habitat at a landscape scale (e.g., Lunetta *et al.* (1997) and Buffington *et al.* (2004)). The break in slope that separates supply and capacity limited channel segments is typically estimated at ~3% in this type of analysis. Flores *et al.* (2006) used the classification tree analysis software CART to identify a break between supply and capacity limitation at ~2.5%. They also discussed several opportunities and limitations for basin-scale mapping of stream types in GIS, and described challenges in using drainage area as a surrogate for streamflow in regions that are climatically heterogeneous.

Noted stream ecologist H.B.N. Hynes (1975) once wrote that "In every respect, the valley rules the stream." Valley context determines the hydraulic forces exerted by overbank flow events and the potential for hillslope inputs of sediment and other debris. It also constrains the range of channel planforms that a segment of river can attain. In describing their typology of mountain rivers, Montgomery and Buffington (1997, 1998) identified several important indices at the valley scale. Although developed in the Pacific Northwest, several of their valley descriptors should prove relevant to scientific assessments of southern California streams:

- valley slope;

- confinement;

- entrenchment;

- riparian vegetation influences; and

- overbank deposits.

Additionally, they identified the importance of major disturbances such as debris flows from landslides, which can trigger complex system-wide responses. The importance of incorporating major disturbances, such as fires, is evident for a region with fire regime of such high frequency (~less than every 10 years).

Previous work indicates that assessments incorporating different levels of effort for assessments and phased approaches to data collection provide an effective strategy. For example, Downs and Thorne (1996) argued for tailored reconnaissance surveys as an initial geomorphic assessment. Should the initial investigation indicate a need, detailed surveys would be completed as a next step. Thorne (2002) presented a mapping scheme for fluvial audits of large alluvial rivers. The Vermont Agency of Natural Resources (2004) procedure described above, synthesizes a large volume of previous efforts into a very extensive three-phased stream geomorphic assessment, tailored to Vermont streams:

> Phase I – Remote sensing,
>
> Phase II – Rapid assessment, and
>
> Phase III – Survey level.

Incorporating remotely sensed data along with a tiered approach to field-data collection may be valuable to a project with such a broad geographic setting and the hierarchical goals of both screening and modeling. Resources may be better utilized with data-collection protocols that are tailored to the levels of precision necessary for assessments of individual sites. For example, watershed metrics may be collected using remotely sensed data on all sites by trained GIS staff. Next, a screening level (i.e., 'rapid assessment') field collection effort could be conducted to determine baseline field conditions by which a judgment on the risk of susceptibility to hydromodification effects could be made. Finally, for those sites considered highly susceptible to the effects of hydromodification, a detailed geomorphic survey could be conducted in order to better model the predicted magnitudes of the effects of hydromodification.

SUMMARY AND IMPLICATIONS FOR SOUTHERN CALIFORNIA HYDROMODIFICATION TOOLS

The foregoing inventory and review of existing channel-classification schemes, although not exhaustive, indicate that there many quantitative, qualitative, and conceptual tools that are at least relevant to managing hydromodification in southern California. It is also apparent, however, that the vast majority of these tools and frameworks were developed in very different geologic and hydroclimatic contexts where channel-adjustment processes are different than those in southern California - notably, less episodic and dynamic. This final section attempts to summarize general findings and implications for developing stream classification/mapping schemes and hydromodification management tools for southern California how the regional context limits or precludes application of the existing tools described above.

Given both the geologic heterogeneity and the highly stochastic nature of sediment delivery and hydrologic forcing in the region, it can be argued that many of the tools and concepts described above are insufficient for predicting the response and susceptibility of these systems. Although significant progress has been made in quantifying sediment-water imbalances reflecting the early work of Gilbert, Lane, and Schumm, the shortcomings of existing techniques underscore the need for further development and integration of tools that can accurately estimate relative changes in both the sediment-transport potential of continuous-flow regimes and changes in sediment delivery in urbanizing watersheds. Equilibrium models and hydraulic-geometry approaches derived from existing form-based classification systems (e.g., Rosgen 1996, Vermont Agency of Natural Resources 2004) would almost certainly prove inadequate for managing the effects of hydromodification because they are not designed to explicitly account for the extreme variability in sediment loading and flow regime inherent to this region.

Furthermore, assessment must occur at multiple spatial scales. Channels are not disjointed pieces, but rather parts of the overall fluvial system. Disturbances in one part of the watershed can affect the rest of the system both up and downstream. The extent to which hydromodification effects propagate and dissipate downstream depends on basin and drainage network physiography, as well as stream type. The widespread distribution of infrastructure in southern California must also be accounted for due to its potential to influence the migration of system-wide effects (e.g., bridge and pipe crossings as mentioned in Chin and Gregory 2001). Such heterogeneity reinforces the idea that assessment procedures should ideally be flexible and adaptable across watershed contexts and spatial scales.

Based on this inventory of classification/mapping schemes and extensive field reconnaissance in the study region, it is suggested that the implications and guidelines for developing hydromodification tools in southern California include:

- A tiered, hierarchical approach (watershed, valley/reach, and cross-section scales) should be employed to provide the capacity to evaluate multiple channel types and to adjust the intensity of analysis based on the likelihood of channel response (or complexity of the specific situation being evaluated). Such a tiered approach should include aspects of office (remotely sensed), screening, and modeling levels of data collection.

- At the broadest spatial scale, the appropriate strategies and tools for managing hydromodification will vary significantly among geomorphic contexts, e.g. an alluvial fan, a broad valley bottom or an incised headwater channel.

Predictions of geomorphic response direction and relative severity are much more tractable than predictions of absolute magnitudes and durations of response to hydromodification.

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 stream types is not likely to protect 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.

- Tools that account for land-use change effects on both the continuous flow regime and sediment delivery are much more likely to provide the minimum prediction accuracy needed for managing hydromodification effects on streams in the region.

- A linked modeling framework that combines continuous (or pseudo-continuous) hydrologic-simulation, sediment-delivery, and channel-erosion models is more likely to produce reliable assessments of effects than a threshold-based evaluation.

- Proposed screening tools will be most useful if they incorporate multiple scales of risk and sensitivity (*sensu* Downs and Gregory 1995):
    - proximity to thresholds;
    - response (strain) ratio relative to given stress; and
    - rate of recovery.

- Although deterministic models are an appealing framework, tools should be placed within the context of their respective uncertainties. Probabilistic tools offer an acknowledgement of the uncertainties and provide decision makers with the ability to choose management options based on their perception of an acceptable risk of adverse response? (e.g., 10%, 50%).

- Existing planform predictors lack metrics describing valley-scale constraints, tributary influences, and sediment loading. Including at least surrogate measures of these important controls could enhance the predictive accuracy of planform predictors calibrated for the study area. To this end, it is worth exploring measures or surrogates of sediment supply as candidates for incorporation into such planform predictors for southern California.

- Key geomorphic thresholds can be identified but must be regionally calibrated to the study region. These include:
    - single-thread to braiding planform transitions;
    - critical bank heights and angles in different materials; and
    - transitions from threshold channel to live-bed behavior (i.e., from episodic sediment transport to continuous sediment transport).

- Existing CEM approaches do not adequately reflect the range of stream response trajectories observed in southern California, and therefore must be modified to include bifurcations between single- and multi-thread channels.

- Any segment or reach scale classification of streams that stratifies susceptibility to hydromodification should, at a minimum, include the following key characteristics and boundary conditions at the reach/segment scale:
    - transportability of bed (indexed by grain size relative to exerted shear stress or stream power);
    - erodibility of bed and banks (as influenced by their cohesiveness and presence of bedrock);
    - lateral mobility (within the context of the valley floor).

Ultimately, southern California streams must be assessed not as "things in space," but as "processes through time." Probabilistic predictions of future alternative response trajectories of fluvial systems altered by hydromodification will aid managers both in assessing the potential severity of impacts and designing effective mitigation strategies.

Finally, it should be acknowledged that over-controlling either the flow or the physical channel form can have adverse effects as well. Native biological communities are adapted to and tolerate a range of aquatic habitat conditions that may become less available or completely disappear during land-use changes. There is broad consensus among river scientists that sustaining biological communities, especially sensitive biota, requires maintaining flow and habitat dynamics within some range of variability (e.g., Bunn and Arthington 2002). Full channel stabilization via artificial methods, such as preventing substrate entrainment, disturbance, and lateral adjustments, may impact the long-term ecological integrity of the stream (Sudduth and Meyer, 2006). Future analysis of the effects of hydromodification and associated management activities should account for implications on the instream and adjacent biological resources of the stream.

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