MODELING AND MANAGING HYDROMODIFICATION EFFECTS: SUMMARY OF AVAILABLE TOOLS AND DECISION-MAKING APPROACH

Technical Report 753
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EXECUTIVE SUMMARY

Hydromodification management has traditionally focused on addressing excessive erosion or deposition in channels and the resulting geomorphic changes. The evolution of stormwater management beyond a focus on water chemistry is an important step forward in holistic efforts to protect the physical, chemical, and biological integrity of water courses. However, current approaches to hydromodification have been limited to managing runoff at the site of new or re-development. Although this approach is beneficial, there is a need for hydromodification management to evolve to a watershed-based approach focused on restoration and protection of watershed processes. Accomplishing this requires developing and organizing new tools and approaches that support integrative assessment and management. This document summarizes suites of modeling tools that can be used to help characterize and predict the complex and multifaceted effects of hydromodification. We also present an approach for developing management prescriptions that account for the specific needs and constraints of individual stream reaches in the context of the watershed in which they exist.

Modeling tools can be organized into four basic categories in increasing level of complexity: descriptive tools, statistical models, mechanistic models with deterministic outputs, and probabilistic models. Descriptive tools are the easiest to apply, but typically provide only general or coarse resolution output. Statistical and mechanistic models are more precise, yet require more data input for their use. Finally, probabilistic models are relatively new for stream analysis, but have the advantage of providing an explicit account of model uncertainty. In most cases, multiple modeling tools will be necessary to fully assess potential hydromodification effects; however, the precise combination of tools applied will vary based on needs, quality of streams being managed, and available resources.

We have developed several new tools, which are also described in this document. These include:

- Revised ***regional hydrologic curves*** for estimating discharge in ungauged basins.
- Analytical ***regime diagrams*** that allow prediction of changes in channel dimensions based on changes in water or sediment discharge.
- A regional update to the ***channel evolution model*** that illustrates expected trajectories of channel response to hydromodification.
- Several statistical ***channel enlargement models*** based on regression using local data.
- An ***artificial neural network model*** for predicting change in channel cross-sectional area based on a suite of watershed variables.
- An updated version of the ***GeoTools spreadsheet package*** for assessing geomorphic response.

These tools, in combination with existing tools, have the potential to advance hydromodification management by:

- Providing a physical basis for making predictions of stream response to watershed development.
- Assessing alternative future states of streams under different management scenarios.
- Avoiding one-size-fits-all solutions through:
    - Improved prediction of relative magnitude of potential channel change and proximity to response thresholds; and

- Tailoring mitigation strategies to streams with different levels of susceptibility.

Statistical models developed in this study indicate that the magnitude of channel enlargement and overall risk of channel instability are highly dependent on the ratio of post-to pre-urban sediment-transport capacity over cumulative duration simulations of 25 years. This ratio is often termed the *erosion potential (Ep)* or *load ratio (Lr)* and is a better predictor of long-term channel response than stream discharge. In addition, hydraulic variables (such as *Ep*, shear stress, or stream power) provide a "common currency" for managing erosion and associated effects that can be applied across many streams in a region. *Overall, the enlargement models point to the importance of balancing the post-development sediment transport to the pre-development setting over an entire range of flows rather than a single flow in order to reduce the risk of adverse channel responses to hydromodification*.

As with modeling, management strategies should also address the complexity of processes that affect stream response to hydromodification through application of a broad suite of management strategies beyond traditional site-based flow control. The foundation of any hydromodification management approach should be a watershed-scale analysis of existing and proposed future land uses and stream conditions that identifies the relative risks, opportunities, and constraints of various portions of the watershed. Site-based control measures should be determined in the context of this analysis.

Clear objectives should be established to guide management actions. These objectives should articulate desired and reasonable physical and biological conditions for various reaches or portions of the watershed. Management strategies should be customized based on consideration of current and expected future channel and watershed conditions including constraints that may limit the ability to apply certain approaches (e.g., existing development and channelization). A one-size-fits-all approach should be avoided.

An effective management program will likely include combinations of on-site measures (e.g., low-impact development techniques), in-stream measures (e.g., stream habitat restoration), and off-site measures. Off-site measures may include compensatory mitigation measures at upstream locations that are designed to help restore and manage flow and sediment yield in the watershed. To address existing, legacy and anticipated future effects, management approaches will need to focus on controlling erosion, deposition, and planform change as well as restoring watershed processes that ensure movement of water and sediment in ways that help maintain the dynamic equilibrium of stream channels. Such process-based management actions include:

- Protecting and restoring coarse sediment-supply areas.
- Maintaining and sediment transport capacity through critical stream reaches.
- Protecting and restoring floodplain connections and infiltration areas adjacent to channels.

Modeling and management programs should be connected to robust monitoring that can provide data to calibrate, test, and refine models and improve management approaches and the empirical basis upon which they are constructed.

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1.0 Introduction and Purpose of the Document

Hydromodification management is aimed at addressing issues of excessive erosion or deposition in channels and the associated geomorphic changes. The evolution of stormwater management beyond solely focusing on water chemistry is an important step forward in holistic efforts to protect the physical, chemical, and biological integrity of water courses. However, current approaches to hydromodification have been limited to managing only runoff, only at the site of new or re-developments, and without a watershed context. This approach has been shown to be insufficient to fully address hydromodification impacts in other regions (Booth and Jackson, 1997; Maxted and Shaver, 1999). Moreover, the focus on new and redevelopment does not include mechanisms to address legacy effects that may be affecting channel conditions. Present understanding of the causes and effects of urbanization suggest that site-based runoff control must be expanded to include integrated flow and sediment management at the watershed scale, along with targeted stream corridor/floodplain restoration (National Research Council (NRC), 2009; Stein *et al*., 2012).

Hydromodification management approaches should be selected and designed to protect and restore agreed upon or designated beneficial uses and overall receiving water conditions, *by maintaining or reestablishing the watershed processes that support those conditions.* "Restoration" does not imply the return to a pre-development condition; instead, it may be defined as assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system (Wohl *et al*., 2005). Achieving this goal will require that hydromodification management strategies be broadly considered beyond the location of individual projects and operate across programs beyond those typically regulated by National Pollutant Discharge Elimination System (NPDES)/MS4 requirements. Successful strategies will need to be developed, coordinated, and implemented through land use planning, non-point source runoff control, Section 401 Water Quality Certifications and Waste Discharge Requirement programs, in addition to traditional stormwater management programs.

A technical workgroup commissioned by the State Water Resources Board produced a broad set of recommendations for watershed-scale hydromodification management as part of their Technical Report #667 *Hydromodification Assessment and Management in California* (Stein *et al*., 2012). The proposed management framework included on-site actions, floodplain management, and in-stream restoration. The goal of this document is expand on the recommendations from Stein *et al.* (2012) and provide a more detailed roadmap for 1) evaluating the efficacy of existing modeling tools in support of hydromodification management, and 2) selecting a suite of management measures at the appropriate scale and intensity. As such, the report is divided into two sections. Section 2 provides an overview of available modeling tools (including novel models developed in this project), and Section 3 provides a broad perspective on decision-making approaches for selecting hydromodification management measures. Both sections are intended to provide a set of potential tools and approaches that can be applied based on individual needs, stream conditions, and priorities. The approaches are not intended to be prescriptively used in all instances.

2.0 SUMMARY OF AVAILABLE TOOLS

Watershed urbanization alters natural hydrologic storage processes and leads to increased runoff volumes and rates with consequent increases in erosion and sedimentation potential if left unmitigated. In many southern California watersheds, altered flows of water and sediment resulting from urbanization and other land use changes (i.e., hydromodification) have resulted in channel incision, widening, and other forms of stream instability, as well as loss of riparian functions and connectivity. Even where interactions between climate and land use changes do not result in significant increases in upslope erosion, altered runoff processes may accelerate channel erosion and negatively affect water quality both upstream and downstream of a localized disturbance. The adverse impacts of hydromodification include threats to property and infrastructure, reduced habitat for aquatic life, increased water treatment costs, and diminished reservoir capacity.

Hydromodification results in variable hydrologic, geomorphic, and ecologic responses depending on site-specific factors like the connectivity of impervious areas and stormwater drainage systems, watershed soil characteristics, and the inherent resistance of stream channels to increased erosive forces. Characterizing, predicting, and managing the complex and multifaceted effects of hydromodification is therefore challenging, and there is no single model or predictive assessment tool that can answer the basic questions that are increasingly confronted by managers. These questions include:

- To what extent are patterns of stream flow altered by urban development?
- How do streamflow alterations relate to channel erosion, enlargement, and instability?
- In what ways and how much are the channel and its physical structure likely to respond after development – a little or a lot?
- Do different kinds of streams require different kinds of best management practices (BMPs) to protect channel structure and processes?
- What are reasonable expectations for effects of individual or combinations of BMPs, i.e., how can the location and type of BMP(s) relate to changes in channel structure, stability or recovery?
- What are reasonable expectations for achieving restoration based on specific conditions in a watershed?

Despite the plethora of existing tools and models that are relevant to hydromodification analysis and management (e.g., US Environmental Protection Agency (USEPA, 2007)), most predictive assessments of hydromodification impacts and analyses supporting site design decisions and mitigation activities currently rely on a few relatively-simplistic tools and models. For example, new developments may be required to match pre-development peak discharges for certain design storms or across some portion of a flow-duration curve regardless of the type of receiving stream (e.g., a sand bed vs. a boulder bed). Although uncomplicated and widely transferable approaches for minimizing the impacts of hydromodification are highly desirable from a practical standpoint, they may not sufficiently control the post-development discharges across the full spectrum of erosive flows as defined by the boundary conditions and inherent susceptibility of the receiving streams (both on-site and nearby). Therefore, there is a need for identifying modeling and assessment approaches that better balance the need for simplicity with the need for adequately representing the stream system being managed.

There are currently a number of gaps in the typical modeling toolbox that is utilized in hydromodification management. These gaps include:

- Hydrologic prediction at ungauged sites;
- Channel evolution models that conceptualize the predominant geomorphic processes and thresholds in disturbed channels of a particular region;
- More detailed and physically-rigorous channel response tools that build on rapid field assessments;
- Spreadsheet tools that facilitate computation of geomorphic metrics such as erosion potential and effective discharge;
- Models to estimate reduction in sediment supply (and sediment type) from developed land surfaces;
- Probabilistic models of stream response that explicitly quantify uncertainty; and
- An assessment of whether mobile boundary hydraulic models are appropriate for predicting stream response in this region.

Finally, there is a parallel need for practical guidance that enables managers to better evaluate models and their appropriate uses. When reviewing modeling-based hydromodification studies prepared by consultants, managers are often confronted with questions such as:

- Is this model appropriate for the question(s) at hand?
- What are the key considerations associated with a particular tool (e.g., scale, vintage of data, parameterization, etc.)?
- What are the underlying assumptions about physical and hydrological processes that are used by the model?
- What information and data are sufficient to drive the model?
- What is the simplest model that will provide adequate prediction accuracy?
- What is level of certainty associated with the output?

This section of the report begins to address the broad question of "how do we begin to organize models in a way that is useful to managers for decision-making?" There are two target audiences: 1) those who will actually be doing hydromodification modeling and 2) those who must review their work. The specific aims of this section are to:

- Present a general framework for understanding the role of models in hydromodification management.
- Provide a concise evaluation of selected modeling tools that are most relevant to hydromodification management in southern California (while highlighting some of the modeling tools developed in this project) in terms of the types of management questions the tools can address, input data requirements, scale of application, etc.
- Put individual models into the broader context of some complementary sets or suites of tools that are important in hydromodification management.
- Discuss ongoing limitations, key uncertainties, and priorities for future model development.

This section of the report complements Southern California Coastal Water Research Project (SCCWRP) Technical Report #667 *Hydromodification Assessment and Management in California* (Stein *et al*., 2012) by 1) providing more specific information on novel modeling tools that address some of the gaps in current modeling tool box, and 2) delving more into some practical considerations of how models can inform hydromodification management. The new modeling tools developed in this study are described and put into the context of existing tools in terms of the management questions they can inform, and practical considerations in application and interpretation.

2.1 A General Framework for Understanding Models in Hydromodification Management

In the context of hydromodification, tools and models are typically used to help answer one or more of the following questions involving an assessment of natural and human influences at various spatial and temporal scales:

- What is the present stability status of the stream system and what are the dominant processes and features within the system?
- How have past human influences affected the current state and future potential of the stream?
- What is the likely future trajectory of the stream in the absence of any changes in land use or mitigation measures (e.g., no action alternative)?
- How will the stream likely respond to alterations in runoff and sediment supply?
- What level of flow control or other mitigation measures are necessary to protect the receiving stream(s)?

Many studies have underscored the variability and complexity of relationships between watershed land use, hydrologic processes, and the physical and ecological conditions of stream systems. Clearly, the process of assessing stream condition and predicting future conditions is very challenging and subject to uncertainty. Therefore, it is important to understand the strengths and limitations of available tools, especially with respect to prediction uncertainty, so one can choose an appropriate model for the question at hand. In addition to prediction uncertainty, considerations in choosing a model for a particular application include appropriate spatial and temporal detail, cost of calibration and testing, meaningful outputs, and simplicity in application and understanding (National Research Council (NRC), 2001; Reckhow, 1999a,b).

Figure 1 presents an organizing framework developed as part of this study for understanding general types of available tools that may be applied in support of hydromodification management and policy development. Tools fall into three major categories: 1) descriptive tools, 2) mechanistic and empirical/statistical models that are used deterministically, and 3) probabilistic models/predictive assessments with explicitly quantified uncertainty. The organizing framework relates these categories to the types of questions the tools are designed to answer, specifically: characterization of stream condition, prediction of response, establishment of criteria/requirements, or evaluation of management actions. The framework also characterizes the tools according to the following features: intensity of resource requirements (i.e., data, time, cost), and the extent to which uncertainty is explicitly addressed. Subsequent portions of this section discuss each of the three major categories in turn, highlighting examples of specific tools within each category with particular emphasis on new tools developed in this project.

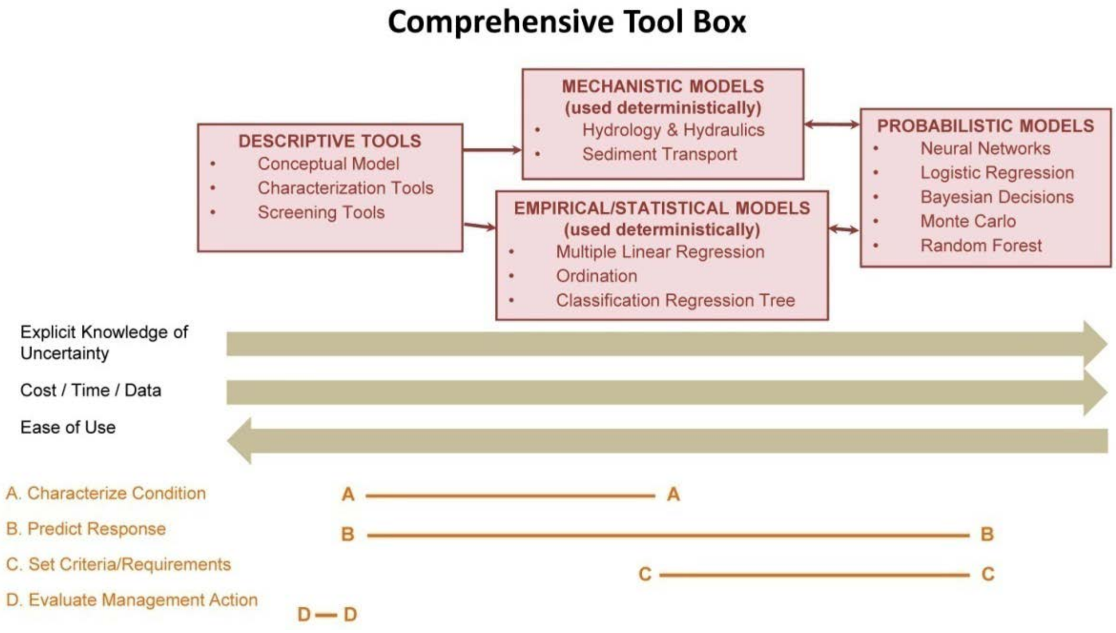

Figure 1. Organizing framework for understanding hydromodification assessment and management tools.

Tool selection should mirror the level of resolution that is required based on the point in the planning process. In the early stages of conducting an assessment, descriptive tools will be sufficient, but more precise tools will be required toward the design phase. Currently, most projects rely solely on deterministic models. However, given the uncertainty associated with predicting hydromodification impacts, probabilistic models should be incorporated into analysis and design, particularly where resource values or potential consequences of impacts are high.

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2.1.1 Descriptive Tools

Descriptive tools include conceptual models, screening tools, and characterization tools. These tools are used to answer the question: *What is the existing condition of a stream or watershed?* Although descriptive tools are not explicitly predictive, they can be used to assess levels of susceptibility to future stressors by correlation with relationships seen elsewhere. The application of some type of descriptive tool, such as a characterization tool, is usually necessary before applying a deterministic model because descriptive tools aid in understanding the key processes and boundary conditions that may need to be represented in a more detailed model.

Conceptual models

A conceptual model, in the context of river systems, is a written description or a simplified visual representation of the system being examined, such as the relationship between physical or ecological entities, or processes, and the stressors to which they may be exposed. Conceptual models have been used to describe processes in a wide range of physical and ecological fields of study, including stream-channel geomorphology (Bledsoe *et al*., 2008). For example, Channel Evolution Models (CEMs) are conceptual models which describe a series of morphological stages of a channel, either as a longitudinal progression from the upper to the lower watershed, or as a series at a fixed location over time subsequent to a disturbance. The incised channel CEM developed by Schumm *et al.* (1984) is one of the most widely-known conceptual models within fluvial geomorphology. This CEM documents a sequence of five stages of adjustment and ultimate return to quasi-equilibrium that has been observed and validated in many regions and stream types (American Society of Civil Engineers (ASCE), 1998; Simon and Rinaldi, 2000). Conceptual models in fluvial geomorphology also include planform classifications of braided, meandering and straight, and many other typologies that categorize streams by metrics such as slope, sinuosity, width-to-depth ratio, and bed-material size. The famous qualitative response model described by Lane's diagram (1955) is also a conceptual model.

A novel CEM for southern California

A new CEM with quantitative extensions was developed in this project to provide managers with a framework for understanding channel responses and rehabilitation alternatives in the region. The Schumm *et al.* (1984) CEM was modified for streams characteristic of southern California, including transitions from single-thread to multi-thread and braided evolutionary endpoints (Hawley *et al*., 2012). The CEM is based on southern California data from 83 detailed channel surveys, hundreds of synoptic surveys, and historical analyses of aerial photographs along 14 reaches. The field surveys indicate that channel evolution sometimes follows the well-known sequence described by Schumm *et al.* (1984) for incising, single-thread channels; however, departures from this sequence are common and include transitions of single-thread to braided evolutionary endpoints, as opposed to a return to quasi-equilibrium single-thread planform. Thresholds and risk factors associated with observed channel response were also identified. In particular, distance to grade control and network position emerged as key controls on channel response trajectory.

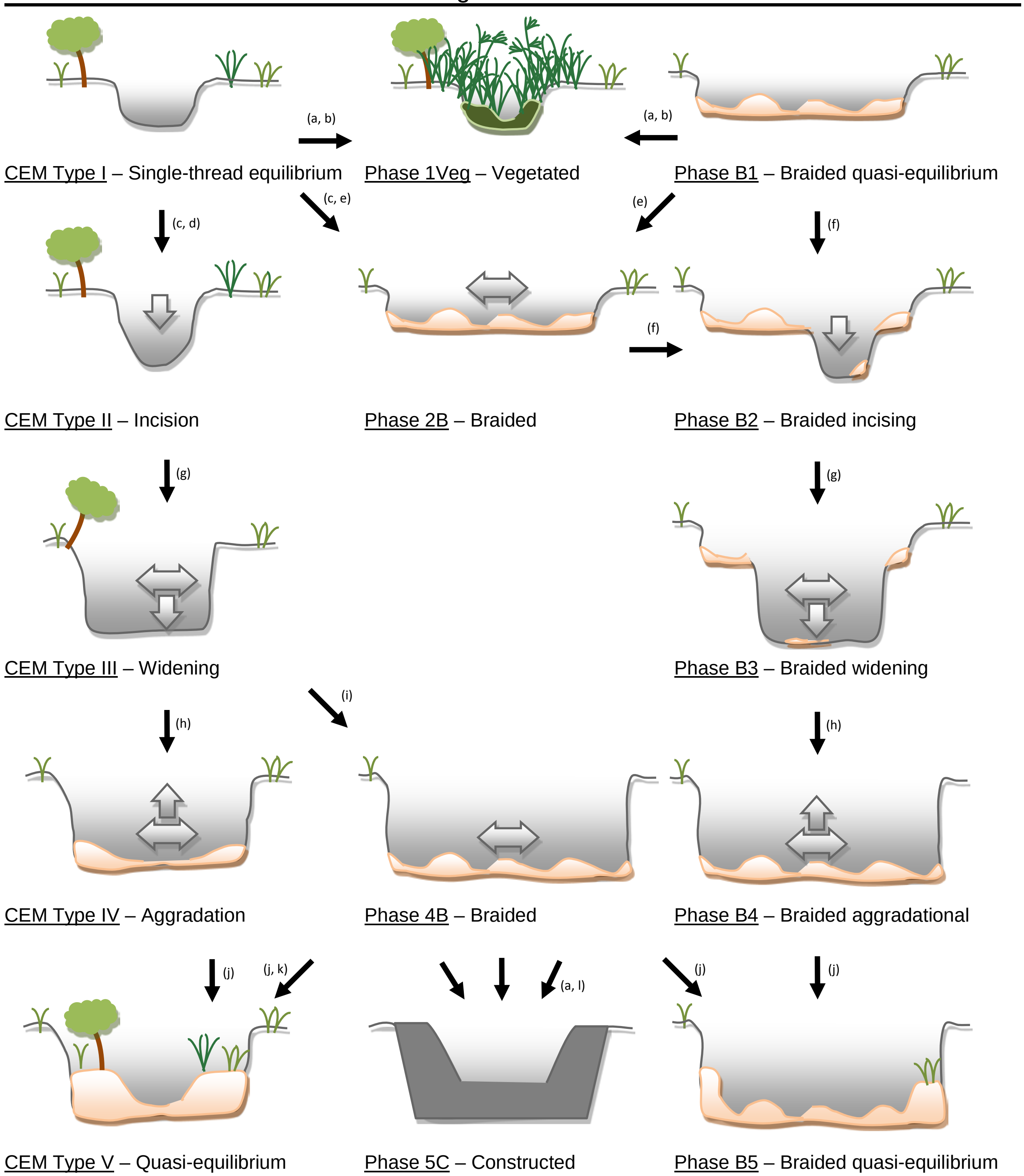
Channels in southern California were observed to respond in ways that were at the same time analogous to and departed from the CEM of Schumm *et al.* (1984) (Figures 2 and 3). The fundamental importance of grade control in promoting the eventual return to quasi-equilibrium stages such as CEM Type IV or Type V is underscored in Figure 3, as incision-driven responses almost exclusively revolved around a hardpoint fulcrum. Self-stabilized reaches without a proximate grade control structure were rare, both during field reconnaissance and in our dataset (2 of 33 reaches, 3 of 83 sites). A similar trajectory was observed in a subset of braided systems which in some cases follow a sequence analogous to the Schumm *et al.* (1984) CEM for incising single-thread channels. This was especially true for the initial stages of incision (Phase B2), widening (Phase B3), and aggrading (Phase B4); which were primarily triggered by a base-level drop and the resulting headcutting. This was also caused by artificial increases in and/or concentration of flow from new stormwater outfalls or at road crossings via culverts that concentrate the hydraulic energy but reduce sediment through flow, consistent with Chin and Gregory's (2001) observations in urbanizing ephemeral streams of Arizona. Indeed, this response sequence was routinely observed in predominantly rural watersheds (i.e., <1% imperviousness) where it seemed almost exclusively attributable to sediment discontinuities induced by channel fragmentation from infrequent human infrastructure, consistent with the widely-documented response of channel incision downstream of dams.

Although braided channels are widely considered less stable than single-thread channels (Ferguson, 1993; Hoey and Sutherland, 1991; Nanson and Croke, 1992; Schumm, 1977, 1981, 1985) with many classic examples of frequent and large shifts in channel position (Chien, 1961; Gole and Chitale, 1996), audits of historical aerial photography at several sites suggest that braided systems can also attain quasi-equilibrium for ca. 50 years in this region. This is consistent with recognition by other researchers that braiding can be an equilibrium channel state, given the necessary boundary conditions that result in no net change in the vertical or lateral dimensions over time (Chang, 1979; Klaassen and Vermeer, 1988; Leopold and Wolman, 1957; Parker, 1976; You, 1987).

CEM for Incised Single-Thread Channels
(adapted from Schumm *et al.* (1984))

Southern California Bifurcations from Conventional Five-stage CEMs

CEM for Braided Channels



(Continued Next Page)

(a) Can be preceded by any CEM stage

(b) Induced by urban base flow such as lawn irrigation or wastewater treatment plant (WWTP) effluent

(c) Relative erodibility of bed and bank material, available valley width, and downstream distance to hardpoint are key boundary conditions

(d) Possible drivers include: S^+, Q^+, and/or $Q_s{}^-{}_{basin}$

(e) Possible drivers include: $Q_s{}^+{}_{basin}$, and/or Q^+ with $Q_s{}^+{}_{channel}$

(f) Possible drivers include: S^+, Q^+, $Q_s{}^-{}_{basin}$, and/or $Q_s{}^-{}_{channel}$

(g) Incision depth exceeds critical bank height for given angle (i.e., failure via mass wasting)

(h) $Q_s{}^+{}_{channel}$ exceeds transport capacity leading to toe protection of banks via aggradation

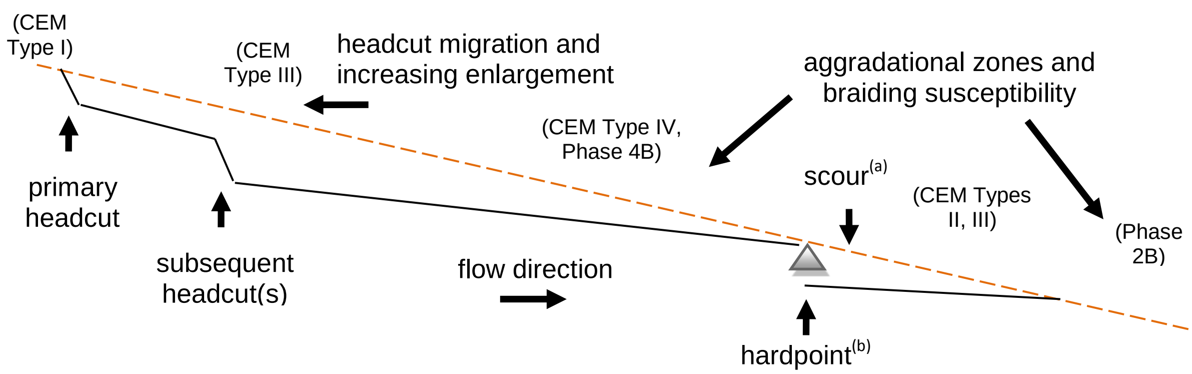
(i) $Q_s{}^{++}{}_{channel}$ leads to excessive/irregular aggradation, flow deflection, and continued bank failure (bank strength and general cohesiveness of floodplain are key boundary conditions)

(j) In most unstable southern California systems, a proximate downstream hardpoint (natural or artificial) is critical as a fulcrum for complex response sequences and the eventual return to quasi-equilibrium

(k) Conceivable from any prior braided state; however, increasing braiding extent (i.e., degree of departure from reference channel width) would seem to decrease the probability of a return to single-thread quasi-equilibrium

(l) Predominant terminal condition in urban/suburban channels of southern California

Figure 2. CEM of semiarid stream response to urban-induced hydromodification.



Notes:

CEM stages in parentheses

(a) the discontinuous effects of urban infrastructure such as scour downstream of grade control and increasing width-to-depth ratio moving downstream has also been observed in ephemeral Arizona streams in response to urbanization (Chin and Gregory, 2001)

(b) natural (e.g., bedrock) or artificial (e.g., riprap/concrete) grade control

Figure 3. Profile view of one common evolution sequence in southern California channels in response to hydromodification.

A preliminary quantification of the CEM was performed using hydraulic and geomorphic metrics from all 83 study sites. Plotting the specific stream power (omega) of the 10-year flow vs. median grain size of bed material (d_{50}) by aggregated CEM stage (Figure 4) shows separation between states of dynamic equilibrium and disequilibrium. Single-thread channels in unconfined valleys that are in or approaching states of dynamic equilibrium (CEM Type I, Phase 1Veg, and CEM Types IV and V) tend to have the lowest specific stream power for a given bed-material resistance. Braided channels in states of dynamic equilibrium (Phase B1) typically have slightly higher erosive energy than single-thread equilibrium; however, they tend to have lower erosive energy than disequilibrium states (CEM Types II and III and Phases B2, 2B, and 4B).

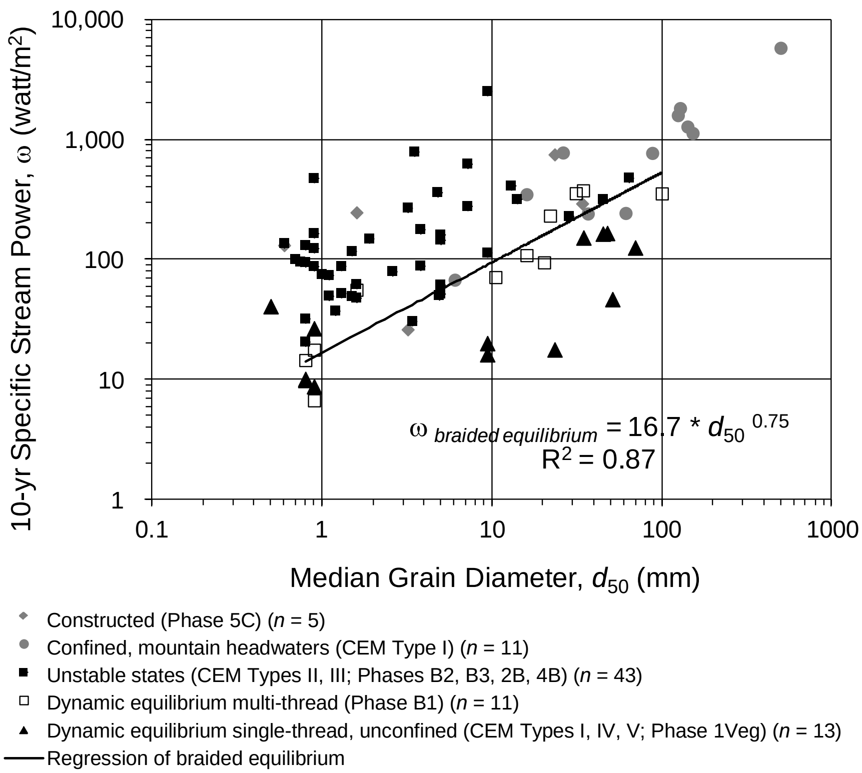


Figure 4. Ten-year specific stream power vs. median grain diameter by CEM stage of all 83 sites with superimposed power function of Phase B1 channels for visual separation.

Plotting the top width for a 10-year water-surface elevation vs. the 10-year peak flow for single-thread equilibrium systems in unconfined valleys and unconstructed settings resulted in a well-fit power function as a regional representation of forms sufficiently wide to dissipate energy without resulting in multiple flow paths (Figure 5). For reference, braided channels and incising channels (CEM Types II and III) are included in Figure 5, and indicated nearly-perfect separation over the power function. The relationship was then used to estimate a reference width (W_{ref}) for each site as a function of the 10-year peak discharge that is used to define a valley width index that was incorporated into the channel susceptibility screening tool that was developed in this project (Bledsoe *et al*., 2012).

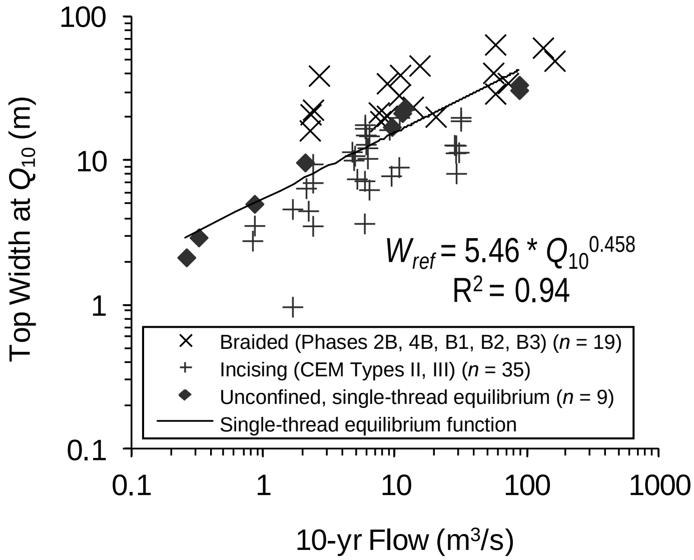


Figure 5. Top width vs. 10-year flow at unconfined, unconstructed single-thread equilibrium, braided, and incising sites with superimposed power function fitted to single-thread equilibrium sites.

The southern California CEM is a conceptual model that has utility for guiding management strategies as detailed in Hawley *et al.* (2012). For example, arresting channel instabilities in systems that are beginning to braid but have a width near W_{ref}, may have a higher likelihood of promoting a return to single-thread equilibrium than those systems with substantially greater widths. In this case, management of a new channel state may be more feasible than attempting to “restore” the channel to a prior state. With respect to incision, the CEM underscores the importance of employing rehabilitation measures before reaching critical bank height (prior to CEM Type III of the Schumm *et al.* (1984) model) in terms of cost and the disproportionate increase in channel erosion and downstream sedimentation/habitat degradation. In another example of using the CEM to guide rehabilitation, the distance away from the equilibrium lines in Figures 4 or I.5 could be used to help establish a threshold between channel restoration and “reconstruction to a new form” because it reflects likelihood of success. That is, CEM Type I could be targeted for preservation, restoration activities would be focused on Type II and early Type III channels, with the latter stages managed as a new form.

Regional CEMs can partially address the needs of the hydromodification management community by providing a framework for interpreting past and present response trajectories, identifying the relative severity of potential response sequences, applying appropriate models in estimating future channel changes, and developing strategies for mitigating the impacts of processes likely to dominate channel response in the future (Simon, 1995). CEMs can be useful in assessing channel instability both independently and as a part of a broader field-screening / reconnaissance tool. More details on specific channel trajectories and other aspects of the southern California CEM are provided in Hawley *et al.* (2012).

Characterization tools

Examples of characterization tools include baseline geomorphic assessments, river habitat surveys, and fluvial audits. A fluvial audit (Sear *et al*., 1995, 2009) uses contemporary field surveys, historical map and documentary information, and scientific literature resources to gain a comprehensive understanding of a river system in its watershed context and how it arrived at its present state. Fluvial audits, along with watershed baseline surveys are a standardized basis for monitoring change in fluvial systems. These types of comprehensive assessments are comprised of numerous, more detailed field methodologies, such as morphologic surveys, discharge measurements, and estimates of boundary material critical shear strength through measurements of resistance (for cohesive sediments) or size. Baseline assessments may also draw on empirical relationships such as sediment-supply estimation models to explain stream responses to past watershed disturbances.

Screening tools

Screening tools can be used to predict the relative severity of morphologic and physical-habitat changes that may occur due to hydromodification, as a critical first step toward tailoring appropriate management strategies and mitigation measures to different geomorphic settings. The practical need for rapid assessments in stream management have prompted many efforts to develop qualitative or semi-quantitative methods for understanding the potential response trajectories of channels based on their current state.

Most screening-level tools for assessing channel instability and response potential, especially in the context of managing bridge crossings and other infrastructure, have borrowed elements of the CEM approach and combined various descriptors of channel boundary conditions and resisting vs. erosive forces. For example, Simon and Downs (1995) and Johnson *et al.* (1999) developed rapid assessment techniques for alluvial channels based on diverse combinations of metrics describing bed material, CEM stage, existing bank erosion, vegetative resistance, and other controls on channel response. Although based on a strong conceptual foundation of the underlying mechanisms controlling channel form, these tools were developed with goals and intended applications (e.g., evaluating potential impacts to existing infrastructure such as bridges or culverts) that differ somewhat from what is needed by current hydromodification management programs.

This project has resulted in a general framework for developing screening-level models that help assess channel susceptibility to hydromodification, and a new region-specific tool for rapid, field-based assessments in urbanizing watersheds of southern California (Bledsoe *et al.*, 2010, 2012). The criteria used to assign susceptibility ratings are designed to be repeatable, transparent, and transferable to a wide variety of geomorphic contexts and stream types. The assessment tool is structured as a decision tree with a transparent, process-based flow of logic that yields four categorical susceptibility ratings through a combination of relatively simple but quantitative input parameters derived from both field and geographic information system (GIS) data. The screening rating informs the level of data collection, modeling, and ultimate mitigation efforts that can be expected for a particular stream-segment type and geomorphic setting. The screening tool incorporates various measures of stream bed and bank erodibility, probabilistic thresholds of channel instability and bank failure based on regional field data, integration of rapid field assessments with desktop analyses, and separate ratings for channel susceptibility in vertical and lateral dimensions.

This project has also produced a screening-level model that predicts changes in post-development sediment delivery based on watershed analyses of "Geomorphic Landscape Units" (GLUs) in a GIS (Booth *et al*., 2010). A GLU analysis integrates readily-available data on geology, hillslope, and land cover to generate categories of relative sediment production under a watershed's 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 reassessing the relative 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 sediment yield to receiving channels.

2.1.2 Mechanistic and Empirical/Statistical Models with Deterministic Outputs

Mechanistic/deterministic models are simplified mathematical representations of a system based on physical laws and relationships. Empirical/statistical models describe the extent to which variation in output can be explained by (associated with) input variables. Both types of models are typically used to generate a single output or answer for a given set of inputs (despite the fact that statistical models are usually quite amenable to producing distributions of outputs). These tools can be used to help answer such questions as: *What are the expected responses in the stream and watershed given some future conditions? What criteria should be set to prevent future hydromodification impacts?* However, hydromodification modeling embodies substantial uncertainties in terms of both the forcing processes and the stream response. Deterministic representations of processes and responses can, therefore, mask uncertainties and be misleadingly precise, unless prediction uncertainty is explicitly characterized.

Hydrologic models

These models are used to simulate watershed hydrologic processes, including runoff and infiltration, using precipitation and other climate variables as inputs. Some models, such as the commonly-used Hydrologic Engineering Centers (HEC) – Hydrologic Modeling System (HMS), can be run for either single-event simulations or in a continuous-simulation mode which tracks soil moisture over months or years. Single-event simulations are focused on producing the hydrograph generated by individual storms, such as the 2-year flood or a less frequent flood event. In contrast, continuous simulations provide an unbroken series of discharges at daily or sub-daily (e.g., 15-min) time steps over a period of years to decades. Other hydrologic models that are commonly used for event-based and continuous simulation modeling include Hydrologic Simulation Program Fortran (HSPF) and Storm Water Management Model (SWMM). It is widely accepted that continuous simulation modeling, rather than event-based modeling, is required to assess the long-term changes in geomorphically-significant flow events (Booth and Jackson, 1997; Roesner *et al*., 2001) that are critical in designing hydromodification mitigation strategies.

Several HSPF-based continuous-simulation models with standardized parameters have been developed specifically for use in hydromodification planning. These include the Western Washington Hydrology Model (WWHM) and the Bay Area Hydrology Model (BAHM). Hydromodification Management Plans (HMPs) in Contra Costa County, San Diego County, and Sacramento County have developed sizing calculators for BMPs based on modeling done using HSPF models. To illustrate the point about uncertainly in mechanistic models, HSPF contains approximately 80 parameters, only about 8 of which are commonly adjusted as part of the calibration process.

Hydraulic models

These models are used to simulate water-surface profiles, shear stresses, stream power values, and other hydraulic characteristics generated by stream flow, using a geometric representation of channel segments. The industry standard 1-dimensional hydraulic model is the HEC – River Analysis System (HEC-RAS).

Coupled hydrologic and hydraulic models

These models represent a valuable tool in hydromodification management. Because the streamflow regime interacts with its geomorphic context to control physical habitat dynamics and biotic organization, it is often necessary to translate discharge characteristics into hydraulic variables that provide a more accurate physical description of the controls on channel erosion potential, habitat disturbance, and biological response. For example, a sustained discharge of 100 cfs could potentially result in significant incision in a small sand-bed channel, but have no appreciable effect on the form of a large channel with a cobble bed. By converting a discharge value into a hydraulic variable (common choices are shear stress, or stream power per unit area of channel relative to bed sediment size), a "common currency" for managing erosion and associated effects can be established and applied across many streams in a region. Such a common currency can improve predictive accuracy across a range of stream types. As opposed to focusing on the shear stress or stream power characteristics of a single discharge, it is usually necessary to integrate the effects of hydromodification on such hydraulic variables over long simulated periods of time (on the order of decades) to fully assess the potential for stream channel changes. By using channel morphology to estimate hydraulic variables across a range of discharges, models like HEC-RAS provide a means of translating hydrologic outputs from continuous simulations in HEC-HMS, SWMM, or HSPF into distributions of shear stress and stream power across the full spectrum of flows.

"By converting a discharge value into a hydraulic variable (common choices are shear stress, or stream power per unit area of channel relative to bed sediment size), a "common currency" for managing erosion and associated effects can be established and applied across many streams in a region."

Sediment-transport models

These models such as HEC-6T, the sediment-transport module in HEC-RAS; CONservational Channel Evolution and Pollutant Transport System (CONCEPTS); MIKE 11; and FLUVIAL12 use sediment-transport and supply relationships to simulate potential changes in channel morphology (mobile boundary) resulting from imbalances in sediment continuity. This means that hydraulic characteristics are calculated as channel form and cross section evolve through erosion and deposition over time. Such models have high mechanistic detail but are often difficult to apply effectively. Although it is not a mobile boundary model, the SIAM (Sediment Impact Analysis Method) module in HEC-RAS represents an intermediate complexity model designed to predict sediment imbalances at the stream network-scale and to describe likely zones of aggradation and degradation.

In this project, we evaluated the potential applicability of various movable bed and/or boundary models, including HEC-RAS (Brunner, 2008), CONCEPTS (Langendoen, 2000), and FLUVIAL12 (Chang, 2006) to predicting channel response to hydromodification in southern California. The tests involved modeling a prismatic floodplain with channel geometry, bed slope, and bed gradation corresponding to the Hasley Canyon study site in Orange County which represents a braided channel with a bed slope of 0.0258 and a median grain size of 1.6 mm. These tests indicated that mobile boundary hydraulic models are generally difficult to apply and have high prediction uncertainty due to flows near critical, split flow conditions, and lack of fidelity to complex widening, bank failure, and bed-armoring processes (Dust, 2009). For example, normal depth computations for the downstream-most cross section at the Hasley Canyon study site indicated that the Froude number ranges from approximated 0.97 to 1.14 for estimated flows corresponding to the 2- through 100-year events. These models are designed for sub-critical flows and it is common for such near-critical flows to produce numerical instabilities. Our extensive field reconnaissance indicates that armoring and channel widening resulting from both fluvial erosion and mass-wasting processes are key influences on channel response in southern California, and these processes are not well-represented and constrained in current mobile boundary models. Sediment transport rating curves based on field measurements have the potential to improve the efficacy of these models, especially for lower energy, single thread channels that are primarily vertically adjustable.

> "These tests indicated that mobile boundary hydraulic models are difficult to apply and have high prediction uncertainty due to flows near critical, split flow conditions, and lack of fidelity to complex widening, bank failure, and bed-armoring processes."

Regime diagrams

The relationship between inflowing water and sediment loads and equilibrium channel dimensions can be described mechanistically by combining several governing equations including conservation of mass, conservation of momentum, flow resistance, and sediment transport. Analytical solutions to this system of governing equations can be summarized in a variety of ways, including charts that express channel slope and dimensions in relation to inflowing discharges of water and sediment. This project has developed a set of "regime diagrams" for assessing the potential direction and relative response of channel geometry to long-term changes in discharge and sediment supply due to hydromodification. A regime diagram is a plot of physical control variables overlain with isoclines of geometric parameters for the purpose of assessing potential channel response. *The diagrams are physically-based but designed to provide managers with a relatively simple form of output from analytical channel design models. Managers can use these diagrams to examine the channel dimensions and slope predicted the deterministic models described above without performing additional modeling.* In developing the regime diagrams, we stratified the channel types of study region into three general types (Figure 6):

1. Live-bed, sand-dominated channels,
2. Mixed-bed, gravel channels with considerable sand content, and
3. Cobble-bed channels with some gravel and sand content.

and selected governing equations that are well-suited to each geomorphic setting (Figure 7).

(a) Dry Canyon Wash (b) Stewart Creek (c) Santiago Creek

Figure 6. Examples of the 3 geomorphic types from southern California (courtesy of Hawley, 2009).

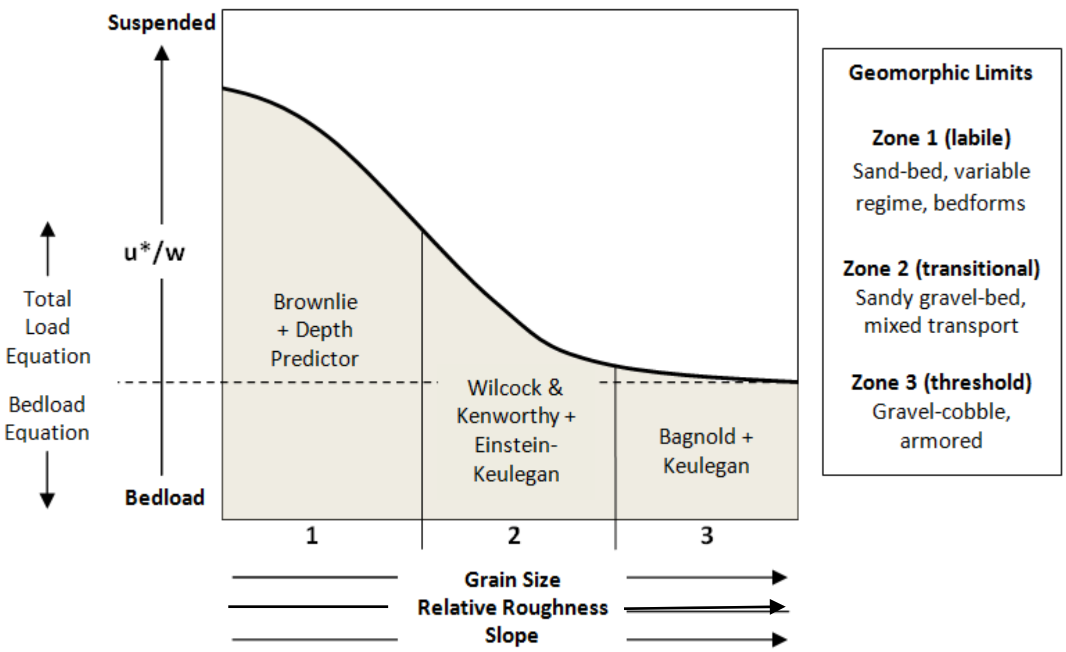


Figure 7. Geomorphic types used in this study. Labile, transitional, and threshold are terms used by Church (2006) to describe the hydraulic and sediment-transport processes occurring within each type.

Several regime diagrams were developed to provide an additional line of evidence describing the effect of long-term alterations of channel-forming discharge and the inflowing sediment concentration at that discharge on channel geometry (Figure 8). Separate diagrams have been developed for each geomorphic type using sediment-transport and flow-resistance relationships that are appropriate for those conditions. These relationships were plotted on log-log scales to compare the equilibrium channel geometry associated with wide ranges of discharge and sediment concentrations between channels. Each regime diagram contains a series of isoclines, each corresponding to select values of width, depth, and slope.

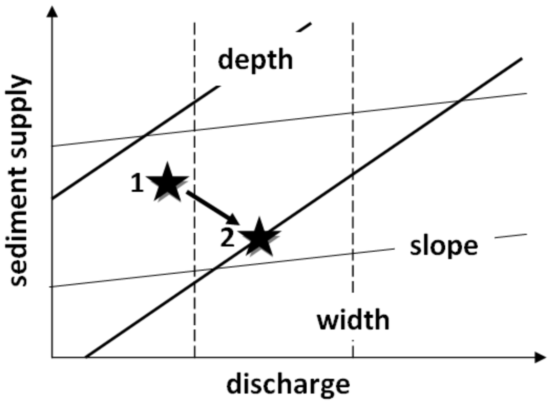


Figure 8. General framework of channel response diagrams. Long-term changes in discharge and sediment supply will be accompanied by a new equilibrium form (from plotting position 1 to 2).

Channel response diagrams for width, depth, and slope in Type 3 based on the Bagnold (1980) bedload transport equation are provided in Figures 9, 10, and 11, respectively. In these "relative response" diagrams, it is assumed that all variables are held constant except for the dependent parameter (width, depth or slope) and independent variables of relative discharge and sediment concentration. The initial state for each channel is indicated by the ratios of post-development to pre-development reference discharges of inflowing water and sediment (Q^* and Q_s^*, respectively) having values of 1 (no change). The post hydromodification state is typically represented by values of $Q^* > 1$ and $Q_s^* < 1$ (i.e., more runoff and less sediment); which translates into a new estimate of width, depth, and slope that theoretically represents the new equilibrium channel geometry. For instance, a Q^* of 2 and a Q_s^* of 0.8 would correspond to a doubling of the channel-forming discharge and a 20% reduction in sediment supply in an urbanizing watershed based on the Bagnold bedload relationship.

In the diagrams below (Figures 9 through 11), hypothetical relative changes in width, depth, and slope in response to changes in inflowing water and sediment discharges of +50% and -25%, respectively, are depicted by the dashed line labeled "regime." For example, a more than five-fold change in width (departure from initial state of Q^* and Q_s^* equal 1; Figure 9) would be expected in the absence of concurrent slope and depth change. Similarly, the equilibrium slope required to balance inflowing water and sediment would be less than 60% of the pre-disturbance slope in the absence of width and depth change. These estimates bracket the maximum response that might be expected given a particular combination of altered discharge and sediment supply. In most instances, width, depth, and slope mutually adjust; however, in a stream with bedrock or other effective grade control, width increase would be expected to dominate the response to urbanization. In this case, the width equation would be most relevant. Alternatively, the response of a stream with highly-resistant banks and a sand bed without grade control would be expected to incise in its initial response to urbanization. In this case, the slope diagram would be most relevant. Such diagrams can also provide additional resolution to channel susceptibility ratings in terms of expected relative changes in discharges of water and sediment. For example, this might be especially relevant for channels that rate from HIGH to VERY HIGH for lateral and/or vertical response in the SCCWRP screening tool. This would be accomplished by comparing the projected change in discharge of water and sediment based on watershed characteristics between streams in the same susceptibility class.

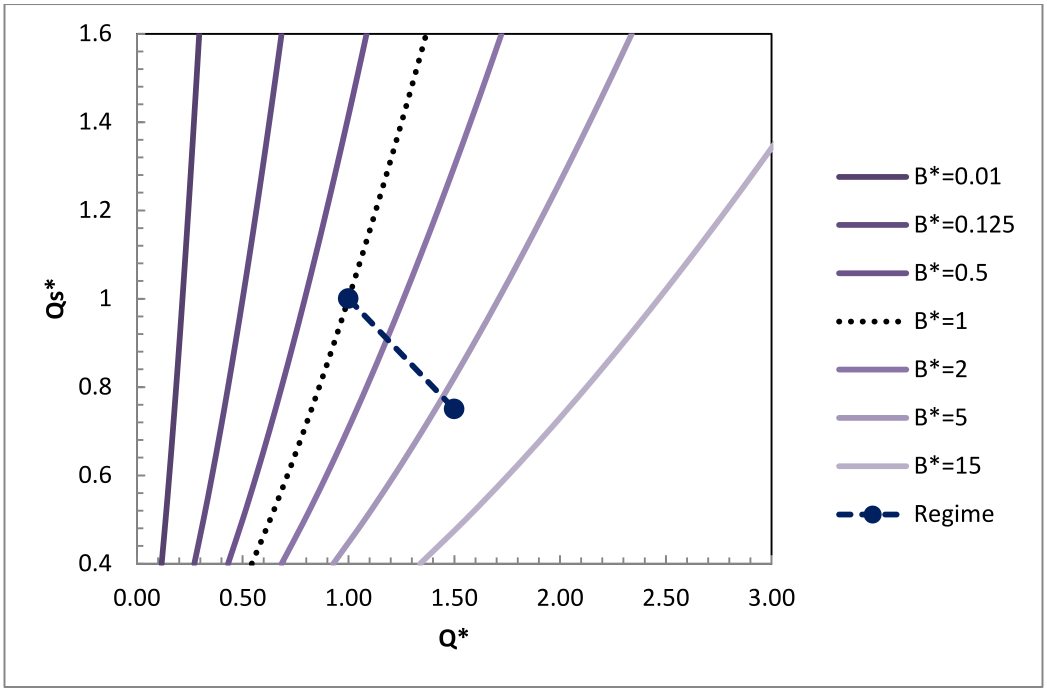


Figure 9. Maximum channel response diagram for width based on the quantitative approximation of Lane's balance using the Bagnold (1980) sediment-transport function. B* represents an estimated maximum post-development width / pre-development width in the absence of mitigation.

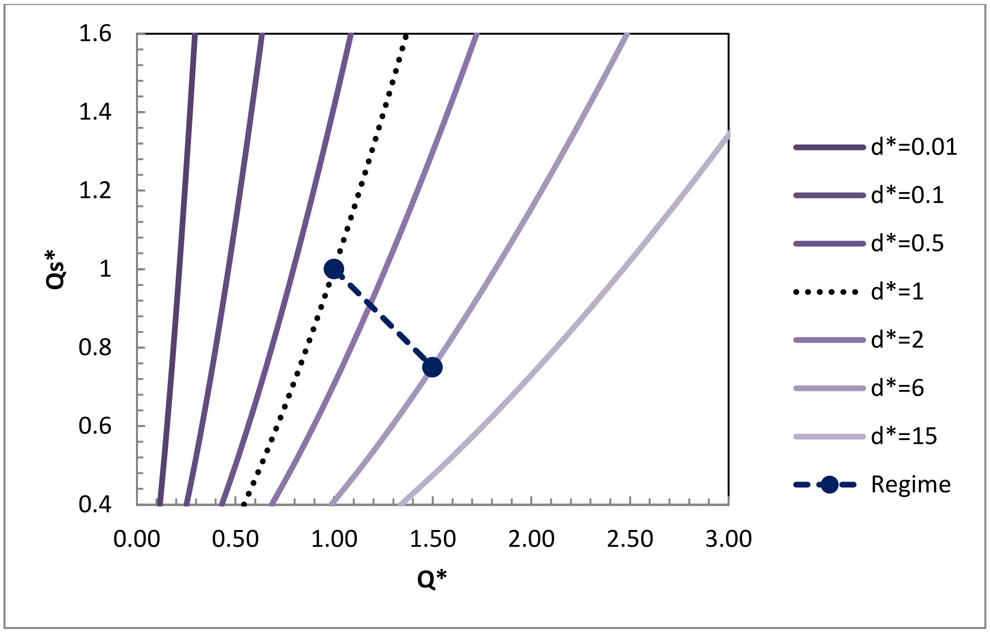


Figure 10. Maximum channel response diagram for depth based on the quantitative approximation of Lane's balance using the Bagnold (1980) sediment-transport function. d* represents an estimated maximum post-development depth / pre-development depth in the absence of mitigation.

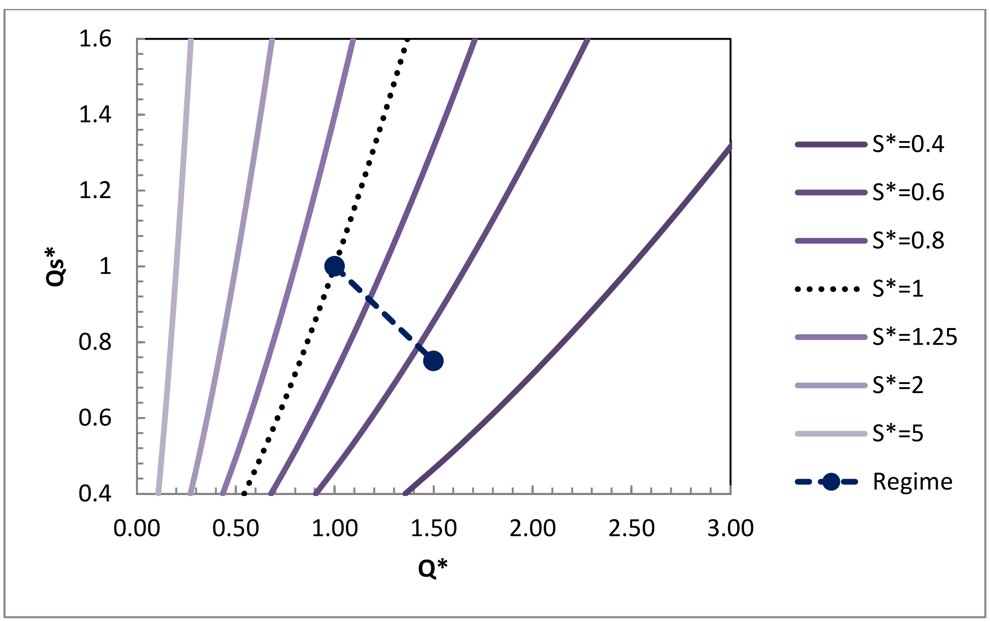


Figure 11. Maximum channel response diagram for slope based on the quantitative approximation of Lane's balance using the Bagnold (1980) sediment-transport function. S* represents an estimated maximum post-development slope / pre-development slope in the absence of mitigation. For channels with lateral and vertical constraints, S* values greater than one suggest aggradation, while those less than one suggest degradation.

Regime diagrams expressing absolute values of slope and depth in relation to channel-forming discharge and inflowing sediment concentration were developed by constraining width predictions based on field data collected in this study. Regime diagrams based on the median relationships for downstream hydraulic geometry in Types 1 and 2 are illustrated below (Figures 12 and 13, respectively). The resulting diagrams are unique in that they are based on regional stream width data stratified by type, as opposed to estimating widths by invoking a theoretical hypothesis like minimum stream power (Chang, 1988) or neglecting width by using a unit discharge of water and sediment (Parker, 1990).

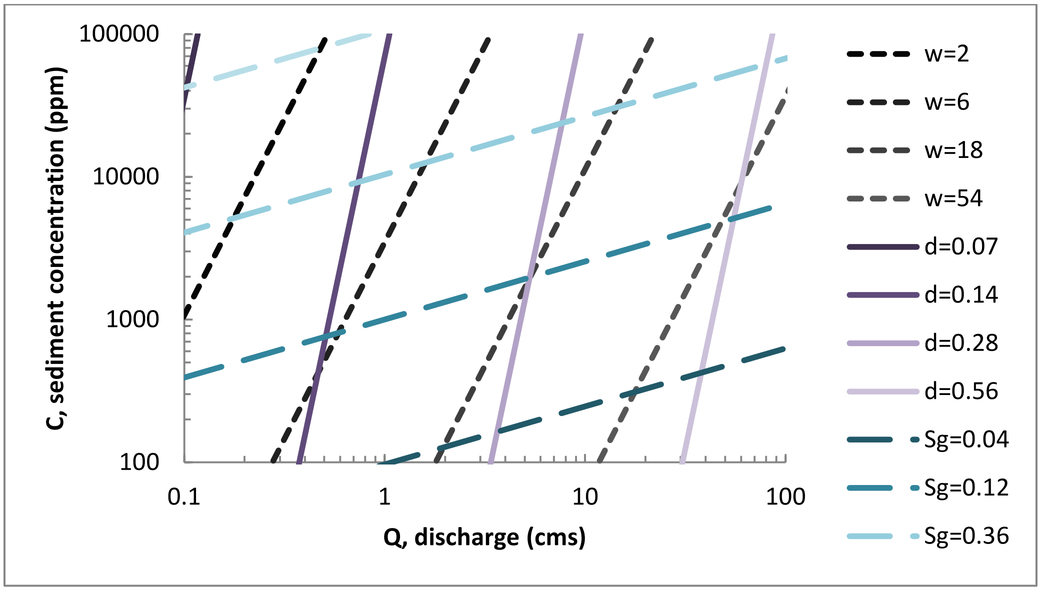


Figure 12. Type 1 regime diagram for absolute values of width, depth, and slope/$d_{50}^{0.5}$.(Sg).

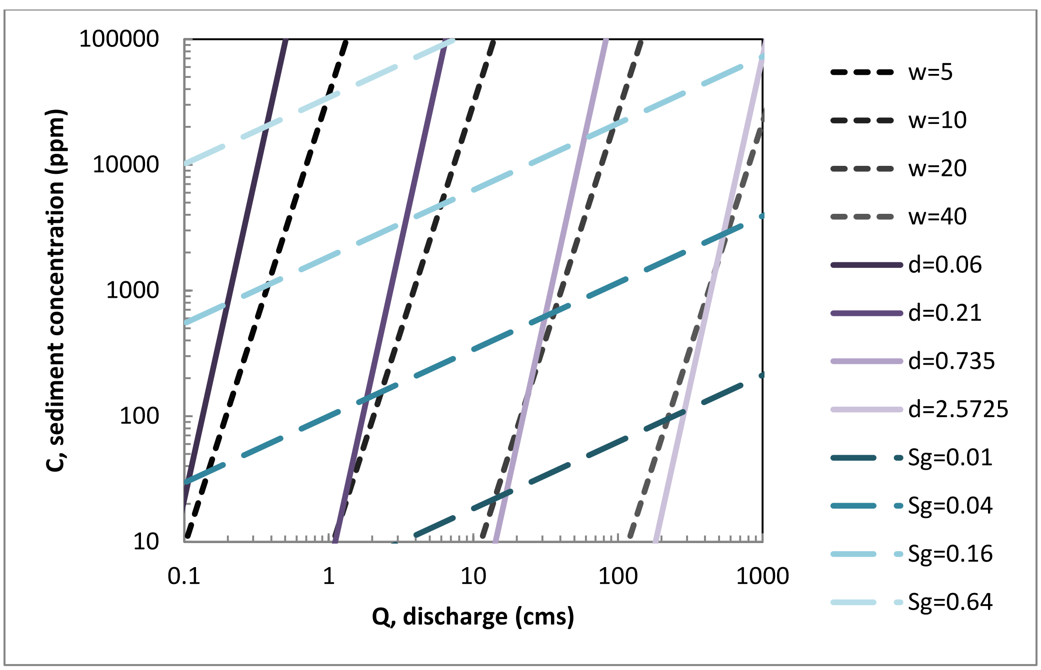


Figure 13. Type 2 regime diagram for absolute values of width, depth, and slope/$d_{50}^{0.5}$.(Sg).

The regime diagrams based on field-calibrated widths are arguably more directly applicable to southern California than those previously available. Although regime diagrams for sand- and gravel-bed channels have already been developed (Buffington and Parker, 2005; Chang, 1980, 1985), they vary markedly in underlying framework, and were developed using different assumptions, parameters, and procedures that are not transferable across the broad spectrum of stream types encountered in southern California. This approach is unique in its development of a series of hydraulic geometry functions and regime diagrams based on a combination of regional channel data and governing equations categorized by channel type. This framework allows for comparisons between channel types, and allows users to assess the relative susceptibility of differing channel types to hydromodification. Another aspect of this approach is that it can be developed for any study area, and updated when new data are made available, as regional regression models for width and sediment gradation can be easily developed from existing or new field data. Although we selected large ranges of sediment size to represent transitional and threshold channels, the boundaries of geomorphic types are flexible based on field observations and measurements. The use of synthetic channel data and theoretical regression models increase the effective sample size, and models the mutual adjustment of geometric parameters based on the governing equations of flow continuity, flow resistance, and sediment-transport continuity.

Our approach has several limitations including the calibration ranges of the data used to develop the underlying regression models, several simplifying assumptions, and the inherent difficulty of estimating changes in sediment supply. For example, it was necessary in a few instances to extrapolate sediment transport functions beyond the range of field and laboratory conditions in which they were calibrated to accommodate large predicted increases in water and sediment supply from watersheds undergoing hydromodification. Moreover, our relatively small sample sizes have artificially limited the range of variability inherent to channel types observed within the study area. Spatial and temporal variability are also simplified through the use of reach-averaged characteristics and one-dimensional, steady, uniform flow at single return interval discharges. An assumption of rectangular channel geometry was used to simplify in-channel hydraulics and sediment transport analyses. We performed a sensitivity analysis that provided some insight into how the models respond to variability in input parameters; however, this analysis was not exhaustive. For example, in the development of diagrams for transitional channels, the median grain size of sand in the gravel matrix was fixed to 1 mm. This assumption was necessary to simplify an otherwise unwieldy sediment-transport function.

It is important to underscore that the diagrams were developed to examine trends in single-thread quasi-equilibrium channel geometry due to long-term changes in discharge and sediment supply from urbanizing watersheds. As such, the approach does not make short-term predictions of transient channel response, such as incision or widening, nor do the models describe the sequence of channel evolution stages that might occur during the time period that a watershed is urbanized and the receiving channels respond. Rather, the diagrams can be used to predict the likely ultimate channel response to changes in factors affected by development or mitigation (e.g., flow and sediment). The predicted channel responses are best utilized in a comparative sense to assess relative response potential between channels in different watershed settings. For example, one could compare the potential response of two streams that have different levels of estimated sediment supply and net change in runoff potential based on the GLU method described above. Although these two streams might be in the same susceptibility class based on a rapid field screening, the regime diagrams would indicate non-linear differences in the potential magnitude of width, depth, and slope response to altered water and sediment inputs. Some users may find it difficult to understand separate predictions of ultimate channel depth versus slope, given that the channel depth to the top of bank will increase with incision (slope decrease) and decrease with aggradation that can result in a slope increase. The depth prediction represents the theoretical depth that would be necessary to balance sediment and water continuity if slope and width did not change. It is not the depth that results in response to some other slope change. *For practical applications, it is recommended that managers focus on relative potential changes in width and slope as the primary indicators of channel response potential*.

The regime diagrams are mechanistic models based on physical relationships governing hydrogeomorphic processes within the study area; however, the models should not be used in isolation without consideration of the cumulative error and uncertainty that are inherent. Given the necessary assumptions involved in their formulation and application, regime diagrams are not intended to be used as a stand-alone tool for predicting channel responses. Instead, they should be used in conjunction with other hydromodification tools described in this report to develop multiple lines of evidence for bracketing the possible range of channel responses to perturbations in discharge and inflowing sediment. Future versions of these tools could potentially be designed to explicitly replace single event descriptions of inflowing water and sediment with descriptors of long-term cumulative transport capacity and bed sediment supply rate. In either case, other modeling tools described below must be used to generate estimates of changes in inflowing water and sediment, and this remains the primary challenge (especially inflowing sediment) in applying these tools.

Regime diagrams should do not make short-term predictions of transient channel response, such as incision or widening. Rather, the diagrams can be used to predict the likely ultimate channel response to changes in factors affected by development or mitigation (e.g., flow and sediment).

Empirical/statistical models

These models describe associations between response variables and predictor variables, and the extent to which variation in output can be explained by input data. In the context of hydromodification management, statistical models are developed to describe empirical relationships that help predict stream responses to stressors like increased streamflow volumes and rates. With sufficient data, statistical models can be developed to describe significant associations between land use change and hydrologic, geomorphic, and/or biological responses. Such relationships do not mechanistically link cause and effect but can nevertheless provide important evidence for making management decisions, including evaluating the performance of mechanistic models. For example, most lower-order streams affected by hydromodification are ungauged and streamflow characterization necessarily relies on modeling. Statistical models provide a relatively-simple alternative to rainfall-runoff modeling if there are comparable streamflow gages that can be extrapolated to an ungauged site and a truly continuous series of streamflows is not required. Statistical predictions of streamflow metrics in ungauged basins also support mechanistic modeling efforts by providing information that can be used for model testing when calibration data are not available. In this project, we developed regional statistical models of streamflow that support a wide range of hydromodification modeling efforts aimed at assessing channel susceptibility and predicting geomorphic response to urbanization (Hawley and Bledsoe, 2011). In particular, the regression models can be used to estimate changes in both peak flows and flow durations that result from unmitigated watershed urbanization. The prediction of pre- and post-development flow-duration curves at ungauged sites provides a relatively-straightforward means of estimating erosion potential metrics that can be used in probabilistic models of channel response.

Statistical models have also been used to explain variance in channel enlargement in response to hydromodification based on measures of watershed urbanization, erosive energy, and other factors. Such models sometimes include independent variables derived from the mechanistic models described above; however, a key difference is that statistical models are not designed to explicitly represent actual physical processes in their mathematical structure. Instead, these models simply express observed correlations between dependent and independent variables. Like mechanistic models, the output from these models is commonly treated deterministically as a precise answer for use in management decisions, despite the fact that estimates from most statistical models could be readily (and more realistically) expressed in terms of distributions or prediction intervals with a range of uncertainty. As part of this project, we developed multivariate regression models of cross-sectional channel enlargement at 61 sites in southern California. Results indicate that channel enlargement is highly dependent on the ratio of post- to pre-urban sediment-transport capacity over cumulative duration simulations of 25 years (load ratio, a.k.a. erosion potential, Ep), which explained nearly 60% of the variance (Tables 1 and 2 and Figure 14). A logistic regression analysis of the same sites (classified categorically as stable vs. unstable channels) with erosion potential as the sole predictor variable indicates that Ep values of 0.79, 1.0, 1.23, and 2.0 correspond to 10, 27, 50, and 92% risk of instability, respectively (Figure 15). Classification accuracies for stable and unstable sites were 93 and 73%, respectively. The appreciably high probabilities of instability associated with values of erosion potential near unity likely reflect the influence of decreased sediment delivery, i.e., matching the flow duration curve for a wide spectrum of erosive flows may not be sufficiently protective of channel stability when inflowing sediment loads are substantially decreased through impervious and other land use changes.

"Results indicate that channel enlargement is highly dependent on the ratio of post- to pre-urban sediment-transport capacity over cumulative duration simulations of 25 years (load ratio, a.k.a. erosion potential), which explained nearly 60% of the variance."

Table 1. Channel enlargement risk factors. Ranked in relative order of importance based on how well they explain changes in channel cross-sections over time.

Variable	Description	Qualitative Influence	Partial R^{2} §	
			n = 66	n = 61¥
Lr (Ep)	Sediment-transport capacity load ratio (erosion potential) between 25-yr developed and undeveloped DDF simulations: $L_{developed}/L_{undeveloped}$ (m^3/m^3)	+	.28	.58
Imp	total impervious area as fraction of total drainage area (m^2/m^2)	+	.21	.56
D_{hp}/W_{10}	downstream distance to nearest 'hardpoint' (bedrock or artificial) scaled by top width at 10-yr flow (m/m). **term goes to 0 if Lr <1.20 for d_{50} >16 mm OR if Lr <1.05 for d_{50} < 16 mm**	+	.32	.34
Chnlz	binary variable representing historic channelization along reach (0 = unchannelized, 1 = channelized)	+	.20	.01
Confined	binary variable representing valley confinement as defined as a Valley Width Index (VWI) threshold of 2 (0 = VWI >2, 1 = VWI < 2)	-	.01	.02
Srf	average surface slope of watershed (m/m)	+	.02	.01
DD	drainage density: total stream length via National Hydrography Dataset (NHD) / total drainage area (km/km^2)	+	.01	.01
Veg	binary variable representing bank vegetation (0 = poor, 1 = dense)	-	.03	.01
Cohesion	binary variable representing relative bank cohesion (0 = low, 1 = high)	-	.01	.01

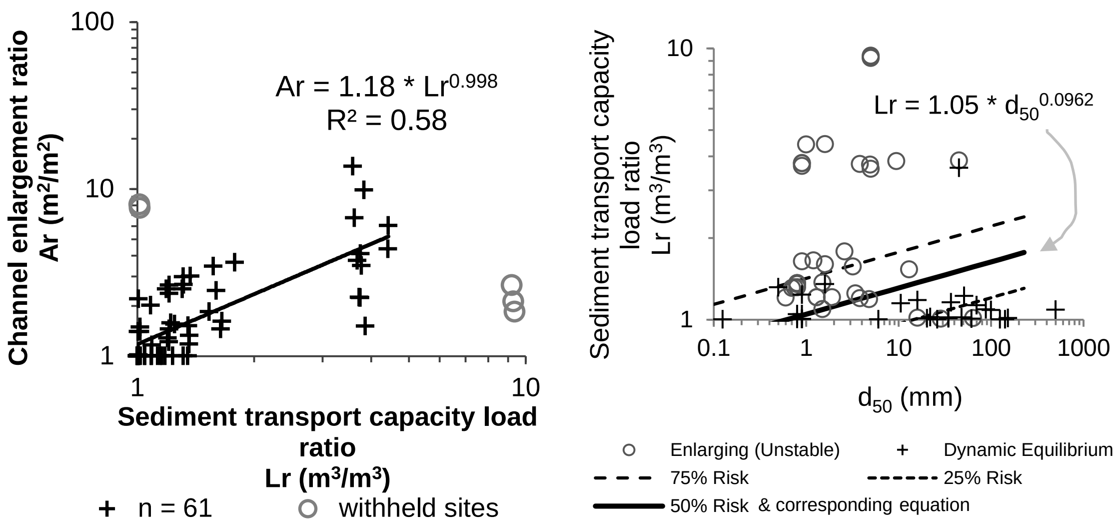
§ typical partial R^2 based on model forward selection

¥ withheld stream reaches where enlargement was primarily driven by historic channelization (San Antonio) or kept artificially low due to dense vegetation (Agua Hedionda); both factors were poorly distributed in our dataset

Table 2. Enlargement models and performance.

Enlargement Function, n = 66	Adj. R^2	p-value Exceptions
$Ar = 0.757 * Lr^{0.433} * (D_{hp}/W_{10})^{0.133} * e^{(1.65*Srf)} * e^{(-0.373*Veg)} * e^{(0.613*Chnlz)}$	0.58	
Enlargement Functions after Systematic Screening§, n = 61		
$Ar = 0.845 * Lr^{0.831} * (D_{hp}/W_{10})^{0.0751} * e^{(1.11*Srf)} * e^{(-0.246*Veg)}$	0.61	Veg = 0.14, Srf = 0.05
$Ar = 0.863 * e^{(8.83*Imp)} * (D_{hp}/W_{10})^{0.0862} * e^{(0.987*Srf)} * e^{(-0.252*Veg)}$	0.60	Veg = 0.13, Srf = 0.09
$Ar = 0.885 * Lr^{0.846} * (D_{hp}/W_{10})^{0.0770} * e^{(0.715*Srf)}$	0.60	Srf = 0.16
$Ar = 0.906 * e^{(8.98*Imp)} * (D_{hp}/W_{10})^{0.0885} * e^{(0.575*Srf)}$	0.59	Srf = 0.26
$Ar = 0.868 * Lr^{0.904} * (D_{hp}/W_{10})^{0.0650} * e^{(0.149*DD)}$	0.60	DD = 0.17
$Ar = 1.09 * Lr^{0.836} * (D_{hp}/W_{10})^{0.0614}$	0.59	
$Ar = 1.07 * e^{(8.97*Imp)} * (D_{hp}/W_{10})^{0.0750}$	0.59	
$Ar = 1.18 * Lr^{0.998}$	0.57	
$Ar = 1.18 * e^{(11.0*Imp)}$	0.55	

§ withheld stream reaches where enlargement was primarily driven by historic channelization (San Antonio) or kept artificially low due to dense vegetation (Agua Hedionda); both factors were poorly distributed in our dataset



(a) enlargement vs. erosion potential (b) risk of enlargement associated with d_{50} and erosion potential

§ based on the withholding of two stream reaches where enlargement was primarily driven by historic channelization (San Antonio) or kept artificially low due to dense vegetation (Agua Hedionda); both factors were poorly distributed in our dataset

Figure 14. Models of cross-sectional channel enlargement§: a) power regression of Lr vs. enlargement indicating that channel enlargement increases with increasing erosional potential, and b) multivariate logistic regression of stable vs. enlarged channels as a function of Lr and d_{50}. This model indicates increasing risk of enlargement with decreasing grain size and erosion potential (Hawley and Bledsoe, In Review).

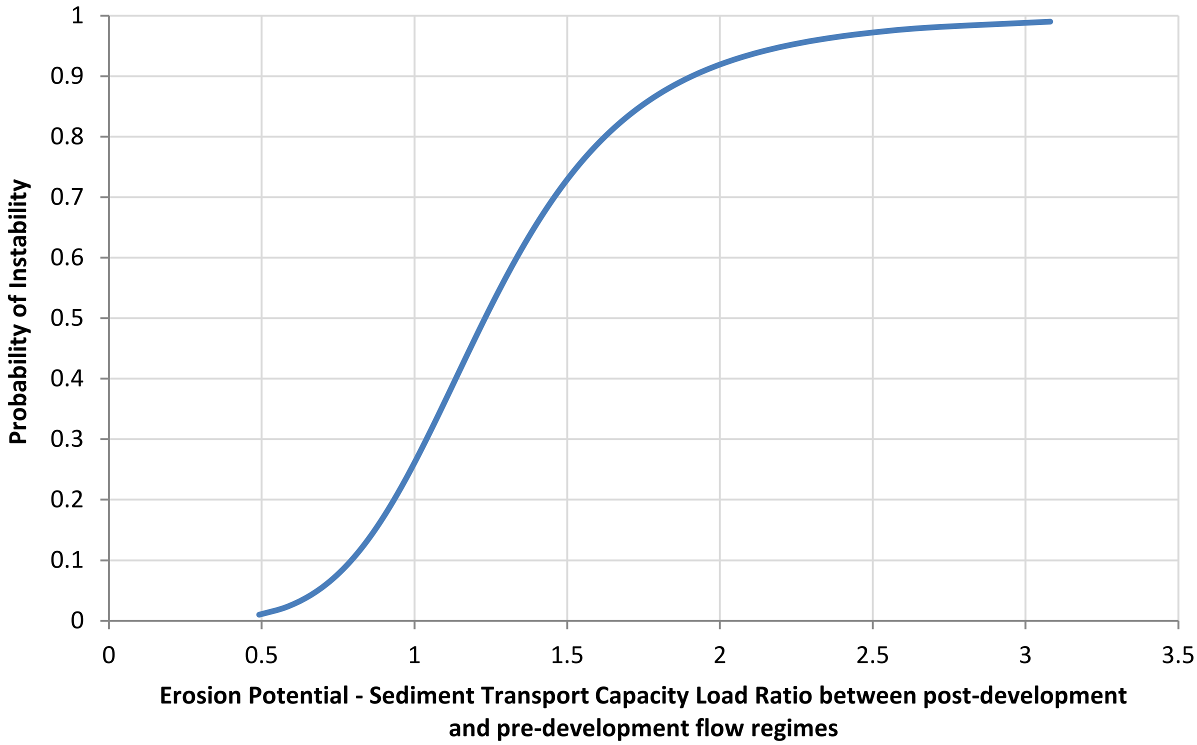


Figure 15. Logistic regression model based on classification of stable vs. unstable streams at 61 sites in southern California described by Hawley and Bledsoe (In Review) indicates increasing risk of channel instability with increasing erosion potential. The vertical axis represents the probability of stream instability which increases rapidly for channels with sediment-transport capacity increased by hydromodification.

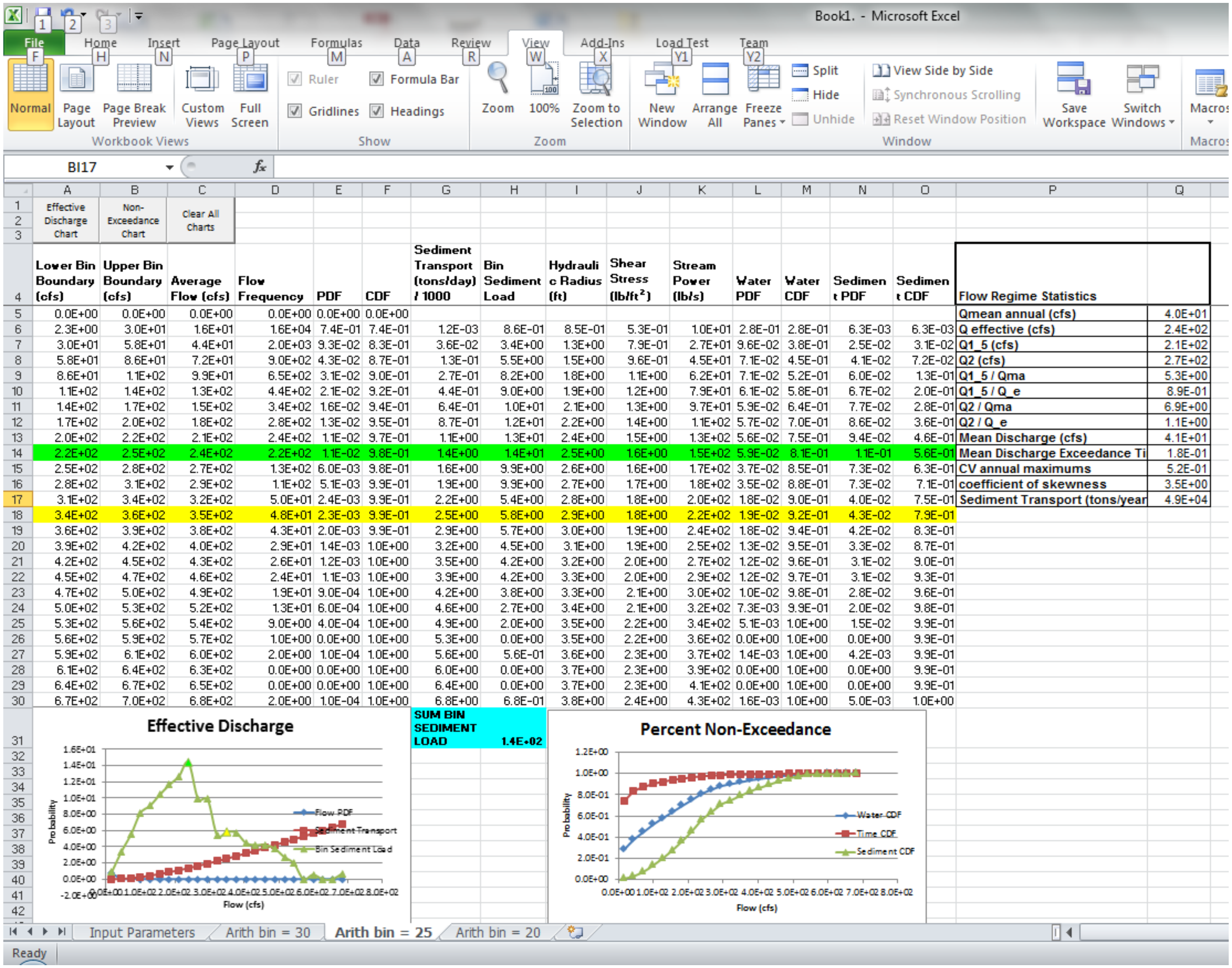
Results consistently indicate that susceptibility tends to increase with increasing erosion potential and distance from a downstream hardpoint, and decreasing bed-material particle size. Most of the variance in cross-sectional channel enlargement could be explained by the downstream distance to a hardpoint and the cumulative sediment-transport imbalance quantified over 25-year simulations. For example, ~five-fold enlargement was correlated to D_{hp}/W_{10} ~30 and Lr ~3.5 (~15% imperviousness); ~two-fold enlargement would be expected with the same hardpoint distance and Lr ~1.2 (~5% imperviousness).

The models demonstrate that the risk of adverse morphologic channel responses is best reduced by minimizing increases in time-integrated sediment-transport capacity on future developments. This conclusion was further affirmed with statistically-significant ($p < 0.0001$) logistic-regression models based on erosion potential and d_{50}, which suggested that fine-grained systems, especially those with d_{50} less than 16 mm, have little capacity to resist any increases in sediment-transport potential. Thus, the statistical models point to the importance of balancing the post-development sediment transport to the pre-development setting over a ~25-year range of sediment-transporting flows rather than a single flow in order to reduce the risk of adverse channel responses to hydromodification. The primary step to achieving this criterion in management is matching the pre-development flow duration curve above the shear stress that mobilizes the most erodible channel boundary, which is often the bed material.

Integrative tools that support statistical models

Integrative tools are designed to combine hydrologic and geomorphic data to identify physically-based descriptors of channel-forming discharges, frequency distributions of stream power and shear stress, and cumulative sediment transport. In most instances, such tools are created by analysts in spreadsheet applications because there are very few “off-the-shelf” software packages that perform these types of calculations. One exception is GeoTools, an existing suite of analysis tools for fluvial systems written in Visual Basic for Applications (VBA) / Excel®. Based on flow time series and basic geomorphic data, GeoTools automates computation of numerous hydrologic, hydraulic, and geomorphic descriptors including effective discharge, sediment transport and yield, temporal distributions of hydraulic parameters (e.g., shear stress and specific stream power), cumulative erosion potential, channel stability indices, and over 100 flow regime metrics (Bledsoe *et al*., 2007). GeoTools accepts input flow records in standard US Geological Survey (USGS) format and a variety of other formats and temporal densities. The package also serves as a post-processor for SWMM and HSPF / Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) model output.

As newer versions of Excel® have become available since GeoTools was developed in Excel® 2003, some of the original functionality of GeoTools has not transferred due to changes in Excel® 2007 and 2010 (e.g., reference libraries and chart options in VBA). In this project, we updated GeoTools to make it fully functional in Excel® 2010. This facilitates the calculation of erosion potential and flow metrics, and allows users to readily generate several new charts related to effective discharge analysis and other analyses that combine continuous streamflow records and sediment-transport relationships (Figure 16). The erosion potential metrics output by GeoTools are a key input for the channel enlargement models developed in this study and the probabilistic models described in the next section.



	Lower Bin Boundary (cfs)	Upper Bin Boundary (cfs)	Average Flow (cfs)	Flow Frequency	PDF	CDF	Sediment Transport (tons/day) / 1000	Bin Sediment Load	Hydraulic Radius (ft)	Shear Stress (lb/ft²)	Stream Power (lb/s)	Water PDF	Water CDF	Sediment PDF	Sediment CDF
5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00									
6	2.3E+00	3.0E+01	1.6E+01	1.6E+04	7.4E-01	7.4E-01	1.2E-03	8.6E-01	8.5E-01	5.3E-01	1.0E+01	2.8E-01	2.8E-01	6.3E-03	6.3E-03
7	3.0E+01	5.8E+01	4.4E+01	2.0E+03	9.3E-02	8.3E-01	3.6E-02	3.4E+00	1.3E+00	7.9E-01	2.7E+01	9.6E-02	3.8E-01	2.5E-02	3.1E-02
8	5.8E+01	8.6E+01	7.2E+01	9.0E+02	4.3E-02	8.7E-01	1.3E-01	5.5E+00	1.5E+00	9.6E-01	4.5E+01	7.1E-02	4.5E-01	4.1E-02	7.2E-02
9	8.6E+01	1.1E+02	9.9E+01	6.5E+02	3.1E-02	9.0E-01	2.7E-01	8.2E+00	1.8E+00	1.1E+00	6.2E+01	7.1E-02	5.2E-01	6.0E-02	1.3E-01
10	1.1E+02	1.4E+02	1.3E+02	4.4E+02	2.1E-02	9.2E-01	4.4E-01	9.0E+00	1.9E+00	1.2E+00	7.9E+01	6.1E-02	5.8E-01	6.7E-02	2.0E-01
11	1.4E+02	1.7E+02	1.5E+02	3.4E+02	1.6E-02	9.4E-01	6.4E-01	1.0E+01	2.1E+00	1.3E+00	9.7E+01	5.9E-02	6.4E-01	7.7E-02	2.8E-01
12	1.7E+02	2.0E+02	1.8E+02	2.8E+02	1.3E-02	9.5E-01	8.7E-01	1.2E+01	2.2E+00	1.4E+00	1.1E+02	5.7E-02	7.0E-01	8.6E-02	3.6E-01
13	2.0E+02	2.2E+02	2.1E+02	2.4E+02	1.1E-02	9.7E-01	1.1E+00	1.3E+01	2.4E+00	1.5E+00	1.3E+02	5.6E-02	7.5E-01	9.4E-02	4.6E-01
14	2.2E+02	2.5E+02	2.4E+02	2.2E+02	1.1E-02	9.8E-01	1.4E+00	1.4E+01	2.5E+00	1.6E+00	1.5E+02	5.9E-02	8.1E-01	1.1E-01	5.6E-01
15	2.5E+02	2.8E+02	2.7E+02	1.3E+02	6.0E-03	9.8E-01	1.6E+00	9.9E+00	2.6E+00	1.6E+00	1.7E+02	3.7E-02	8.5E-01	7.3E-02	6.3E-01
16	2.8E+02	3.1E+02	2.9E+02	1.1E+02	5.1E-03	9.9E-01	1.9E+00	9.9E+00	2.7E+00	1.7E+00	1.8E+02	3.5E-02	8.8E-01	7.3E-02	7.1E-01
17	3.1E+02	3.4E+02	3.2E+02	5.0E+01	2.4E-03	9.9E-01	2.2E+00	5.4E+00	2.8E+00	1.8E+00	2.0E+02	1.8E-02	9.0E-01	4.0E-02	7.5E-01
18	3.4E+02	3.6E+02	3.5E+02	4.8E+01	2.3E-03	9.9E-01	2.5E+00	5.8E+00	2.9E+00	1.8E+00	2.2E+02	1.9E-02	9.2E-01	4.3E-02	7.9E-01
19	3.6E+02	3.9E+02	3.8E+02	4.3E+01	2.0E-03	9.9E-01	2.9E+00	5.7E+00	3.0E+00	1.9E+00	2.4E+02	1.8E-02	9.4E-01	4.2E-02	8.3E-01
20	3.9E+02	4.2E+02	4.0E+02	2.9E+01	1.4E-03	1.0E+00	3.2E+00	4.5E+00	3.1E+00	1.9E+00	2.5E+02	1.3E-02	9.5E-01	3.3E-02	8.7E-01
21	4.2E+02	4.5E+02	4.3E+02	2.6E+01	1.2E-03	1.0E+00	3.5E+00	4.2E+00	3.2E+00	2.0E+00	2.7E+02	1.2E-02	9.6E-01	3.1E-02	9.0E-01
22	4.5E+02	4.7E+02	4.6E+02	2.4E+01	1.1E-03	1.0E+00	3.9E+00	4.2E+00	3.3E+00	2.0E+00	2.9E+02	1.2E-02	9.7E-01	3.1E-02	9.3E-01
23	4.7E+02	5.0E+02	4.9E+02	1.9E+01	9.0E-04	1.0E+00	4.2E+00	3.8E+00	3.3E+00	2.1E+00	3.0E+02	1.0E-02	9.8E-01	2.8E-02	9.6E-01
24	5.0E+02	5.3E+02	5.2E+02	1.3E+01	6.0E-04	1.0E+00	4.6E+00	2.7E+00	3.4E+00	2.1E+00	3.2E+02	7.3E-03	9.9E-01	2.0E-02	9.8E-01
25	5.3E+02	5.6E+02	5.4E+02	9.0E+00	4.0E-04	1.0E+00	4.9E+00	2.0E+00	3.5E+00	2.2E+00	3.4E+02	5.1E-03	1.0E+00	1.5E-02	9.9E-01
26	5.6E+02	5.9E+02	5.7E+02	1.0E+00	0.0E+00	1.0E+00	5.3E+00	0.0E+00	3.5E+00	2.2E+00	3.6E+02	0.0E+00	1.0E+00	0.0E+00	9.9E-01
27	5.9E+02	6.1E+02	6.0E+02	2.0E+00	1.0E-04	1.0E+00	5.6E+00	5.6E-01	3.6E+00	2.3E+00	3.7E+02	1.4E-03	1.0E+00	4.2E-03	9.9E-01
28	6.1E+02	6.4E+02	6.3E+02	0.0E+00	0.0E+00	1.0E+00	6.0E+00	0.0E+00	3.7E+00	2.3E+00	3.9E+02	0.0E+00	1.0E+00	0.0E+00	9.9E-01
29	6.4E+02	6.7E+02	6.5E+02	0.0E+00	0.0E+00	1.0E+00	6.4E+00	0.0E+00	3.7E+00	2.3E+00	4.1E+02	0.0E+00	1.0E+00	0.0E+00	9.9E-01
30	6.7E+02	7.0E+02	6.8E+02	2.0E+00	1.0E-04	1.0E+00	6.8E+00	6.8E-01	3.8E+00	2.4E+00	4.3E+02	1.6E-03	1.0E+00	5.0E-03	1.0E+00

Flow Regime Statistics	
Qmean annual (cfs)	4.0E+01
Q effective (cfs)	2.4E+02
Q1_5 (cfs)	2.1E+02
Q2 (cfs)	2.7E+02
Q1_5 / Qma	5.3E+00
Q1_5 / Q_e	8.9E-01
Q2 / Qma	6.9E+00
Q2 / Q_e	1.1E+00
Mean Discharge (cfs)	4.1E+01
Mean Discharge Exceedance Ti	1.8E-01
CV annual maximums	5.2E-01
coefficient of skewness	3.5E+00
Sediment Transport (tons/year	4.9E+04

Figure 16. Example output from effective discharge / erosion potential module of GeoTools updated for Excel 2010.

2.1.3 Probabilistic / Risk-based Models

Probabilistic / risk-based models integrate many of the tools discussed above, using modeled changes in hydrology as input to hydraulic models, which in turn provide input to various types of statistical models to predict response. However, the predictions based on these inputs are not represented as deterministic outputs. Instead, the range of (un)certainty in the likelihood of the predicted response is explicitly quantified. Although not commonly used for hydromodification management at this time, there are well-established models of this type that are currently in use in other scientific disciplines. An example of a probabilistic approach that has been used for hydromodification management is a logistic regression analysis that was used to produce a threshold "erosion potential metric" that can be used to quantify the probability of a degraded channel state. More details on this approach are provided below in the section on suites of modeling tools.

In this project, we examined the use of General Regression Neural Network (GRNN) models to predict channel enlargement due to the effects of hydromodification on regional streams. Results indicated that this and other artificial neural network (ANN) modeling techniques represent a viable probabilistic modeling approach for hydromodification management. When applied to our field dataset, the GRNN models indicated that estimated increases in Q_2, based on regional flood regression equations (Hawley and Bledsoe, 2011), consistently ranked as the most important predictor of channel enlargement despite the inclusion of a large pool of watershed and geomorphic descriptors at various spatial scales. The best models also consistently included key variables used in the SCCWRP Colorado State University (CSU) susceptibility screening tool such as distance to hardpoint, Valley Width and Valley Expansion Ratio that are not directly related to the extent of watershed development. Few attempts have been made to comprehensively model a broad set of parameters that influence geomorphic response in southern California streams, mostly due to the computational limitations of deterministic models and the relative simplicity of regression models. This project has shown that GRNNs can capture many of the non-linear relationships that influence hydromodification response in channels of southern California and provide quantitative estimates of change and the uncertainty associated with those estimates.

> "When applied to our field dataset, the GRNN models indicated that estimated increases in Q_2, based on regional flood regression equations, consistently ranked as the most important predictor of channel enlargement despite the inclusion of a large pool of watershed and geomorphic descriptors at various spatial scales."

Like all models, GRNNs come with caveats and inherent weaknesses, such as, the choice of model inputs, network structures and internal model parameters, and method of pre-processing of model inputs (Maier and Dandy, 2000). Because most ANN models are data-driven (Chakraborty *et al.*, 1992) and are able to determine critical parameters, users tend to pay little attention to the selection of appropriate model inputs (Faraway and Chatfield, 1998). It is important to ensure that the model includes process-based surrogate measures of response drivers and mechanisms that can accurately represent the real system, and are not just built on available data. GRNNs rely on associations between target and predictor variables; therefore, the more process-based the predictor variables used, the less complex a GRNN will need to be. For example, in this study the GRNN that was developed with the urban-amplified Q_2 required 25% fewer variables to match the performance of the higher recurrence interval flow models, which did not inherently reflect watershed imperviousness. Pre-processing for GRNN networks includes standardization to ensure all variables are treated equally (Maier and Dandy, 2000). Scaling the variables to fall within the limits of activation functions used in the outer layer is also recommended as a pre-processing step (Maier and Dandy, 2000; Minns and Halls, 1996). Nevertheless, GRNNs can help in support of rating channel susceptibility to hydromodification and identifying target variables for detailed data collection. In this way, GRNN can be used to support not only predictive modeling, but also to inform effective field monitoring and assessment programs. Overall, our results suggest that GRNN predictions can be used in concert with other tools to help inform management decisions, such as the need for flow duration based stormwater controls, and to tailor monitoring programs.

A probabilistic representation of possible outcomes also improves understanding of the uncertainty that is inherent in model predictions, and can inform management decisions about acceptable levels of risk.

2.2 Strengths, Limitations, and Uncertainties

The organizing framework shown in Figure 1 depicts the applicability of the three major categories of tools in support of various management actions. This section addresses a range of issues relating to strengths, limitations, and uncertainty of the tools discussed above. Detailed analysis of individual models is beyond the scope of this document, but *EPA/600/R-05/149* (Shoemaker *et al*., 2005) contains an extensive comparison of functions and features across a wide range of hydrologic and hydraulic models.

General considerations

The well-known statistician George Box famously said that “all models are wrong, some are useful.” The usefulness of a model for a particular application depends on many factors including prediction accuracy, spatial and temporal detail, cost of calibration and testing, meaningful outputs, and simplicity in application and understanding. There is no cookbook for selecting models with an optimal balance of these characteristics. Models of stream response to land use change will always be imperfect representations of reality with associated uncertainty in their predictions. In addition to the prediction errors of standard hydrologic models, common limitations and sources of uncertainties include insufficient spatial and/or temporal resolution, and poorly-known parameters and

> “Ultimately, the focus of scientific study in support of decision making should be on the decisions (or objectives) associated with the resource and not on building more-detailed models with the hope that they will provide the answers that elude us.”
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> “The predictive models that hold the most promise in hydromodification management are best thought of as predictive scientific assessments; that is, flexible, changeable mixes of small mechanistic models, statistical analyses, and expert scientific judgment.”

boundary conditions. Ultimately, the focus of scientific study in support of decision-making should be on the decisions (or objectives) associated with the resource and not on building more-detailed models with the hope that they will provide the answers that elude us. Each model has limitations in terms of its utility in addressing decisions and objectives of primary concern to stakeholders. Prediction error in terms of decision endpoints, not perception of mechanistic correctness, should be the most important criterion reflecting the usefulness of a model (NRC, 2001; Reckhow, 1999a,b). The predictive models that hold the most promise in hydromodification management are best thought of as predictive scientific assessments; that is, flexible, changeable mixes of small mechanistic models, statistical analyses, and expert scientific judgment.

Region-specific considerations

Because all models are vulnerable to improper specification and omission of significant processes, caution must be exercised in transferring existing models to new regional conditions. For example, mobile boundary hydraulic models are mechanistically detailed but not generally well-suited to many southern California streams given the prevalence of near-supercritical flow, braiding, and split flow. In addition, bed armoring and channel widening resulting from both fluvial erosion and mass-wasting processes are key influences on channel response in semiarid environments. These processes are not well-represented and constrained in current mobile boundary models. Accordingly, the appropriateness of existing models for addressing a particular hydromodification management question should be empirically tested and supported with regionally-appropriate data from diverse stream settings.

Sediment supply

As described above, a reduction in sediment supply to a stream may result in instability and impacts, even if pre- and post-land use change flows are perfectly matched. Thus, there is a need to develop management approaches to protect stream channels when sediment supply is reduced, and to refine and simplify tools to support these approaches. This continues to prove challenging because, the effects of urban development on sediment supply in different geologic settings are not well-understood and poorly represented in current models. As a starting point, models used to analyze development proposals that reduce sediment supply could be applied with more protective assumptions with respect to parameters and boundary conditions (inflowing sediment loads). Effects of altered sediment supply on stream response could be addressed in a probabilistic framework by adjusting conditional probabilities of stream states to reflect the influence of reductions in important sediment sources due to land use change.

Managing uncertainty

To date, hydromodification management has generally relied on oversimplified models or deterministic outputs from numerical models that consume considerable resources but yield highly uncertain predictions that can be difficult to apply in management decisions. Numerical models are nevertheless an important part of the hydromodification toolbox, especially in characterizing rainfall-response and hydraulic behavior over decades of land use change. It is challenging to rigorously quantify the prediction accuracy of these mechanistic numerical models; however, their utility can be enhanced by addressing prediction uncertainties in a number of ways (Cui *et al.*, 2011). Candidate models can, for example, be subjected to sensitivity analysis to understand their relative efficacy for assessment and prediction of hydromodification effects. Moreover, it should also be demonstrated that selected models can reasonably reproduce background conditions before they are applied in predicting the future. Modeling results that are used in relative comparisons of outcomes are generally much more reliable than predictions of absolute magnitudes of response.

Hydromodification modeling embodies substantial uncertainties in terms of both the forcing processes and stream response. Deterministic representations of processes and responses can mask uncertainties and can be misleading unless prediction uncertainty is explicitly quantified. Errors may be transferred and compounded through coupled hydrologic, geomorphic, and biologic models. Accordingly, explicit consideration, quantification, and gradual reduction of model uncertainty will be necessary to advance hydromodification management. This points to two basic needs. First, there is a need to develop more robust probabilistic modeling approaches that can be updated and refined as knowledge increases over time. Such approaches must be amenable to categorical inputs and outputs, as well as combining data from a mix of sources including mechanistic hydrology models, statistical models based on field surveys of stream characteristics, and expert judgment. Second, the uncertainty inherent to hydromodification modeling underscores the need for carefully-designed monitoring and adaptive management programs.

> "There is a need to develop more robust probabilistic modeling approaches that can be updated and refined as knowledge increases over time. Such approaches must be amenable to categorical inputs and outputs, as well as combining data from a mix of sources including mechanistic hydrology models, statistical models based on field surveys of stream characteristics, and expert judgment."
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> "The uncertainty inherent to hydromodification modeling underscores the need for carefully-designed monitoring and adaptive management programs."

A probabilistic / risked-based framework can provide a more rational and transparent basis for prediction and decision-making by explicitly recognizing uncertainty in both the reasoning about stream response and the quality of information used to drive the models. Prediction uncertainty can be quantified for any of the types of models described above; however, some types are more amenable to uncertainty analysis than others. For example, performing a Monte Carlo analysis of a coupled hydrologic-hydraulic model is a very demanding task. A simple sensitivity analysis of high, medium, and low values of plausible model parameters is much more tractable and still provides an improved understanding of the potential range of system responses. Such information can be subsequently integrated with other model outputs and expert judgment into a probabilistic framework. For example, Bayesian probability network approaches can accommodate a mix of inputs from mechanistic and statistical models, and expert judgment to quantify the probability of categorical states of stream response. Such networks also provide an explicit quantification of uncertainty, and lend themselves to continual updating and refinement as information and knowledge increase over time. As such, they have many attractive features for hydromodification management, and are increasingly used in environmental modeling in support of water quality (Reckhow, 1999a,b) and stream-restoration decision-making (Stewart-Koster *et al*., 2010).

2.3 Summary of Modeling Tools

At present, there is no definitive inventory and evaluation of hydromodification modeling tools in terms of the specific management questions the models address, relationships between models, and data requirements. Moreover, there are no formal guidelines for helping managers review and evaluate the appropriateness of modeling-based hydromodification analyses. With this goal in mind, Table 3 was developed to provide a tentative summary of the models that are currently considered most relevant to hydromodification management. It is important to note that decisions regarding which models to apply should be made based on a consideration of the questions being asked, the level of certainty required in the output, and ability to compile or collect necessary input data. In addition, the complexity and condition of the watershed of interest should be considered when selecting modeling tools.

Table 3. Summary of the models that are currently considered most relevant to hydromodification management.

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Descriptive (D) Tools								
Rapid riparian/wetland assessments	CRAM	D	Level of wetland / riparian function?	reach to segment	Complements geomorphic assessment tools.	Field visit, readily available GIS and desktop data.	Low - Moderate	Were protocols properly followed?
Rapid channel susceptibility assessments	Bledsoe *et al.,* 2010, 2012	D	Relative channel susceptibility to hydromodification High, Medium, or Low?	reach to segment	Complements riparian assessment tools, vertical and lateral rating point to additional modeling tools, suggests in a coarse sense the level of mitigation that may be required.	Field visit, readily available GIS and desktop data.	Low - Moderate	Were protocols properly followed? For relative comparisons of susceptibility.
Geomorphic Landscape Units	Booth *et al.,* 2011	D	Where will development most affect runoff processes? Where are key sources of coarse sediment supply to stream channels? Where are priority areas for restricting development to maintain watershed processes? Where might "over-control" be necessary to mitigation reductions in sediment supply?	watershed - region	Complements channel stability assessments, land use planning.	Readily available GIS data.	Low - Moderate	Were protocols properly followed? For relative comparisons of potential sediment delivery.
Channel Evolution Model	Schumm *et al.,* 1984; Hawley *et al.,* 2012	D	What is the sequence of incision and/or braiding that can be expected over decades in disturbed channels? What geomorphic thresholds are most relevant to understanding channel response? How can unstable channels be classified for targeting rehabilitation measures?	reach to watershed	Identifies geomorphic thresholds quantified by braiding/incision predictors, highlights key processes that models of channel response may need to account for.	Field visit, expertise in fluvial geomorphology.	Low - Moderate	Are the predictions of other channel response models consistent with this framework, which processes / thresholds in the CEM are not accounted for in a modeling analysis?

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use§
Mechanistic (M) / Empirical-Statistical (E/S)								
Rainfall-runoff models	HSPF, SWMM, HEC-HMS	M	What are the estimated streamflows at an ungauged site? How will different types of land use change affect streamflow? How will peak flows change (single event modeling)? How will the long-term streamflow regime change in terms of magnitude, frequency, duration, flashiness, etc. (continuous modeling)?	watershed	Provide inputs in hydraulic models, shear stress and effective discharge calculators, SIAM, mobile boundary models. Continuous simulation outputs necessary to create flow-duration curves and to estimate important metrics like erosion potential for probabilistic models.	Several watershed GIS layers (e.g., precipitation, land cover, soils), streamflow data needed for calibration - long-term records of precipitation, land use change, calibration data required for continuous simulation.	Low - High, depends on data availability, calibration and testing	Is there match in the spatial and temporal scales and vintage of input data, are infiltration parameters consistent with standardized values for the study region, were 15-min data generated for flashy streams, was the model calibrated and validated?
Regional streamflow regressions	Hawley and Bledsoe, 2011	E/S	What are estimates of streamflow metrics at ungauged sites? How will urbanization affect streamflow at this ungauged site? How will peak flows and flow durations change in response to urbanization?	watershed	Complement rainfall-runoff models by providing an additional estimate of flow characteristics that is relatively straightforward to estimate. Can be used as a check of more detailed hydrology models.	Watershed GIS layers.	Moderate if not extrapolated beyond calibration data	Are the regressions applied within the range of conditions used to develop the model?
Hydraulic models	HEC-RAS	M, E/S	What are the hydraulic characteristics (e.g., shear stress, stream power) in a stream at a given discharge (or over some hydrograph)?	watershed to reach	Provides relationships between discharge and hydraulic variables like depth, slope, shear stress and stream power that are required inputs for any model that performs sediment-transport calculations.	Channel and structure geometry, flow resistance values, boundary conditions, and other parameters.	Low - High, depends on data availability, calibration and testing	How accurate are the channel geometry data, flow resistance parameters? Are structures and boundary conditions correctly specified?

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Mechanistic (M) / Empirical-Statistical (E/S) (Continued)								
Erosion models	WEPP (Water Erosion Prediction Project), SWAT (Soil and Water Assessment Tool)	M, E/S	How will hillslope erosion and watershed sediment delivery change in response to a change in land use or natural disturbance?	site - watershed	Provides an estimate of sediment delivery that can be used in sediment budgets and as a boundary condition in channel response models including mobile boundary models.	Several watershed GIS layers (e.g., precipitation, land cover, soils), sediment-delivery data needed for calibration – long-term records of precipitation, land use change, sediment data for calibration required for continuous simulation.	Very high	Difficult to obtain order of magnitude accuracy. Unreliable for most hydromodification applications except for relative comparisons of potential sediment delivery.
Gross erosion models	RUSLE2 (Revised Universal Soil Loss Equation)	E/S	How will gross erosion change in response to a change in land use or natural disturbance?	site - region	Provides an estimate of sediment delivery that can be used in sediment budgets and in models of relative channel response such as regime diagrams.	Readily available GIS data and table values needed. Some hydrologic data may be needed depending on model selection. Erosion data needed for testing.	High	Most accurate at annual time scales in relative comparisons of gross erosion. Must also account for gullies, sediment delivery.
Braiding / incision thresholds	Hawley *et al.,* 2012	E/S	Is this stream currently near a threshold of abrupt change in terms of accelerated widening or downcutting and bank failures?	reach to segment	Can be embedded in susceptibility screening tools, quantitative channel evolution models, and regime diagrams. Choice of incision vs. braiding discriminator requires understanding of channel evolution and boundary conditions.	Geomorphic and hydraulic characteristics – channel slope, discharge(s), grain size, stream power.	Moderate if not extrapolated beyond calibration data	Applied within range of applicability with consideration of lateral vs. vertical susceptibility.

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Mechanistic (M) / Empirical-Statistical (E/S) (Continued)								
Regression-based channel enlargement models	Hawley and Bledsoe, In Review	E/S	How much might the cross-sectional area of a channel increase in response to an increase in watershed impervious area, a peak discharge, or cumulative erosion potential?	reach to segment	Provide a prediction of channel response that can be used in probabilistic modeling, provide a second line of evidence on relative channel response along with regime diagrams.	Watershed, geomorphic and hydraulic characteristics – channel slope, discharge(s), grain size, stream power, cumulative erosion potential.	Moderate if not extrapolated beyond calibration data	Applied within range of applicability, supported with other lines of evidence? Erosion potential-based models more physically-based than impervious-based models.
Regime diagrams	Chang, 1988; Parker, 1990; Haines, In Preparation	M, E/S	What is the equilibrium slope, width, and depth of a channel given a dominant discharge and inflowing sediment load? If channel-forming discharge and inflowing sediment load are altered, what is the new equilibrium channel slope, width, and/or depth in absolute terms or relative to a current equilibrium condition?	reach to segment	Provide a second line of evidence on relative channel response along with empirical enlargement models, and assessing relative sensitivity to changes in water and sediment delivery.	Channel-forming discharge, inflowing sediment concentration / load, boundary conditions including grain size, flow resistance.	Moderate to High depending on regional calibration	Typically provide maximum response of one channel dimension while other dimensions are not allowed to mutually adjust, brackets maximum response in a relative senses. Applied within range of applicability? Channel-forming discharge is poorly defined in many instances – regime diagrams may not be appropriate in such situations.
Effective discharge calculators	GeoTools	M, E/S	What range(s) of streamflow transport have the most capacity to transport sediment and influence channel form over periods of years to decades? What is the change in cumulative erosion potential associated with a change in the continuous series of streamflows? What is the time-integrated capacity to transport sediment relative to the capacity of an upstream supply reach?	reach to segment	Can help identify channel-forming discharge required by many channel response predictors (e.g., stable channel design calculators). Integrate continuous flow simulations from rainfall-runoff models, hydraulic model outputs, sediment-transport calculations to provide outputs like erosion potential that often form the basis of probabilistic models (e.g., logistic	Continuous streamflow data (15-min preferred for small watersheds in southern California), channel hydraulic geometry, grain sizes.	Moderate if not extrapolated beyond calibration data	Input flow series should be at least 10 and preferably 20 to 30 yrs of 15-min data. USACE (Biedenharn *et al*., 2000) provide standard procedures for bin selection and other decisions. Was appropriate sediment-transport relationship used (bedload vs. total load, range of calibration)? Were channel boundary materials accurately defined?

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Mechanistic (M) / Empirical-Statistical (E/S) (Continued)								
					and quantile regression, neural networks, Bayesian networks) of channel response.			
Sediment-transport / shear stress calculators	GeoTools, HEC-RAS, BAGS (Bedload Assessment for Gravel-bed Streams), San Diego tool	M, E/S	What is the estimated sediment-transport capacity of a stream at some discharge(s) of interest?	reach to segment	Provide an independent check on sediment-transport calculations performed by other software packages.	Channel hydraulic geometry, grain sizes, bed slope (uniform flow) or energy slope (varied flow).	Moderate to High depending on selection of appropriate relationship for local conditions	Was appropriate sediment-transport relationship used (bedload vs. total load, range of calibration)? Were channel boundary materials accurately defined? Were shear stresses or other hydraulic inputs generated using appropriate methods (e.g., see HEC-RAS above)? If single-event discharges are used, how are the full spectrum of transport events accounted for?
Stable channel design calculators	HEC-RAS, SAM, iSURF	M, E/S	What is the equilibrium slope, width, and depth of a channel given a dominant discharge and inflowing sediment load (or upstream supply reach characteristics)? If channel-forming discharge and inflowing sediment load are altered, what is the new equilibrium channel slope, width, and/or depth in absolute terms or relative to a current equilibrium condition?	reach to segment	Another way of expressing a regime diagram and assessing relative sensitivity to changes in water and sediment delivery. Facilitates examination of possible mutual adjustments in width, depth, and slope.	Channel-forming discharge, inflowing sediment concentration / load, boundary conditions including grain size, flow resistance.	Moderate to High depending on selection of appropriate relationship for local conditions	Was appropriate sediment-transport relationship used (bedload vs. total load, range of calibration)? Were channel boundary materials accurately defined? Were hydraulic geometry relationships or other hydraulic inputs generated using appropriate methods (e.g., see HEC-RAS above). If single-event discharges are used, how are the full spectrum of transport events accounted for? Channel-forming discharge is poorly defined in many instances - may not be appropriate in such situations.

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Mechanistic (M) / Empirical-Statistical (E/S) (Continued)								
Bank stability charts – regression of regional field data	Bledsoe *et al.*, 2012	E/S	Does this stream reach have banks that are close to a threshold of failure given its height and angle?	reach to segment	Can be embedded in susceptibility screening tools, quantitative channel evolution models, and regime diagrams. A much simplified empirical version of highly-detailed, mechanistic approaches like Bank Stability and Toe Erosion Model (BSTEM).	Field visit, bank height/angle, expertise in fluvial geomorphology.	Moderate to High depending on selection of appropriate relationship for local conditions	Requires consistency and expertise in fluvial geomorphology for adequate accuracy. Applied within range of applicability with consideration of lateral vs. vertical susceptibility.
Sediment budgeting tools	HEC-RAS - SIAM, Reid and Dunne, 1996		Given knowledge of streamflows and inflowing sediment loads, how do annualized sediment reach transport capacities compare to supplies? What are the locations of reaches of overall sediment surplus or deficit?		Can provide a network perspective on sediment imbalances that segment-scale approaches and mobile boundary models cannot. Does not translate changes into channel morphologic change like regime diagrams, stable channel design calculators and mobile boundary models.	Channel and structure geometry, flow resistance values, boundary conditions, and other parameters, flow-duration curves, sediment-supply data – source type (gully, surface, bank, U/S, and other), rate (tons/yr) and gradation.	High	Very difficult to define boundary conditions / inflowing sediment loads in southern California.
Bank stability / toe erosion models	USDA – BSTEM	M, E/S	How stable is this bank given its profile, stratigraphy, root reinforcement, drainage, scour, etc.?	sub-reach	Provides site-specific, physically-rigorous basis for predicting bank failures but more data and resource intensive than simplified field assessments.	Extensive parameterization required, e.g., geometric data, geotechnical properties, plant root properties, etc.	Moderate to High depending on availability of numerous input parameters	Meeting extensive input data requirements will rarely be feasible for hydromodification management.

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Mechanistic (M) / Empirical-Statistical (E/S) (Continued)								
Mobile boundary models	HEC-RAS, HEC-6T, CONCEPTS, FLUVIAL12	M, E/S	What degree of aggradation, degradation, and change in channel form is expected along this stream reach?	reach to segment	Provide greatest resolution in morphologic change at the expense of complexity and difficult parameterization.	Extensive parameterization required, e.g., geometric data, sediment gradation and channel boundary conditions, flow resistance, inflowing sediment loads, etc.	Very High	Generally not applicable to southern California streams given high prediction uncertainty due to flows near critical, split flow conditions, and lack of fidelity to complex widening, bank failure, and bed-armoring processes.

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Probabilistic (P) Models								
Logistic regression models of channel instability and enlargement	Palhegyi and Bicknell, 2004; Hawley and Bledsoe, In Review	P	What is the probability of channel instability (or some other undesirable state) given some change in streamflow / sediment-transport characteristics (e.g., erosion potential)? What is the probability of some level of channel enlargement given some increase in impervious-ness or erosion potential without mitigation? What is the uncertainty in a prediction of instability, enlargement of some other impact?	reach to segment	Integrates several of the models above (hydrologic, hydraulic, sediment transport) to predict likelihood of channel response based on process-based metrics that control erosion potential. More familiar and easier to understand than neural networks or Bayesian approaches.	Metric(s) of hydromodification impact and context (e.g., erosion potential) typically based on combination of channel geometry, continuous flow series, and channel boundary conditions (bed and bank materials).	Explicitly known, typically moderate with appropriate data	Perhaps most appropriate balance of physical detail and simplicity in application currently available. Several of the models described above supply input information; therefore, all the considerations and questions associated with those models apply to these integrative tools as well. Standard statistical diagnostics should be performed.

Tools / Models	Example(s)	Type	Question(s) Addressed	Scale	Relation to Other Tools	Data Requirements	Relative Uncertainty	Key Considerations / Questions in Appropriate Use[§]
Probabilistic (P) Models (Continued)								
Neural network models of channel enlargement	Sengupta *et al.,* In Review	P	What is the probability of some level of channel enlargement given some increase in imperviousness or erosion potential without mitigation? What is the uncertainty in a prediction of instability, enlargement of some other impact?	reach to segment	Integrates several of the models above (hydrologic, hydraulic, sediment transport) to predict likelihood of channel response based on process-based metrics that control erosion potential. Can handle many types of input data and complex interactions and non-linear responses.	Metric(s) of hydromodification impact and context (e.g., erosion potential) typically based on combination of channel geometry, continuous flow series, and channel boundary conditions (bed and bank materials).	Explicitly known, typically moderate with appropriate data	Appropriate balance of physical detail and simplicity in application currently available. Several of the models described above supply input information; therefore, all the considerations and questions associated with those models apply to these integrative tools as well. Somewhat more difficult to interpret than more familiar models like logistic regression.
Bayesian networks	Borsuk *et al.,* 2004; Stewart-Koster *et al.,* 2010; Shultz *et al.,* 2011	P	What is the probability of channel instability (or some other undesirable state) given some change in streamflow / sediment-transport characteristics (e.g., erosion potential)? What is the probability of some level of channel enlargement given some increase in impervious-ness or erosion potential without mitigation? What is the uncertainty in a prediction of instability, enlargement of some other impact?	reach to segment	Integrates several of the models above (hydrologic, hydraulic, sediment transport) to predict likelihood of channel response based on process-based metrics that control erosion potential. Combines many types of data and models along with expert judgment into a unified probabilistic framework. Prediction uncertainty is clearly expressed in outputs.	Metric(s) of hydromodification impact (e.g., erosion potential) typically based on combination of channel geometry, continuous flow series, and channel boundary conditions (bed and bank materials), can readily incorporate data from mechanistic models, categorical data, and expert judgment.	Explicitly known, typically moderate with appropriate data	Appropriate balance of physical detail and simplicity in application currently available. Several of the models described above supply input information; therefore, all the considerations and questions associated with those models apply to these integrative tools as well. Somewhat more difficult to interpret than more familiar models like logistic regression. Prior probabilities should be non-informative without clearly documented evidence from literature or formal elicitation process.

[§] Key considerations that control precision and accuracy for all models: 1) model structure, detail, resolution, and boundaries; and 2) calibration, validation, and extrapolation.

Managers must also attempt to ensure that the level of analysis of potential hydromodification impacts is commensurate with the risks associated with a particular decision. Rapid geomorphic assessments and screening tools like the one developed by SCCWRP and CSU assess the relative susceptibility of channels to hydromodification. Susceptibility is described in terms of lateral change (bank erosion, widening, shift to braiding) and vertical change (incision and enlargement) based on several physically-based risk factors. It follows that the risk factors leading to a particular susceptibility rating can inform the selection of additional models that can be used to perform a more rigorous assessment of susceptibility. Table 4 illustrates some hypothetical relationships between different combinations of lateral and vertical susceptibility ratings and models that are relevant to more in-depth modeling and analysis of potential channel response to hydromodification. It is important to recognize that the same susceptibility rating can result from different risk factors. For example, one channel may be rated high for lateral susceptibility due to proximity to a braiding threshold and another channel may be rated high due to unconsolidated materials in the bank toe. Thus, the screening ratings do not map directly to a specific set of models that are appropriate for a more in-depth analysis. Instead, it is recommended that managers focus on the risk factors (e.g., proximity to critical bank height and angle) that result in a particular rating and to choose supporting models that provide more resolution in understanding the processes associated with those specific risk factors. It is important to note that we are not including single-event hydrologic modeling in Table 4 because: 1) single-event modeling does not provide critical information on how altered flow frequencies and durations affect cumulative sediment transport capacity, and 2) the highly significant influence of time-integrated erosion potential in the statistical models focused on channel enlargement and instability as described above suggests that single event modeling does not produce sufficiently reliable predictions of future conditions.

Table 4. Matrix illustrating combinations of geomorphic modeling tools for each combination of V and L ratings.

Vertical (V) Rating	H	1,2,4,6,7,8	1,2, ,4,5,6,7,8,9	1,2,3,4,5,6,7,8,9,10,11
	M	1,2,4,6,7,8	1,2, ,4,5,6,7,8	1,2,4,5,6,7,8,9,10
	L	1,2,3	1,2,3,5	1,2,3,5,9,10
		L	M	H
		Lateral (L) Rating		

L Low
M Medium
H High

1. Continuous hydrologic simulation
2. Regional regressions – hydrology
3. Shear stress threshold modeling bed and/or bank
4. Detailed incision threshold models
5. Detailed braiding threshold models
6. Regime diagrams / Copeland method in HEC-RAS
7. Channel enlargement models
8. Erosion potential / CSR with continuous simulation

9..Bank stability models – Osman / Thorne, BSTEM, RootRIP, Iowa bore hole

10. Jet testing
11. Sediment Impact and Assessment Model – SIAM in HEC-RAS

2.4 Combining Tools for Hydromodification Management

This section provides a discussion of four example "suites of tools" that can be used to perform predictive scientific assessments and address specific questions related to hydromodification assessment and management. The suites are changeable mixes of mechanistic models, statistical analyses, and expert scientific judgment that incorporates a number of the tools discussed above, combined in various ways. For example, some suites apply a series of cascading models, in which the output from one is used as input to the next; other suites apply a number of models in parallel to develop an assessment based on the weight of evidence. The suites of tools discussed below are used to perform a baseline stability assessment, a channel-forming discharge analysis, an erosion potential analysis, and a sediment-transport analysis. Most of these standard tools (with the exception of the erosion potential suite) have been widely employed in a variety of stream management activities for decades, and are considered essential components of the broader fluvial geomorphology toolbox. This is far from a comprehensive list of tools, as there are many other important tools (focused on both geomorphic and biologic endpoints) relevant to hydromodification management (Kondolf and Piégay, 2003; Poff *et al*., 2010); however, the purpose of this section is to briefly illustrate how several standard tools can be integrated to answer key questions about stream responses and to provide a stronger technical basis for hydromodification management.

Application of these tools provides basic geomorphic data and knowledge that are typically needed to manage a stream for some desired future state in a watershed with changing land uses. This critical information comes at a cost—the tools require substantially more time and effort to apply than has been the norm in hydromodification management because they involve examining streams within their watershed context with a deeper level of geomorphic analysis. Stormwater management programs typically have made the "practical" assumptions that stream reaches can be managed in isolation from the larger systems of which they are a part, and that effective management prescriptions can be formulated with little or no substantive geomorphic analysis. These assumptions are in direct conflict with current understanding in fluvial geomorphology and stream ecology, which indicates that protection of stream integrity is often predicated upon careful assessments of geologic and historical context, performing detailed hydraulic and sedimentation analyses where appropriate, and developing basic understanding of streamflow-ecology linkages. If hydromodification management policies are to have a reasonable chance of actually achieving their aims, then it will most likely be necessary to reject these simplifying assumptions and instead rely on approaches rooted in current scientific understanding of stream systems.

> "This critical information comes at a cost—the tools require substantially more time and effort to apply than has been the norm in hydromodification management because they involve examining streams within their watershed context with a deeper level of geomorphic analysis."

The suites of tools described below go beyond screening-level assessments that are designed, in part, to identify which streams lend themselves to relatively-straightforward management prescriptions vs. the streams that do not. For streams that do not lend themselves to generic management prescriptions, the level of analysis performed with these tools should increase with the level of risk and geomorphic / biologic susceptibility of the streams. This does not mean that every stream will require in-depth analysis by local permitting agencies. It is not possible to carry out sufficient geomorphic analyses with the tools illustrated below on a permit-by-permit basis, and local governments may lack the resources and/or technical capacity to effectively apply these tools. Instead, the vital information provided by these tools will need to be obtained through proactive regional studies that involve watershed-scale baseline assessments followed by progressively more in-depth analyses as necessary to provide local governments with a sound basis for effective project-by-project decision-making within a broader watershed management framework.

1. **Baseline Stability Assessment**. This suite of tools is designed to answer the following key questions:
   - What is the trajectory of the stream's form over time?
   - How has the channel form responded to changes in water and sediment supply over the years?
   - Is the channel close to a geomorphic threshold that could result in rapid, significant change in response to only minor flow alteration?
   - How can past channel responses provide insight into potential responses to future watershed change, and so aid in prediction of future hydromodification-induced changes?
   - What level of subsequent geomorphic analysis is appropriate given the complexity of the situation and the susceptibility of the streams of interest?

   The goals of a baseline stability assessment are to:
   - Document the historical trends of the system;
   - Establish the present stability status of the system and identify the dominant processes and features within the system;
   - Provide the foundation for projecting future trends with and without proposed project features;
   - Provide critical data for calibration and proper interpretation of models; and
   - Provide a rational basis for identification and design of effective alternatives to meet project goals.

   The key tools that comprise this suite include:
   - GIS mapping of topography, soils, geology, land use / land cover across the contributing watershed (e.g., Thorne, 2002);
   - Analysis of hydro-climatic data, e.g., streamflow gage records, changes in stage-discharge relationships over time (e.g., Thorne, 2002);
   - Analysis of aerial photographs and historical data (e.g., Thorne, 2002);
   - Field reconnaissance (e.g., Thorne, 1998);
   - Qualitative response (e.g., Lane, 1955b; Schumm, 1969; and Henderson, 1966 relations)
   - Classification systems (e.g., Thorne (1997); Schumm (1977); and CEM developed for southern California by Hawley *et al.,* 2012);
   - Relationships between sediment transport and hydraulic variables;
   - Regional hydraulic geometry (e.g., Hawley, 2009) and Haines, In Preparation);

- Regional planform and stability predictors (e.g., Hawley *et al.,* 2012; Bledsoe *et al.,* 2012; and Dust and Wohl, 2010);
- Bank stability analysis (e.g., BSTEM http://www.ars.usda.gov/Research/docs.htm? docid=5044, Hawley, 2009); Bledsoe *et al.,* In Press; Osman and Thorne, 1988; and Thorne *et al.,* 1998);
- Sediment budgets (Booth *et al*., 2010; Reid and Dunne, 1996); and
- Fluvial audit (Thorne, 2002) – a comprehensive framework for performing baseline assessments).

A baseline assessment is completed by integrating information from all the available data sources and analytical tools. Analysis with each of the individual tools may yield a verdict of aggradation, degradation, or dynamic equilibrium with respect to the channel bed, and stable or unstable with respect to the banks. The individual assessments can produce contradictory results. In this case, one should assign a level of confidence to the various components based on the reliability and availability of the data, and the analyst's own experience level. As is often the case in the management of fluvial systems, there is no "cookbook" answer, and we must always incorporate sound judgment.

2. **Channel-forming discharge suite of tools.** This suite of tools is designed to answer the following key questions:
   - What ranges of discharges are most influential in controlling channel form and processes over decadal time scales?
   - What channel-forming discharges should be used in sediment-transport analyses to identify sediment-transport capacity, equilibrium slope and geometry, etc.?

   The tools that comprise this suite include the following:
   - Effective discharge computations (e.g., Soar and Thorne, 2001); Biedenharn *et al.,* 2000; GeoTools – Bledsoe *et al.,* 2007) – an effective discharge analysis directly quantifies the range of discharges that transport the largest portion of the annual sediment yield over a period of many years;
   - Field identification of high water elevations, depositional surfaces, and "bankfull" features;
   - Flood frequency analysis; and
   - Un-gaged site analysis (e.g., USGS StreamStats, http://water.usgs.gov/osw/streamstats/california.html; Hawley and Bledsoe, 2011, regional flow-duration curve extrapolation – Biedenharn *et al.,* 2000).

This suite incorporates a number of parallel analyses that can be used to establish likely upper and lower bounds to the range of influential discharges, and that can be assessed through a weight-of-evidence evaluation. Figure 17 is an example output from the channel-forming discharge suite of tools.

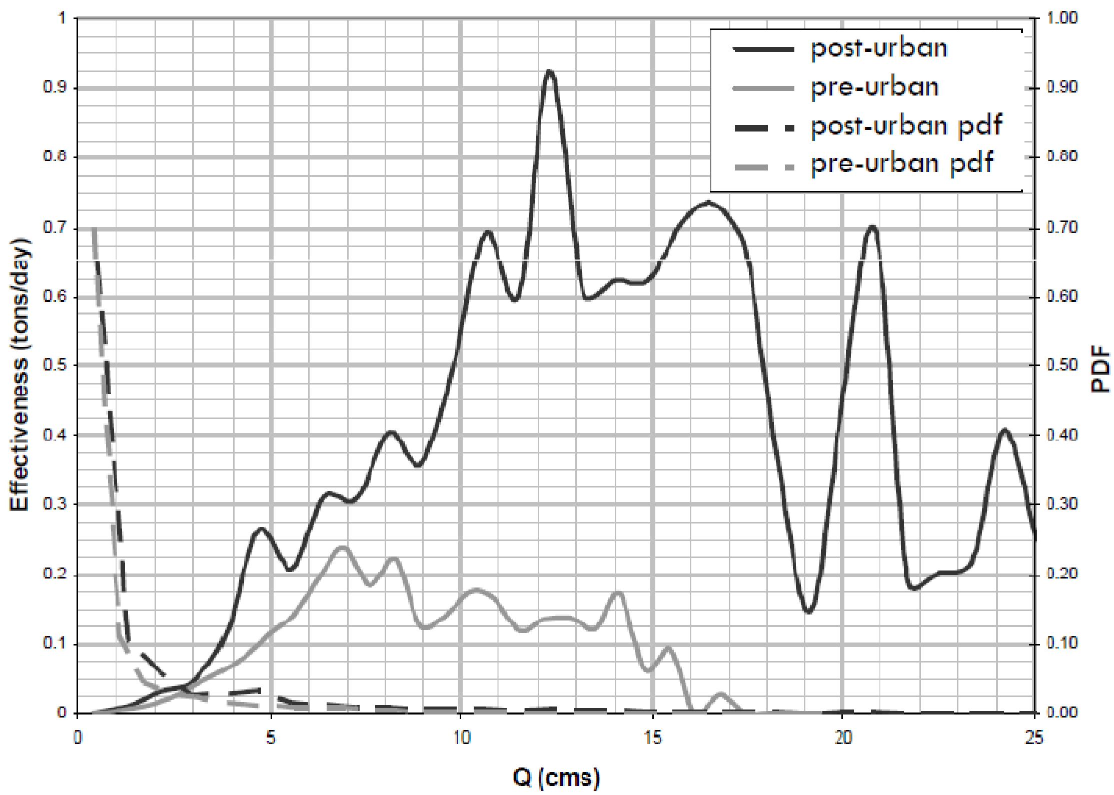

Figure 17. Flow effectiveness curves for continuous series of pre-urban and post-urban discharges (Biedenharn *et al*., 2000; Bledsoe *et al*., 2007). Cumulative sediment yield is approximated by the area under the respective curves. If the stream bed is the most erodible channel boundary, the ratio of areas under these curves would be the erosion potential metric described below in the next suite of tools.

3. **Erosion potential suite of tools.** This suite of tools is designed to answer the following key questions:
   - How do proposed land use changes or channel alteration affect the capacity of a channel to transport the *most erodible material in its boundary* over a period of many years (erosion potential – Ep)?
   - Do proposed mitigation approaches match the pre- vs. post-development erosion potential over the full spectrum of erosive flows?
   - Do past changes in erosion potential correspond to different states of channel stability and degradation in this region?
   - Does a proposed change in streamflow make it more likely that a channel will enter an alternative / degraded state?

The underlying premise of the erosion potential approach advances the concept of flow-duration control (discussed in Chapters 2 and 3 of Technical Report #667 *Hydromodification Assessment and Management in California* (Stein *et al*., 2012)) by addressing in-stream processes related to sediment transport. An erosion potential calculation combines flow parameters with stream geometry to assess long-term (decadal) changes in the sediment-transport capacity. The cumulative distribution of shear stress, specific stream power, and sediment-transport capacity across the entire range of relevant flows can be calculated and expressed using an erosion potential metric, Ep (e.g., Bledsoe, 2002). This erosion potential metric is a simple ratio of post- vs. pre-development sediment-transport capacity over a period of many years. The calculated capacity to transport sediment can be based on the channel bed material or the bank material, depending on which one is more erodible.

This Ep suite of tools has been applied in two primary ways:

1. At a project-level analysis, it has been applied to answer the first two questions above. A municipal stormwater permit may require a project design to achieve an erosion potential (Ep) value of 1.0. This means that a project must be designed so that the long-term erosion potential of the site's stormwater discharge is equal to the erosion potential of the pre-development condition. Item 3.1 below explains the process by which this analysis is conducted.
2. At a regional level, this suite of tools can be applied to answer the third and fourth questions above and to provide further guidance to project-level assessments. For example, practical engineering considerations generally require that a tolerance be permitted around a target design value. It is unlikely that a project design can match an Ep target of 1.0 across all conditions and through all stream reaches, due to variations in a multitude of contributing factors. The selection of an acceptable tolerance or variance from 1.0 is a management decision that should be informed by regional data presented in a risk-based format. Item 3.2 below explains how such a study has been conducted, using the Santa Clara Valley example from northern California.

2.4.1 Project-level Analysis.

As applied to the analysis of project impacts and mitigation design, the steps and associated tools that comprise this suite include the following (Figure 18):

- Perform continuous simulation of hydrology (e.g., SWMM, HEC-HMS, HSPF) for the project site, for both pre-project condition and post-project condition with the proposed mitigation design.
- Convert discharges and field surveys to hydraulic parameters (shear stress and specific stream power) – e.g., for uniform flow analysis use Manning's equation, GeoTools; for varied flow analysis use HEC-RAS.
- Convert hydraulic parameters into sediment-transport capacity – e.g., at-a-station hydraulic geometry, HEC-RAS, GeoTools, sediment-transport relationships (bedload and total load).
- Integrate Ep over time – e.g., GeoToolsCompare Ep values for pre-development and post-development to determine if the proposed mitigation design is adequate. Adjust stormwater controls as necessary to meet target Ep.

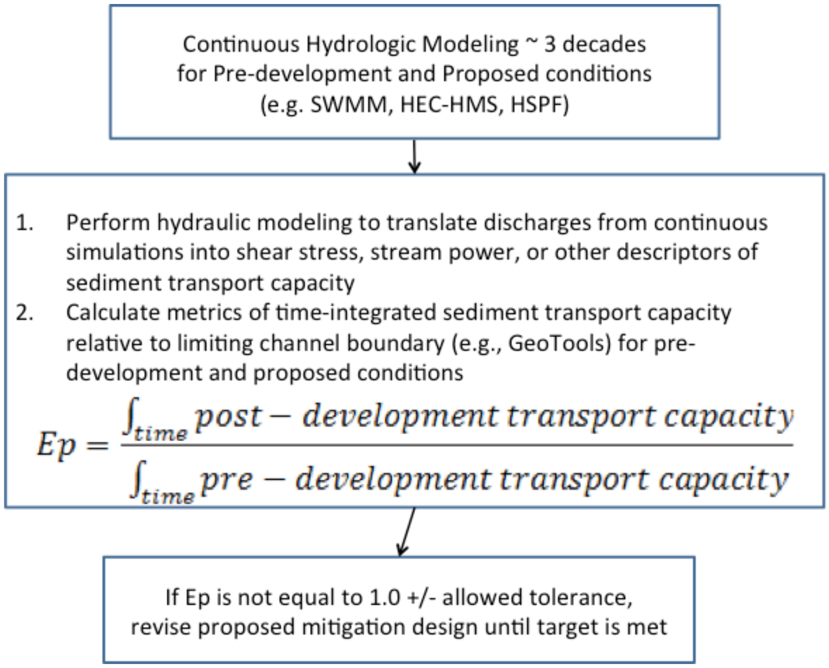

Figure 18. Steps involved in a project-level erosion potential analysis.

2.4.2 Risk-based Regional Analysis.

Risk-based modeling estimates the probability of stream geomorphic states. Decision-makers can then choose acceptable risk levels based on an explicit estimate of prediction error. The foundation of risk-based modeling in the context of hydromodification management is the integration of hydrologic and geomorphic data derived from the output of continuous hydrologic simulation models to generate metrics describing expected departures in the most important stream processes. These physical metrics are provided as inputs to probabilistic models that estimate the risk of streams shifting to some undesirable state. Because the decision endpoint is often categorical (e.g., stable, good habitat) the statistical tools of choice are often logistic regression, classification and regression trees (CART), and/or Bayesian probability networks.

The steps below are used to develop a risk-based framework (Figure 19) for assessing how hydromodification may impact streams within a region, and for understanding the relationships between Ep and the likelihood of channel instability. Both Figure 15 described above and the probabilistic approach that was used in the development of the Santa Clara Valley Urban Runoff Program Hydromodification Management Plan (http://www.SCVURPPP.org) demonstrate that a time-integrated index of erosion potential based on continuous hydrologic simulation and an assessment of stream power relative to the erodibility of channel boundary materials can be used to distinguish between channels of a particular regional type that are stable vs. degraded by hydromodification in urban watersheds. For example, as erosion potential increases from 0.7 to 1.5, the risk of channel instability (vertical axis) increases nonlinearly (Figure 15). The overall steps include:

- Perform project-level analysis as described above for existing developments throughout the study watersheds.
- Perform stream surveys throughout the study watersheds to characterize condition (i.e., stable, unstable).
- Create statistical relationships between Ep and different channel states – e.g., logistic regression in R, SAS, Statistica, Minitab, etc. Note that standard regression techniques are applied when the dependent variable and the explanatory variables are quantitative and continuous. To analyze a binary qualitative variable (e.g., 0 or 1, stable or unstable, healthy or degraded) as a function of a number of explanatory variables, alternative techniques must be used. The regression problem may be revised so that, rather than predicting a binary variable, the regression model predicts a continuous probability of the binary variable that stays within 0–1 bounds. One of the most common regression models that accomplishes this is the logit or logistic regression model (Menard, 1995; Christensen, 1997).

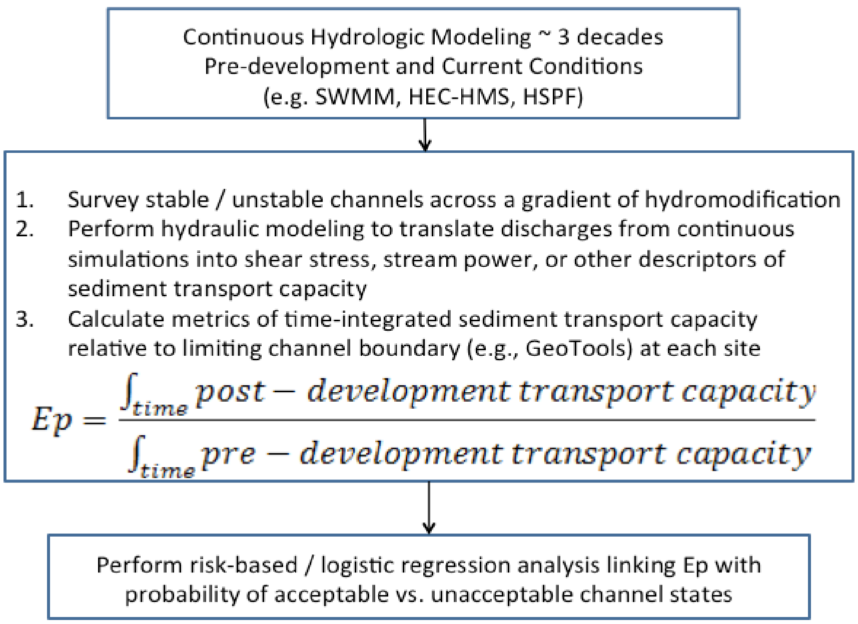

Figure 19. Steps involved in a risk-based erosion potential analysis.

The variables included in risk-based models of stream response are not limited to erosion potential. Additional multi-scale controls could be included. For example, simple categories of physical habitat condition and ecological integrity could be predicted by augmenting erosion potential metrics with descriptors of the condition of channel banks and riparian zones, geologic influences, floodplain connectedness, hydrologic metrics describing flashiness, proximity to known thresholds of planform change, and BMP types. Furthermore, although most of the emphasis to date has been on predicting geomorphic endpoints, the risk-based approach can be extended to the prediction of biological states in urban streams if the necessary data are available.

2.4.3 Strengths and Limitations

The erosion potential approach combines a sound physical basis with probabilistic outputs and requires a substantial modeling effort. Such an effort is necessary to adequately characterize the effects of hydromodification on the stability of streams that are not armored with very coarse material such as large cobbles and boulders. Although policies based on this approach should reduce impacts to channel morphology, they may still fail to protect stream functions and biota. Key simplifying assumptions and prediction uncertainty in the inputs (hydrologic modeling, assumptions of static channel geometry in developing long-term series of shear stresses or stream powers, critical assumptions of stationarity in sediment supply, etc.) have not been rigorously addressed. Its effectiveness also depends on careful stratification of streams in a region such that fundamentally-different stream types are not lumped together (e.g., labile sand channels vs. armored threshold channels with grade control) in developing general relationships for instability risk. Endpoints to date have been rather coarse, e.g., stable vs. unstable; as such, they do not provide a desirable level of resolution for envisioning future stream states. Nevertheless, the erosion potential approach is an important tool in the hydromodification management toolbox. It is recommended that this approach be refined to address sediment-supply changes and to provide more finely resolved endpoints for improved predictive capabilities and management utility.

2.4.4 Sediment-transport Analysis Suite of Tools

This suite of tools is designed to answer the following questions:

- Do I need to incorporate sediment-transport analysis in predicting channel response to hydromodification, i.e., what is the sensitivity of channel slope and geometry to inflowing sediment load?
- At what discharges are different fractions of bed material mobilized in a particular stream segment?
- What is inflowing sediment load to a stream segment, i.e., what is the water discharge Q(t) and sediment-supply rate Q_s(t), and grain size D(t) delivered to the upstream end of the channel segment of interest?
- How will the available flow move the supplied sediment through the segment of interest?
- What is the new equilibrium slope given some change in streamflow, and how much incision would be necessary to achieve this new slope?
- What is the sediment-transport capacity of the segment of interest *relative to* the inflowing sediment load from *upstream* supply reaches?
- What is the sediment-transport capacity of the segment of interest *relative to* the capacity of *downstream* reaches?
- At the network scale, where are zones of low vs. high energy, aggradation vs. degradation potential, and coarse sediment constriction located?

The primary tools that comprise this suite include the following:

- Tools for estimating watershed sediment supply (Reid and Dunne, 1996), including the RUSLE (Renard *et al.,* 1997); http://www.ars.usda.gov/Research/docs.htm?docid=5971) and WEPP (Laflen *et al.,* 1991); http://www.ars.usda.gov/Research/docs.htm? docid=10621) models;
- Effective discharge analysis (see above);
- Incipient motion analysis (tractive force, e.g., ASCE, 2008; Brown and Caldwell, 2011; Buffington and Montgomery, 1997; and Lane, 1955a);
- Regime diagrams that provide relative and absolute predictions of channel dimensions and slope in response to altered discharges of water and sediment (this project)
- Sediment continuity analysis at single dominant discharge with an appropriate sediment-transport relation – e.g., HEC-RAS, Bedload Assessment for Gravel-bed Streams (BAGS – Pitlick *et al.,* 2009); GeoTools);
- Equilibrium slope / geometry analysis, e.g., HEC-RAS – Copeland *et al.* (2001) and iSURF – National Center for Earth-Surface Dynamics (NCED, 2011);
- Sensitivity to inflowing sediment load analysis, e.g., Copeland's method in HEC-RAS and iSURF – NCED (2011);
- Sediment continuity analysis over the entire flow frequency distribution, e.g., Capacity-Supply Ratio of Soar and Thorne (2001), BAGS, GeoTools; and
- Network-scale sediment balance – Sediment Impact Analysis Methods (SIAM) module in HEC-RAS.

Figures 20 and 21 depict example outputs from an application of the sediment-transport suite of tools.

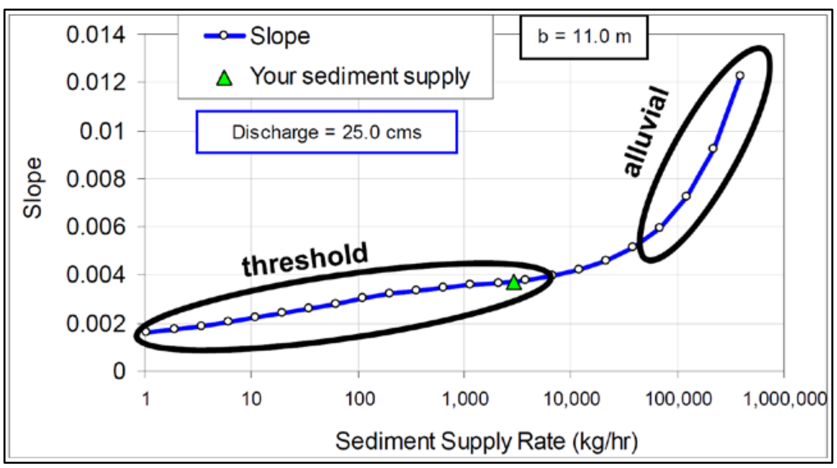

Figure 20. Sensitivity analysis of equilibrium channel slope to inflowing sediment load (from iSURF (NCED, 2011)). Slopes of alluvial channels with high sediment supply are much more sensitive than threshold channels with relatively low sediment supply. Channels with beds composed of sand and fine gravels are generally much more geomorphically sensitive to hydromodification than threshold channels in which coarse-bed sediments are primarily transported at relatively high flows. In the case of the green triangle, this analysis indicates that the slope of the channel in question is relatively insensitive to changes in inflowing sediment load compared to more labile alluvial channels that are adjusted to high sediment supplies.

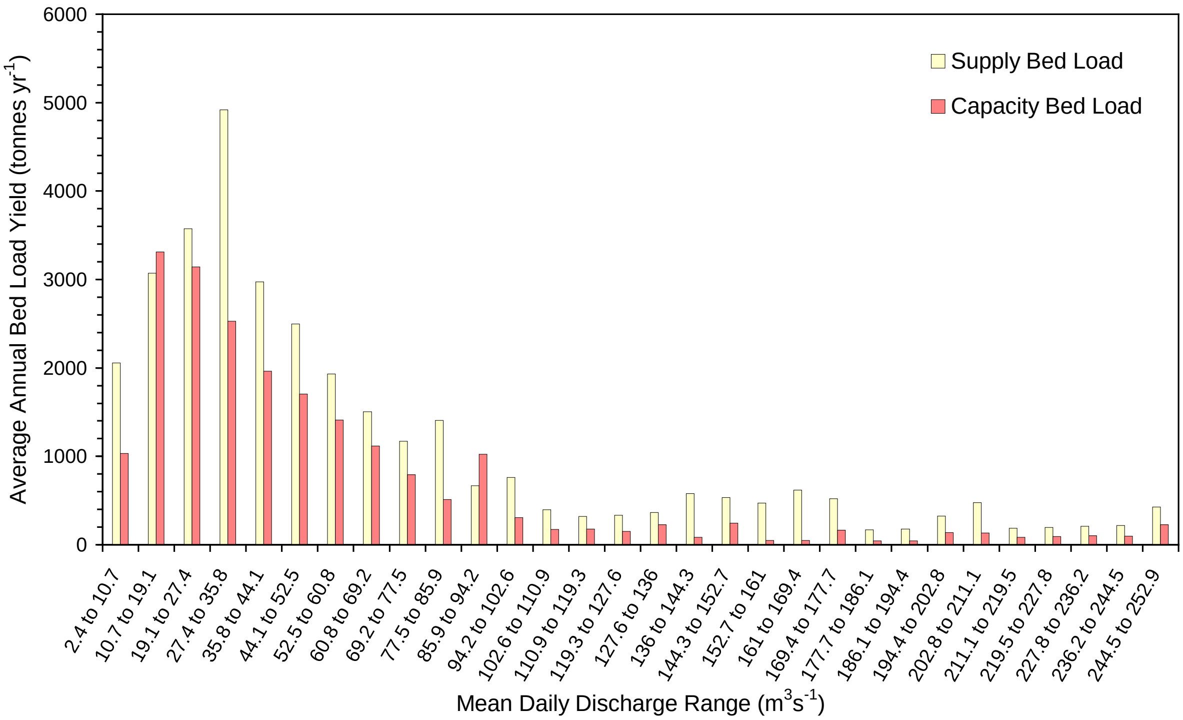

Figure 21. Analysis of sediment-transport capacity vs. inflowing sediment load over the full spectrum of stream discharges (capacity-supply ratio; Soar and Thorne (2001)). In this case, the time-integrated capacity to transport bedload is 64% of the supplied bedload and significant aggradation is expected.

2.4.5 Relationship to Management Framework

These suites of tools could be applied to establish project-specific requirements for hydromodification assessment and mitigation. In the example shown in the diagram below (Figure 22), results of the Baseline Assessment are used to assign risk levels for stream reaches, in conjunction with the proposed land use changes. Thus, the Baseline Assessment suite of tools is used in determining whether a detailed survey-level assessment and additional suites of tools are necessary for an adequate analysis. The need to apply additional suites of tools in formulating a management approach is commensurate with the level of risk and susceptibility of the stream. More complex and rigorous analysis with multiple suites of tools is necessary in predictive assessments for relatively susceptible stream types such as alluvial channels with sand beds.

Although a stream may have relatively low susceptibility for overall geomorphic change, it may nevertheless have ecological attributes that are highly susceptible to hydromodification. Thus, suites of tools (Figure 22) focused on both geomorphic and biological endpoints should be used to fully assess stream susceptibility to hydromodification. More work will be required to develop tools for prediction of biological response to flow alterations throughout California (see Poff *et al.,* 2010) and http://conserveonline.org/workspaces/eloha).

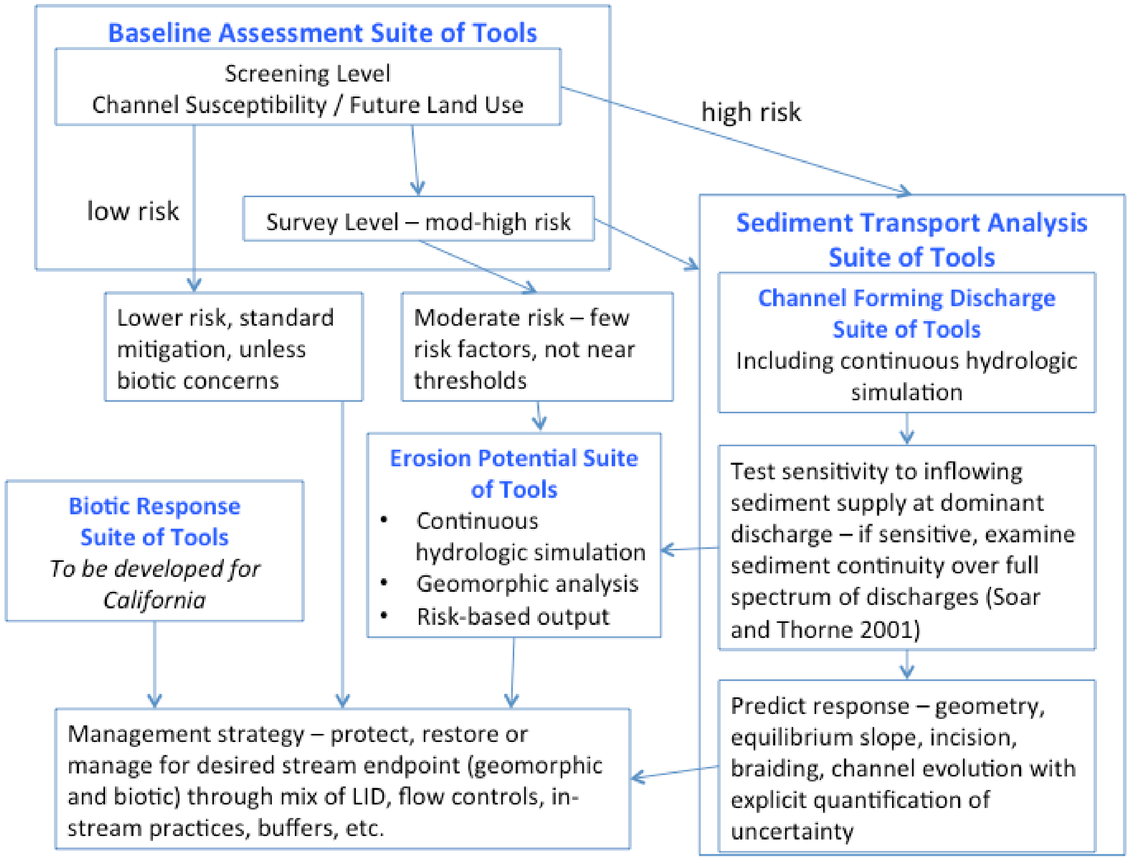

Figure 22. Conceptual diagram showing relationships among the four suites of existing tools and biotic response tools to be developed in the future. Additional analyses will be required for engineering design.

2.5 Available Tools Conclusions

This project has developed several new modeling tools to support hydromodification management in southern California, including hydrologic tools for prediction in ungauged basins, analytical regime diagrams, channel enlargement models based on regression and ANNs, and an updated version of the GeoTools package.

These tools, in combination with existing tools, have the potential to advance hydromodification management by:

- Providing a physical basis for making predictions of stream response to watershed development.
- Assessing alternative future states of streams under different management scenarios.
- Avoiding one-size-fits-all solutions through:
  - o improved prediction of relative magnitude of potential channel change and proximity to response thresholds; and
  - o tailoring mitigation strategies to streams with different levels of susceptibility.

Statistical models developed in this study indicate that channel enlargement is highly dependent on the ratio of post- to pre-urban sediment-transport capacity over cumulative duration simulations of 25 years (load ratio, a.k.a. erosion potential), which explained nearly 60% of the variance in channel response. Neural network models developed in this study indicated that estimated increases in Q_2 based on regional flood regression equations (Hawley and Bledsoe, 2011) consistently ranked as the most important predictor of channel enlargement despite the inclusion of a large pool of watershed and geomorphic descriptors at various spatial scales. Thus, the enlargement models point to the importance of balancing the post-development sediment transport to the pre-development setting over an entire range of flows rather than a single flow in order to reduce the risk of adverse channel responses to hydromodification.

We also evaluated the potential applicability of various movable bed and/or boundary models to predicting channel response to hydromodification in southern California. These tests indicated that mobile boundary hydraulic models are difficult to apply and have high prediction uncertainty due to flows near critical, split flow conditions, and lack of fidelity to complex widening, bank failure, and bed-armoring processes.

The tools developed in this project have a clear physical basis; however, their efficacy for predicting the effects of hydromodification has not been demonstrated. As such, there is a pressing need for monitoring data to test and improve models. There is also an ongoing need to better define predictive scientific assessments (changeable mixes of mechanistic models, statistical analyses, and expert scientific judgment) that are most appropriate for answering hydromodification management questions. The mechanistic models included in such assessments should account for hydraulic characteristics through physically-based metrics like load ratio / erosion potential, as opposed to arbitrary thresholds of discharge. By converting discharge values into hydraulic variables (common choices are shear stress or stream power per unit area of channel relative to bed sediment size), a “common currency” for managing erosion and associated effects can be established and applied across many streams in a region. Assessments of potential stream responses to management decisions should also account for the dominant watershed processes and features within the broader system that constrain future geomorphic potential (and although not emphasized in this study, ecological potential). This critical information comes at a cost—the tools require substantially more time and effort to apply than has been the norm in hydromodification management because they involve examining streams within their watershed context with a deeper level of geomorphic analysis.

Given the uncertainty associated with predicting hydromodification impacts, probabilistic models should be incorporated into analysis and design, particularly where resource values or potential consequences of impacts are high. Probabilistic modeling of urbanizing streams provides a more scientifically-defensible alternative to standardization of stormwater controls across all stream types, and can inform management decisions about acceptable levels of risk. Explicit consideration, quantification, and gradual reduction of model uncertainty will be necessary to advance hydromodification management. Thus, there is a need to develop probabilistic modeling approaches that can be updated and refined as knowledge increases over time. Such approaches must be amenable to categorical inputs and outputs, as well as combining data from a mix of sources including mechanistic hydrology models, statistical models based on field surveys of stream characteristics, and expert judgment. Although valuable, deterministic representations (such as those derived from continuous simulation modeling) of processes and responses can mask uncertainties and be misleadingly precise unless prediction uncertainty is explicitly characterized. Ultimately, the focus of scientific study in support of decision-making should be on the decisions (or objectives) associated with the resource and not on building more-detailed models with the hope that they will provide the answers that elude us.

The uncertainty inherent to hydromodification modeling also underscores the need for carefully designed monitoring and adaptive management programs. Emphasis should be placed on building an empirical basis for these tools through effective monitoring.

3.0 DECISION-MAKING APPROACH

Managing effects of hydromodification is the culmination of all preceding analysis (Figure 23). It entails efforts to remedy existing/past impacts as well as prevent or minimize the potential for future impacts. Hydromodification results from a complex set of processes over long-periods of time; therefore, a suite of management approaches will often be necessary to address the effects. The ultimate management prescription should also account for existing and future constraints in the watershed that may limit the ability to apply certain approaches (e.g., existing development and channelization). As with all other sets of technical recommendations, the guidelines and recommendations provided below are intended to provide resources to guide location-specific decisions rather than prescriptive approaches to be universally applied in all situations.

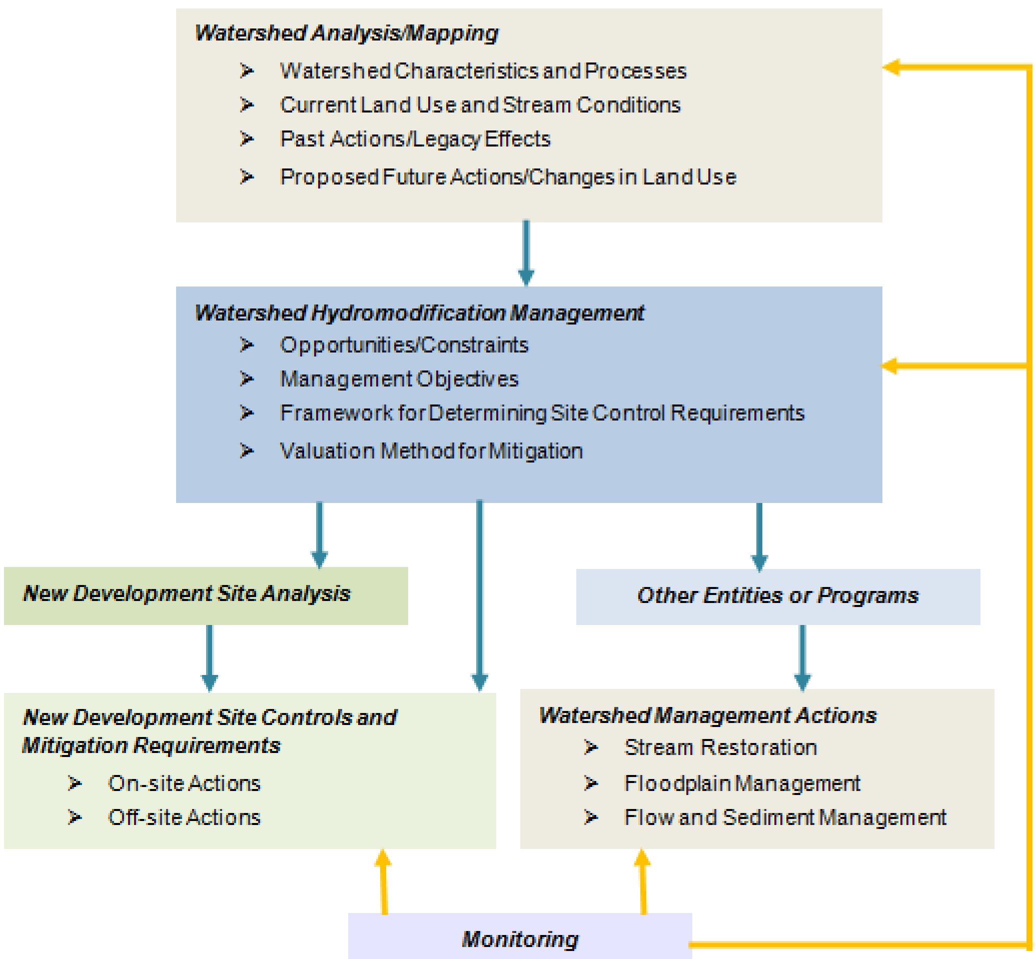

Figure 23. Framework for integrated hydromodification management

3.1 General Guidelines for Hydromodification Management

Hydromodification management plans should be developed around the following general principles:

- Hydromodification management needs to occur primarily at the watershed scale. The foundation of any hydromodification management approach should be an analysis of existing and proposed future land uses and stream conditions that identifies the relative risks, opportunities, and constraints of various portions of the watershed. Site-based control measures should be determined in the context of this analysis.
- Clear objectives should be established to guide management actions. These objectives should articulate desired and reasonable physical and biological conditions for various reaches or portions of the watershed. Management strategies should be customized based on consideration of current and expected future channel and watershed conditions. A one-size-fits-all approach should be avoided.
- An effective management program will likely include combinations of on-site measures (e.g., low-impact development techniques), in-stream measures (e.g., stream habitat restoration), and off-site measures. Off-site measures may include compensatory mitigation measures at upstream locations that are designed to help restore and manage flow and sediment yield in the watershed.
- Hydromodification control measures cannot be driven solely by new development and redevelopment, legacy effects should be remedied in order to restore watershed processes. This also means that management strategies will need to acknowledge pre-existing impacts associated with historical land uses. Restoration goals should be set in the context of existing and anticipated future constraints. This will allow for development of a reasonable set of expectations and restoration targets.
- Management measures should be informed and adapted based on monitoring data. Similarly, monitoring programs should be designed to answer questions and test hypotheses that are implicit in the choice of management measures, such that measures that prove effective can be emphasized in the future (and those that prove ineffective can be redirected).
- Hydromodification potentially affects all downstream receiving waters. For example, bays, harbors, and estuaries may be affected by excessive sediment input. These waterbody types should be considered in the development of hydromodification management plans and accounted for when developing watershed goals and objectives.

In many cases, relying solely on site-based flow control will not be wholly effective at addressing all hydromodification effects, particularly those associated with effects of past land-use practices. Management approaches should shift from a stream centered view of controlling erosion, deposition, and planform change to focus on restoring watershed processes that ensure movement of water and sediment in ways that help maintain the dynamic equilibrium of stream channels:

- <u>Coarse sediment-supply areas should be protected and restored</u> – Coarse sediments, such as larger sands, gravels, and cobbles can erode from hillslopes around streams via a variety of processes including dry ravel, erosion, and via overland runoff. Once in the stream, coarse materials play a substantial role at maintaining equilibrium of work within the channel and reducing the erosive energy of flow on channel bed and banks. Maintaining these supplies is critical to long-term dynamic stability of stream channels.

- <u>Coupling between sediment supply and transport reaches should be maintained or restored</u> – Land use practices, such as housing, roads, and basins often intentionally or unintentionally disrupt or intercept the movement of sediment from hillslopes to floodplains and channels. For coarse sediment to be effective at helping to protect streams from hydromodification, the connection (or coupling) between hillslopes and floodplains must be maintained (or restored).
- <u>Sediment-transport capacity should be maintained</u> – Functioning stream systems facilitate movement of sediment from source areas to downstream areas of deposition that support habitat and encourage channel processes that reduce energy (e.g., meandering, multi-thread flow). The transport function of reaches that typically occur in the middle portions of watersheds should be maintained, managed, and restored (if necessary).
- <u>Floodplain connections should be protected and restored</u> – Floodplains perform a range of hydrologic and ecological functions. In middle- and higher-order streams in low-gradient settings, they are important areas of energy dissipation which function to help protect downstream areas from hydromodification. Maintaining connections between streams and their floodplains allows higher flows to readily access wide overbank areas which slow water and reduce energy.

Example areas that could be managed for each of the functions described above are shown in Figure 24. This more-integrative approach will require creation of mechanisms for placing management resources in the most appropriate portion of the watershed, which may not be at the specific project site being evaluated by a particular regulatory action (e.g., off-site mitigation, fee-based management programs).

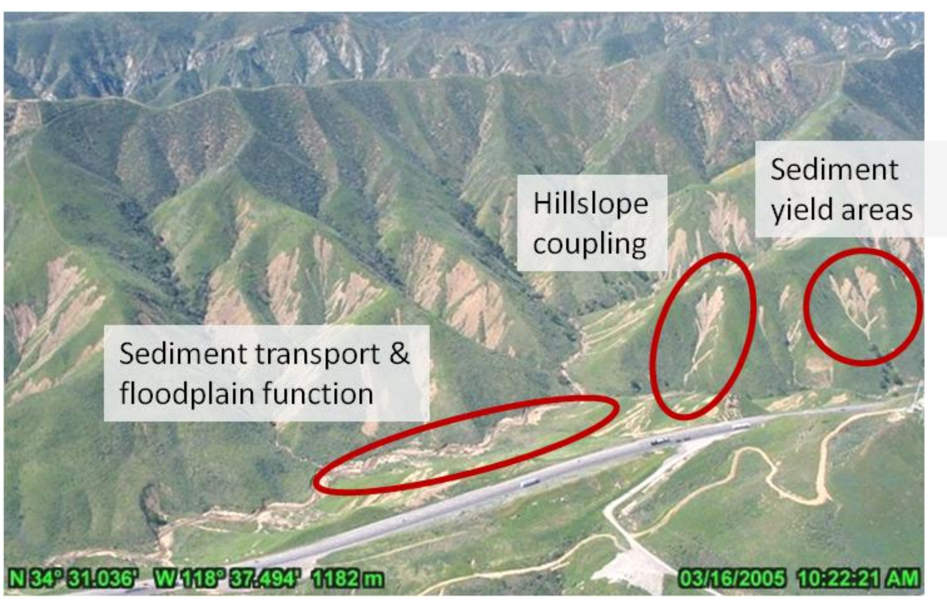

Figure 24. Example areas within a watershed where individual process-based management actions may occur.

3.2 Watershed Analysis

Watershed analysis should be the foundation of all hydromodification management plans. Analysis should identify the nature and distribution of key watershed processes, existing opportunities and constraints in order to help prioritize areas of greater vs. lesser concern.

A general objective should be to identify watershed management zones based on key watershed processes and opportunities (e.g., infiltration, sediment yield). For most watersheds, they can be roughly divided into sediment source areas, transport reaches, and deposition/storage areas (Figure 25).

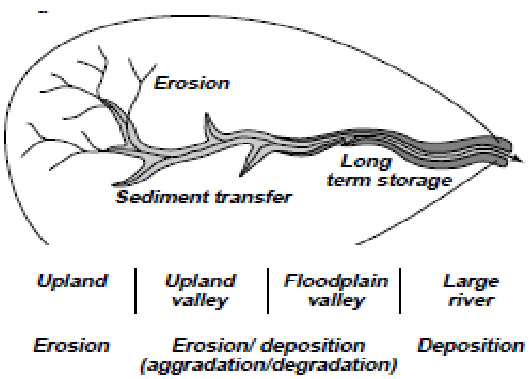

Figure 25. Conceptual functional zones of an idealized watershed (Church, 2002).

Within these general zones, priority activities should be based on a comprehensive watershed analysis. The overall objective of the mapping is to identify major opportunities, such as floodplain protection or restoration, in-stream restoration, protection of sediment-supply areas and major constraints, such as sensitive resources, infrastructure, impending headcuts or other catastrophic channel response.

Watershed analysis can occur at a variety of scales depending on available information and management objectives. In general, *analysis at a hydrologic unit code (HUC) 10 or HUC 12 watershed* provides a balance between analytical complexity and availability of management options. This scale will often translate to the size of tributary watershed upstream of major named rivers. Watershed analysis can also occur at a variety of levels of detail and resolution. Simple analyses that rely on readily available data layers such as stream and wetland maps, land use, existing infrastructure, geology, and slope can provide a valuable starting point for guiding management decisions. These initial maps can be augmented and expanded based on needs as additional information and resources become available.

Watershed analysis can occur at variety of scales and resolutions depending on management needs and available resources.

Mapping, and in some cases modeling, is the basis of watershed analysis and should include data layers to facilitate the following analyses. Most of these data layers are freely available online. Further information on analysis tools is provided in the next section. These maps should be designed for iterative updates over time as new information becomes available:

- Dominant watershed processes – analysis of topography (10-m digital elevation model), hydrology, climate patterns, soil type (Natural Resources Conservation Service (NRCS) soil classifications), and surficial geology can be used to identify the location and type of dominant watershed processes, such as sediment source areas and areas where infiltration is important or where overland flow likely dominates. This can provide a template for the eventual design of management measures that correspond most closely to the pre-development conditions, which support processes that promote long-term channel health.
- Existing stream conditions – At a minimum the NHD can provide maps of streams and lakes in the watershed. Additional information on stream condition should be included to the extent that it is available. This could include major bed-material composition, channel planform, grade control locations and condition, and approximate channel evolution stage. Where channel susceptibility analysis has been done, results should be included (see Bledsoe *et al.,* 2010, 2012)[1]. These maps can also be used to conduct general stream power evaluations.
- Current (past) and anticipated future land use – Current land use and land cover plus proposed changes due to general or specific plans. Existing or proposed floodplain development should be noted. Historical information on past land use practices or stream conditions including historic channel locations or alignments should be included if readily available. Classified land cover (National Land Cover Dataset (NLCD), 2006) is available from the Multi-Resolution Land Characteristics Consortium (MRLC).
- Potential coarse and fine sediment yield areas – methods such as the Geomorphic Land Use (GLU) approach (Booth *et al*., 2010) can be used to estimate potential sediment yield areas based on geology, slope, and land cover.
- Existing flood-control infrastructure and channel structures – maps should include major channels, constrictions, grade control, etc. that affect water and sediment movement through the watershed. Any available information on water quality, flood control, or hydromodification management basins should also be included. The location of engineered flood control channels and their design capacity should be noted.
- Habitat – both upland and in stream, and riparian habitat should be mapped to help determine areas of focus for both resource protection and restoration. This may be based on readily available maps such as the National Wetlands Inventory and National Land Cover Database, aerial photograph interpretation, or detailed local mapping.
- Areas of particular management concern – these may include sensitive biological resources, critical infrastructure, 303(d) listed waterbodies, priority restoration areas, or other locations or portions of the watershed that have particular management needs.
- Economic and social opportunities and constraints – comprehensive watershed management includes consideration of opportunities for improving community amenities associated with streams, economic redevelopment zones, etc. Details on this are beyond the scope of this report, but emphasize the need to include planning agencies in the development of hydromodification management plans.

[1] The channel susceptibility tools produce scores/ratings for both the vertical and horizontal stream dimensions. If there is a need to assign a single rating to a stream reach, the more-sensitive measure should be used.

Results of the watershed analysis should be used to address questions such as:

- What is the inherent susceptibility/risk of various stream reaches to hydromodification?
- Where are natural or developed resources of concern that need to be protected?
- What areas are good candidates for various restoration or management activities?
- What areas are not suitable or highly constrained for future restoration actions?
- What are the likely future changes in land use and associated runoff processes?

The answers to these questions can be used to determine the most appropriate management actions for specific portions of the watershed. Management strategies should be tailored to meet the objectives, desired future conditions, and constraints of the specific channel reach being addressed.

3.3 Types of Management Actions

Comprehensive hydromodification management should include on-site measures, upland protection or restoration, floodplain restoration and management, and in-stream restoration. These measures are summarized below; guidelines for selecting specific actions are provided in the following sections:

<u>On-site measures</u> – *typically applied throughout the watershed*:

- low impact development (LID) practices;
- disconnecting impervious cover through infiltration, interception, and diversion;
- coarse sediment bypass through avoidance of sediment yield areas or measures that allow coarse sediment to be discharged to the receiving stream;
- flow-duration control basins to reduce runoff below a threshold value.

<u>Upland protection through planning processes</u> – *prioritize in source areas of the watershed*:

- avoid coarse sediment yield areas;
- restore upland areas producing excessive fine sediment;
- protect infiltration areas; and
- construct regional basins or other retention facilities.

<u>Floodplain and stream restoration and management</u> – *prioritize in transport and deposition areas*:

- stream corridor restoration;
- restoration and/or protection of floodplain/floodway habitat;
- restoration and/or protection of critical sediment-transport areas;
- upstream or downstream natural/bio-engineered grade control; and
- retrofit or repair of currently undersized structures (e.g., culverts, bridge crossings).

3.4 Selecting Appropriate Management Actions

Management actions should be selected in consideration of the location where the change in land use is planned and the anticipated changes in watershed processes. The location of management actions should be prioritized based on established goals and targeting management actions to the location in the watershed where they will have the greatest potential effect (based on the watershed analysis). In general, a multi-level strategy combining actions at different scales and locations may be necessary. In highly-developed watersheds, management actions may primarily consist of a combination of on-site and off-site flow-duration control facilities. In less-developed watersheds, there may be more opportunities for upland restoration, avoidance of sediment source areas, and floodplain restoration.

In general, it is more effective to try and "prevent" hydromodification effects through land use planning than attempting to manage effects through on-site or regional flow-duration control

In general, it is more effective to try and "prevent" hydromodification effects through land use planning than attempting to manage effects through on-site or regional flow-duration control. In particular, upland restoration and floodplain management or restoration can be effective at reducing the need for aggressive or large-scale flow duration, as indicated in Table 5. Therefore, where opportunities exist, these strategies should be prioritized.

Table 5. Runoff management decision matrices.

upper watershed

sensitivity of d/s resources:		high				moderate				low		
		expected change in runoff				expected change in runoff				expected change in runoff		
		high	medium	low		high	medium	low		high	medium	low
	high				high				high			
channel susceptibility	medium				medium				medium			
	low				low				low			

middle/lower watershed

sensitivity of d/s resources:		high				moderate				low		
		expected change in runoff				expected change in runoff				expected change in runoff		
		high	medium	low		high	medium	low		high	medium	low
	high				high				high			
channel susceptibility	medium				medium				medium			*
	low				low	*	*	*	low	*	*	*

	aggressive flow-duration control
	moderate flow duration control
	low-levels of flow duration control
*	candiate for off-site mitigation

Notes: 1. Upper watershed generally refers to source areas whereas middle and lower watersheds refer to transport and deposition areas, respectively.
2. Sensitivity of downstream resources, change in runoff, and channel susceptibility are determined through the watershed analysis process.
3. High, Medium, and Low categories should be defined based on individual watershed or regional analysis in concert with stakeholder input.

Chapter 3 of SCCWRP Technical Report #667 *Hydromodification Assessment and Management in California* (Stein *et al*., 2012) provides a detailed discussion of potential management endpoint and actions that can be taken at various scales to achieve those endpoints. The following subsections provide considerations for prioritizing management actions.

3.4.1 On-site Flow Control Measures

On-site flow-duration control should be considered a primary management measure to help meet erosion potential/load ratio targets in streams that are at risk for hydromodification effects. Where there is a chance of downstream erosion, on-site flow control can reduce effects of development on channel form and structure. . However, the level of control (i.e., the volume of water retained) can be adjusted based on:

- Expected changes in flow between pre-project (not pre-development) and post-project conditions;
- Susceptibility of the stream channel into which the discharge will occur; and
- Sensitivity of downstream resources (both natural habitats and critical infrastructure).

In contrast, where sites discharge to fully engineered channels[2], in-stream erosion may not be the primary management concern. In these cases, water quality and/or sedimentation in downstream receiving waters may be the primary factor influencing the design of on-site control facilities. In these instances, resources for hydromodification management may be better allocated to regional facilities or to upstream restoration actions.

3.4.2 Regional Flow Control Measures

Projects that discharge directly to fully-engineered channels, confluence points with substantially-larger watersheds, bays, and estuaries may still contribute to downstream water quality effects, but may have minimal effect on in-channel erosion. Furthermore, the contribution from smaller projects at the terminus of watershed management units (e.g., HUC 10 or HUC 12 watersheds) may be relatively small compared to the cumulative upstream discharges. In such cases, minimal on-site impacts may be best mitigated through contributions to regional basins, large restoration projects, or other facilities. A variety of mechanisms can be used to support regional off-sets, such as off-site mitigation, in-lieu fees, impact feeds, or community facilities districts. An example framework for an accounting and tracking system for on and off-site mitigation facilities in Ventura County, California, is provided in Appendix A.

3.4.3 Protection and Management of Floodplains and Adjacent Uplands

Upland protection (i.e., activities outside the stream itself) can be prioritized by position in the watershed, based on opportunities and constraints identified during the watershed analysis. As stated above, the goal is to restore watershed process; consequently, actions should be targeted to the appropriate portions in the watershed:

[2] In some instances a site may discharge to an engineered channel, which eventually transitions to a more natural channel. In these cases, on-site flow duration control may still be appropriate. Decisions should be based on a consideration of all downstream reaches and not just those immediately adjacent to the project site.

Source areas (typically in the upper portions of sub-watersheds): To the extent possible, coarse sediment yield areas should be protected. Development activities should avoid these areas and allow yield areas to be coupled to the appropriate stream. Legacy effect areas that produce excessive sediment, such as heavily grazed or farmed uplands should be restored. *Some source areas may contain key infiltration zones that should be protected. Conversely some source areas are characterized by naturally-impervious surfaces – development should be targeted for these areas to minimize pre- vs. post-project changes in runoff.*

Transport reaches (generally in the middle portion of catchments): Stream corridors can be protected where they are still intact and restored where the opportunity exists. Key infiltration zones that often occur at the transition between source areas and transport reaches should be managed for this function.

Deposition areas (generally in lower catchments): Floodplains can be protected where they are still intact and restored where the opportunity exists in order to support storage and infiltration functions. Management and restoration actions should focus on restoring the connection between streams and their adjacent floodplains.

3.4.4 Stream Restoration

Management strategies should be tailored to meet the objectives, desired future conditions, and constraints of the specific channel reach being addressed. Objectives for specific stream reaches may include stream protection, restoration, or stabilization and management:

Protect: This approach consists of protecting the functions and services of relatively-unimpacted streams in their current form through conservation and anti-degradation programs. This strategy should not be used if streams are degraded, or nearing thresholds of planform adjustment or changes in vegetation community. This strategy may apply following natural disturbances such as floods depending on the condition of the stream reach and the ability for natural rehabilitation to occur (due to how intact watershed processes are). The goal of this strategy is not to create an artificial preserve (such as a created stream running through an urban park) but rather a naturally functioning river system.

Restore: Restoration is considered re-establishing the natural processes and characteristics of a stream. The process involves converting an unstable, altered, or degraded stream corridor, including adjacent riparian zone (buffers), uplands, and flood-prone areas, to a natural condition. In most cases, restoration plans should be based on a consideration of watershed processes and their ability to support a desired stream type. The watershed analysis discussed above should be used to determine how and where watershed process should be protected or restored in order to best support stream and stream-corridor restoration. Restoration should apply to streams that are already on a degradation trajectory where there is a reasonable expectation that a more stable equilibrium condition that reflects previously existing conditions can be recreated and maintained via some intervention. Creating a stream system that differs from “natural conditions” is not considered restoration. Restoration may not be feasible in portions of developed watersheds where processes and floodplains have been irrevocably altered. In those cases, management, as a new channel form may be a more appropriate goal (see below).

Stabilize and manage as a new channel form: Once a stream channel devolves far enough down the channel evolution sequence, it is extremely difficult to recover and restore without substantial investment of resources. If critical thresholds in key structural elements, such as planform or bank height, are surpassed, streams should be allowed to continue progressing toward a new stable equilibrium condition that is consistent with the current setting and watershed forcing functions, if such progress does not pose a danger to property and infrastructure. Substantial alteration of flow or sediment discharge, slope or floodplain width may make it improbable that a stream can be restored to its previous condition. In such circumstances, it may be preferable to determine appropriate channel form given expected future conditions and "recreate" a new channel to match the appropriate equilibrium state under future conditions. For example, a multi-thread braided system may not be the appropriate planform based on new runoff and sediment pattern; instead, a single-thread channel or step-pool structure may be a more appropriate target.

The decision about which endpoint is most appropriate should consider a variety of factors relative to stated goals and objectives for each stream and the existing and expected landscape constraints. Table 6 provides general guidelines on the most appropriate strategy based on a variety of factors. The criteria listed in the first column are defined and assessed via the watershed analysis (previously discussed). The High, Medium, and Low criteria should also be defined through watershed analysis and modeling, in concert with watershed stakeholders.

Table 6. Relationship between various stream management endpoints and contributing factors. H = High, M = Medium, L = Low, which are defined based on the results of the watershed analysis and agreed upon objectives.

		Protect	Restore	Stabilize & Manage
existing channel condition (CEM)		I, II	II, III	IV, V
susceptibiliity class (screening tool)		L	M	H
available floodplain		H	H, M	L
buffer opportunity		H	H, M	L
instream natural resources		H	H, M	L
downstream resources		H	H, M	L
connectivity of stream cooridor		H	H, M	L
future discharge relative to reference		L	L	M, H
sediment supply		H	H, M	L

In practice, a stream should be evaluated for each of the criteria in the first column. Stakeholders can add criteria to the decision matrix based on what is important in their area. Furthermore, criteria can be weighted differentially based on local priorities. The predominant condition for a given location should be used to inform the selected management endpoint. An example application is shown in Table 7.

Table 7. Sample application of the relationship between various stream management endpoints and contributing factors. H = High, M = Medium, L = Low, which are defined based on the results of the watershed analysis and agreed upon objectives. Shading indicates selections for a hypothetical example (see Figure 26). The majority of criteria in this example suggest that a restoration endpoint is appropriate for this stream reach.

		Protect	Restore	Stabilize & Manage
existing channel condition (CEM)		I, II	II, III	IV, V
susceptibiliity class (screening tool)		L	M	H
available floodplain		H	H, M	L
buffer opportunity		H	H, M	L
instream natural resources		H	H, M	L
downstream resources		H	H, M	L
connectivity of stream cooridor		H	H, M	L
future discharge relative to reference		L	L	M, H
sediment supply		H	H, M	L

Hydromodification Management Decision Process

STEP 1 – opportunity for sediment-supply protection and if so, take advantage

STEP 2 – assess channel susceptibility using screening tool

STEP 3 – identify downstream resources of concern and opportunities for restoration

STEP 4 – predict Ep change under unmitigated conditions – can use gage data, regional curves or model

STEP 5 – use Ep change to estimate enlargement for the channel susceptibility class using models/curves (include confidence estimates)

STEP 6 – select size/aggressiveness of BMP/LID

STEP 7 – explore opportunities for off-site mitigation (e.g., regional basins, floodplain restoration, etc.)

STEP 8 – if necessary, and options available – pursue in-channel restoration

Note – STEPS 6, 7, and 8 should be done in concert with each other. Once the suite of management solutions are selected, return to STEP 4 and re-evaluate change in Ep under the mitigated condition.

Figure 26. Hypothetical example of summary of elements of the decision process for determining hydromodification management actions (flow control, upland restoration, stream restoration).

3.5 Decision-Making Conclusions

To improve the likelihood of long-term recovery and protection of beneficial uses, hydromodification management will need to evolve from a narrow focus on flow control to a more integrated approach that focuses on restoration of watershed processes and remediation of past and anticipated future instream effects. Integrated management relies on a watershed analysis that identifies key opportunities and constraints that can be used to prioritize the location and type of management actions. Such watershed analysis can range from simple to complex depending on goals, needs, and available resources.

Unfortunately, the current regulatory and management structure may not always be well suited to implement an integrated watershed-based management approach. Transitioning from site-based to watershed based management may require changes in the development and application of hydromodification policies and plans by the State and Regional Water Boards and local jurisdictions. In the short term, municipalities will need to consider broadening the approaches to on-site management measures and expand monitoring and adaptive management programs based on the tools described in this document. In the long term, regulatory agencies will need to consider developing watershed-based programs that allow for implementation of management measures in the locations and manner that will have the greatest impact on controlling hydromodification effects. A watershed-based approach will also allow the integration of hydromodification management objectives with related programs such as water-quality management, groundwater management, and habitat management and restoration through mechanisms such as Integrated Regional Water Resources Management Plans. A logical next step is to demonstrate the application of integrated hydromodification management through stakeholder driven development of prototype watershed-based management programs. These early efforts will be valuable in guiding early implementation and refining the concepts presented in this document.

4.0 LITERATURE CITED

American Society of Civil Engineers (ASCE), Task Committee on Hydraulics and Modeling of River Width Adjustment (1998). River width adjustment, II: modeling. *Journal of Hydraulic Engineering*, 124(9):903–917.

American Society of Civil Engineers (ASCE) (2008). Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. *Manual of Practice 110*, M. Garcia (Ed.), 1128 p.

Bagnold, R.A. (1980). An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society*, 372(1751):453–473; DOI: 10.1098/rspa.1980.0122.

Biedenharn, D.S., R.R. Copeland, C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson (2000). Effective Discharge Calculation: A Practical Guide. *Technical Report No. ERDC/CHL TR-00-15*, US Army Corps of Engineers, Engineer Research and Development Center, Washington, DC, August, 63 p.; Available at: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA383261&Location= U2&doc=GetTRDoc.pdf.

Bledsoe, B.P., and C.C. Watson (2001). Logistic analysis of channel pattern thresholds: meandering, braiding, and incising. *Geomorphology*, 38:281–300.

Bledsoe, B.P. (2002). Stream erosion potential associated with stormwater management strategies. *Journal of Water Resources Planning and Management*, 128:451–455.

Bledsoe, B.P., M.C. Brown, and D.A. Raff (2007). GeoTools: a toolkit for fluvial system analysis. *Journal of the American Water Resources Association*, 43(3):757–772.

Bledsoe, B.P., R.J. Hawley, and E.D. Stein (2008). Stream Channel Mapping and Classification Systems: Implications for Assessing Susceptibility to Hydromodification Effects in Southern California. *Technical Report #562*, Southern California Coastal Water Research Project, Costa Mesa, CA, 38 p.

Bledsoe, B.P., R.J. Hawley, and E.D. Stein (2009). Hydromodification Screening Tool for Southern California for Field Testing / TAC Review. Southern California Coastal Water Research Project, Costa Mesa, CA, November, 36 p.

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

Bledsoe, B.P., E.D. Stein, R.J. Hawley, and D.B. Booth (2012). Framework and tool for rapid assessment of stream susceptibility to hydromodification. *Journal of the American Water Resources Association*, 48(4):788–808.

Bledsoe, B.P., E.D. Stein, R.J. Hawley, and D.B. Booth (In Press). Framework and tool for rapid assessment of stream susceptibility to hydromodification. *Journal of the American Water Resources Association*.

Booth, D.B., and C. Jackson (1997). Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association*, 33:1077–1090.

Booth, D.B., S.R. Dusterhoff, E.D. Stein, and B.P. Bledsoe (2010). Hydromodification Screening Tools: GIS-based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge. *Technical Report #605*, Southern California Coastal Water Research Project, Costa Mesa, CA.

Borsuk, M.E., C.A. Stow, and K.H. Reckhow (2004). A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. *Ecological Modelling*, 173:219–239.

Brown and Caldwell (2011). Final Hydromodification Management Plan. Prepared for the County of San Diego by Brown and Caldwell, San Diego, CA, March, 129 p. plus Appendices.

Brownlie, W.R. (1981). Prediction of Flow Depth and Sediment Discharge in Open Channels. *Report No. KH-R-43A*, W. M. Keck Laboratory, California Institute of Technology, Pasadena, CA.

Brunner, G.W. (2008). HEC-RAS, River Analysis System User's Manual: Version 4.0. US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 747 p.

Buffington, J.M., and D.R. Montgomery (1997). A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research*, 33:1993–2029.

Buffington, J., and G. Parker (2005). Use of geomorphic regime diagrams in channel restoration. *Eos*, *Transactions*, 86(52); American Geophysical Union, Fall Meeting Supplement, *Abstract H13E-1359*.

Chakraborty, K., K. Mehrotra, C.K. Mohan, and S. Ranka (1992). Forecasting the behaviour of multivariate time series using neural networks. *Neural Networks*, 5:961–970.

Chang, H.H. (1979). Geometry of rivers in regime. *Journal of the Hydraulics Division*, 105:691–706.

Chang, H.H. (1980). Geometry of gravel streams. *Journal of the Hydraulics Division*, 106:1443–1456.

Chang, H.H. (1985). River morphology and thresholds. *Journal of Hydraulic Engineering*, 111:503–519.

Chang, H.H. (1988). Fluvial Processes in River Engineering. Wiley, New York, NY.

Chang, H. H. (2006). Generalized Computer Program: Fluvial-12 Mathematical Model for Erodible Channels User's Manual. San Diego State University, San Diego, CA.

Chien, N. (1956). The present status of research on sediment transport. *Transactions of the American Society of Civil Engineers*, 121:833–868.

Chien, N. (1961). The braided stream of the lower Yellow River. *Scientia Sinica*, 10:734–754.

Chin, A., and K.J. Gregory (2001). Urbanization and adjustment of ephemeral stream channels. *Annals of the Association of American Geographers*, 91:595–608.

Christensen, R. (1997). Log-Linear Models and Logistic Regression. Springer-Verlag, New York, NY, 483 p.

Church, M. (2002). Geomorphic thresholds in riverine landscapes. *Freshwater Biology*, 47(4):541-557.

Church M. (2006). Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Science*, 34:325–354; DOI: 10.1146/annurev.earth.33. 092203.122721.

Copeland, R.R., D.N. McComas, C.R.Thorne, P.J. Soar, M.M. Jonas, and J.B. Fripp (2001). Hydraulic Design of Stream Restoration Projects. *Technical Report No. ERDC/CHL TR-01-28*, US Army Engineer, Research and Development Center, Vicksburg, MS.

Cui, Y., S. Dusterhoff, J. Wooster, and P. Downs (2011). Practical considerations for modeling sediment transport dynamics in rivers. Chapter 10 in A. Simon, S. Bennet, and J. Castro (Eds.), Stream Restoration in Dynamic Systems: Scientific Approaches, Analyses, and Tools, *AGU Monograph Series 194*, American Geophysical Union, Washington, DC.

Dust, D.W. (2009). On the Nature and Mechanics of Floodplain Response and Stability in the Semi-arid Environment of Southern California. Ph.D. Dissertation, Colorado State University, Department of Civil and Environmental Engineering, Fort Collins, CO.

Dust, D., and E. Wohl (2010). Quantitative technique for assessing the geomorphic thresholds for floodplain instability and braiding in the semi-arid environment. *Natural Hazards*, 55:145–160.

Faraway, J., and C. Chatfield, (1998). Time series forecasting with neural networks: a comparative study using the airline data. *Applied Statistics*, 47:231–250.

Ferguson, R.I. (1993). Understanding braiding processes in gravel-bed rivers: progress and unsolved problems. In: J.L. Best and C.S. Bristow (Eds.), Braided Rivers, *Special Publication 75*, Geological Society, London, UK, pp. 73–87.

Gole, C.V., and S.V. Chitale (1996). Inland delta building activity of Kosi River. *Journal of the Hydraulics Division*, 92(HY2):111–126.

Haines, B.E. (In Preparation). Hydraulic geometry equations and state diagrams for assessing potential channel responses to hydromodification. M.S. Thesis, Colorado State University, Department of Civil and Environmental Engineering, Fort Collins, CO.

Hawley, R.J. (2009). Effects of urbanization on the hydrologic regimes and geomorphic stability of small streams in southern California. Ph.D. Dissertation, Colorado State University, Department of Civil and Environmental Engineering, Fort Collins, CO; Available at: http://digitool.library.colostate.edu/webclient/DeliveryManager?pid=79263.

Hawley, R.J., and B.P. Bledsoe (2011). How do flow peaks and durations change in suburbanizing semi-arid watersheds? A southern California case study. *Journal of Hydrology*, 405:69–82.

Hawley, R.J., B.P. Bledsoe, E.D. Stein, and B.E. Haines (2012). Channel evolution model of semiarid stream response to urban-induced hydromodification. *Journal of the American Water Resources Association*, 48(4):722–744.

Hawley, R.J., and B.P. Bledsoe (In Review). Channel enlargement in semiarid suburbanizing watersheds: a southern California case study. *Journal of Hydrology*.

Hawley, R.J., B.P. Bledsoe, E.D. Stein, and B.E. Haines (In Press). Channel evolution model of response to urbanization in southern California. *Journal of the American Water Resources Association*.

Henderson, F.M. (1966). Open Channel Flow. Macmillan, New York, NY.

Hoey, T.B., and A.J. Sutherland (1991). Channel morphology and bedload pulses in braided rivers: a laboratory study. *Earth Surface Processes and Landforms*, 16:447–462.

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

Klaassen, G.J., and K. Vermeer (1988). Channel characteristics of the braiding Jamuna River, Bangladesh. In: W.R. White (Ed.), International Conference on River Regime, Hydraulics Research, Wallingford, UK, pp. 173–189.

Kondolf, G. M., and H. Piégay (Eds.) (2003). Tools in Fluvial Geomorphology. Wiley, 384 p.

Laflen, J.M., Lane, L.J., and Foster, G.R. (1991). WEPP: a new generation of erosion prediction technology. *Journal of Soil and Water Conservation*, 46:30–34.

Lane, E. W. (1955a). Design of stable channels. *Transactions of the American Society of Civil Engineers*, 120:1234–1279.

Lane, E.W. (1955b). The importance of fluvial geomorphology in hydraulic engineering. *Journal of Hydrology Division*, 81(Paper 745):1–17.

Langendoen, E.J. (2000). CONCEPTS – Conservational Channel Evolution and Pollutant Transport System: Stream Corridor Version 1.0. *Research Report No.16*, US Department of Agriculture – Agricultural Research Service, Oxford, MS.

Leopold, L.B., and M.G. Wolman (1957). River Channel Patterns – Braided, Meandering and Straight. *Professional Paper 282B*, US Geological Survey, Reston, VA.

Maier, H.R., and G.C. Dandy (2000). Neural networks for the prediction and forecasting of water resources variables: a review of modelling issues and applications. *Environmental Modelling and Software*, 15:101–124.

Maxted, J.R., and E. Shaver (1999). The use of detention basins to mitigate stormwater impacts to aquatic life. In: National Conference on Retrofit Opportunities for Water Resource Protection in Urban

Environments, Chicago, IL, February 9-12, 1998, pp. 6–15; *EPA/625/R-99/002*, US Environmental Protection Agency, Office of Research and Development, Washington, DC.

Menard, S.W. (1995). Applied Logistic Regression Analysis. Sage Publications, Thousand Oaks, CA, 98 p.

Minns, A.W., and M.J. Hall (1996). Artificial neural networks as rainfall-runoff models. *Journal of Hydrological Sciences*, 41(3):399–417.

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

National Center for Earth-Surface Dynamics (NCED) (2011). iSURF – A Mixed Size Sediment Transport Tool. Available from: http://www.nced.umn.edu/content/isurf-mixed-size-sediment-transport-tool, Accessed October 12, 2011.

National Land Cover Dataset (NLCD) (2006). Dataset. Source: Multi-Resolution Land Characteristics Consortium.

National Research Council (NRC) (2001). Assessing the TMDL Approach to Water Quality Management Committee to Assess the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction. Water Science and Technology Board, National Research Council, National Academies Press, Washington, DC.

National Research Council (NRC) (2009). Urban Stormwater Management in the United States: Committee on Reducing Stormwater Discharge Contributions to Water Pollution. National Academies Press, Washington, DC.

Osman, A.M., and Thorne, C.R. (1988). Riverbank stability analysis, I: theory. *Journal of Hydraulic Engineering*, 114 (2):134–150.

Palhegyi, G.E., and J. Bicknell (2004). Using concepts of work to evaluate hydromodification impacts on stream channel integrity and effectiveness of management strategies. In: G. Sehlke, D.F. Hayes, and D.K. Stevens (Eds.), Critical Transitions in Water and Environmental Resources Management, World Water and Environmental Resources Conference – 2004, American Society of Civil Engineers, Salt Lake City, UT, pp. 1–18; DOI:10.1061/40737 (2004)421.

Parker, G. (1976). On the cause and characteristic scales of meandering and braiding in rivers. *Journal of Fluid Mechanics*, 76:457–480.

Parker, G. (1990). Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research*, 28:417–436.

Pitlick, J., Y. Cui, and P. Wilcock (2009). Manual for Computing Bedload Transport Using BAGS (Bedload Assessment for Gravel-bed Streams) Software. *General Technical Report RMRS-GTR-223*, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 45 p.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden,

K. Rogers, R.E. Tharme, and A. Warner (2010). The Ecological Limits of Hydrologic Alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, 55:147–170.

Reckhow, K.H. (1999a). Water quality prediction and probability network models. *Canadian Journal of Fisheries and Aquatic Sciences*, 56:1150–1158.

Reckhow, K.H. (1999b). Lessons from risk assessment. *Human and Ecological Risk Assessment*, 5:245–253.

Reid, L.M., and T. Dunne (1996). Rapid evaluation of sediment budgets. Catena Verlag (GeoEcology paperback), Reiskirchen, Germany, 164 p.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder (1997). Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). *Agricultural Handbook No. 703*, US Department of Agriculture, Washington, DC.

Roesner, L.A., B.P. Bledsoe, and R.W. Brashear (2001). Are BMP criteria really environmentally friendly? *Journal of Water Resources Planning and Management*, 127:150–154; DOI: 10.1061/(ASCE)0733-9496(2001)127:3(150) (5 pages).

Schumm, S.A. (1969). River metamorphosis. *Journal of Hydraulics Division*, 95 (HY1):255–273.

Schumm, S.A. (1977). The Fluvial System. John Wiley and Sons, New York, NY.

Schumm, S.A. (1981). Evolution and response of the fluvial system, sedimentologic implications. *Society of Economic Paleontologists and Mineralogists Special Publication*, 31:19–29.

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

Schumm, S.A. (1985). Patterns of alluvial rivers. *Annual Review of Earth and Planetary Sciences*, 13:5–27.

Sengupta, A., E.D. Stein, and R.J. Hawley (In Review). General regression neural networks to estimate hydromodification response in semi-arid Southern California streams. *Journal of Hydrology*.

Schultz, M.T., T.D. Borrowman, and M.J. Small (2011). Bayesian networks for modeling dredging decisions. *Report ERDC/EL TR-11-14*, U. S. Army Corps of Engineers, Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS, October, 74 p.

Sear, D.A., M.D. Newson, and A. Brookes (1995). Sediment-related River Maintenance: The Role of Fluvial Geomorphology. *Earth Surface Processes and Landforms*, 20(7):629-647; DOI: 10.1002/esp.3290200706.

Sear, D., M. Newson, C. Hill, J. Old, and J. Branson (2009). A method for applying fluvial geomorphology in support of catchment-scale river restoration planning. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 19(5):506-519; DOI: 10.1002/aqc.1022.

Shoemaker, L., T. Dai, and J. Koenig (2005). TMDL Model Evaluation and Research Needs. *Report EPA/600/R-05/149*, National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, OH, November, 386 p.

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

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

Simon, A., and M. Rinaldi (2000). Channel Instability in the Loess Area of the Midwestern United States. *Journal of the American Water Resources Association*, 36(1):133–150.

Soar, P.J., and C.R. Thorne (2001). Channel Restoration Design for Meandering Rivers. *ERDC/CHL CR-01-1*, US Army Corps of Engineers, Engineer Research and Development Center, Flood Damage Reduction Research Program, Vicksburg, MS.

Stein, E.D., F. Federico, D.B. Booth, B.P. Bledsoe, C. Bowles, Z. Rubin, G.M. Kondolf, and A. Sengupta (2012). Hydromodification Assessment and Management in California. *Technical Report #667*, Southern California Coastal Water Research Project, Costa Mesa, CA.

Stewart-Koster, B., S.E. Bunn, S.J. Mackay, N.L. Poff, R.J. Naiman, and P.S. Lake (2010). The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. *Freshwater Biology*, 55:243–260.

Thorne, C.R. (1997). Channel types and morphological classification. In: C.R. Thorne, R.D. Hey, and M.D. Newson (Eds.), Applied Fluvial Geomorphology for River Engineering and Management, John Wiley, Chichester, UK, pp. 175–222.

Thorne, C.R. (1998). Stream Reconnaissance Handbook: Geomorphological Investigation and Analysis of River Channels. Wiley, Chichester, UK.

Thorne, C.R., C. Alonso, R. Bettess, D. Borah, S. Darby, P. Diplas, P. Julien, D. Knight, L. Li, J. Pizzuto, M. Quick, A. Simon, M.A. Stevens, S. Wang, and C.C. Watson (1998). River width adjustment, I: processes and mechanisms. *Journal of Hydraulic Engineering*, 124(9):881–902.

Thorne, C.R. (2002). Geomorphic analysis of large alluvial rivers. *Geomorphology*, 44:203–219.

US Environmental Protection Agency (USEPA). 2007. National Management Measures to Control Nonpoint Source Pollution from Hydromodification. EPA 841-B-07-002. USEPA. Washington, DC.

Wohl, E.E., P. L. Angermeier, B.P. Bledsoe, G.M. Kondolf, L. MacDonnell, D.M. Merritt, M.A. Palmer, N.L. Poff, and D. Tarboton. (2005). River Restoration. *Water Resources Research* 41, W10301, doi:10.1029/2005WR003985.

You, L.Y. (1987). A study of the formation and evolution of braided channels with stable islands: the middle and lower reaches of the Yangtze River. In: V. Gardiner (Ed.), International Geomorphology 1986, Part I, Wiley, Chichester, UK, pp. 649–662.

APPENDIX A: EXAMPLE OFF-SITE STORMWATER MITIGATION EVALUATION FRAMEWORK, VENTURA COUNTY, CALIFORNIA

Memorandum

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DATE: February 17, 2012

TO: Ventura Countywide Stormwater Management Program: Planning and Land Development Subcommittee

SUBJECT: Offsite Mitigation Framework Options (Tasks 2 & 3 of Offsite Mitigation Framework Study)

INTRODUCTION

This memo is intended to provide agencies with information and options to develop an accounting and tracking framework for the mitigation of the Permit's Low Impact Development (LID) requirement. It is broken out into a brief background on the requirements and the estimated need for offsite mitigation across the county; the challenges of implementing offsite mitigation at different scales; an examination of programmatic and funding approaches; and the administration and accounting options available to public agencies.

BACKGROUND

The Ventura Countywide National Pollutant Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) permit (Order R4-2010-0108) allows technically infeasible new development and redevelopment projects to use alternative compliance measures if onsite retention and/or biofiltration best management practices (BMPs) cannot feasibly be used to meet the 5% Effective Impervious Area (EIA) standard.

Alternative compliance is based on the "mitigation volume." The mitigation volume is the difference between the volume of runoff associated with 5% EIA and the volume of runoff associated with the actual EIA achieved onsite less than or equal to 30% (≤30%) EIA. The offsite mitigation requirement for EIA in excess of 30% (>30%) is 1.5 times the amount of stormwater not managed onsite.

Reporting Requirements

According to the NPDES MS4 permit, Permittees must provide a list of offsite mitigation projects available for funding to project applicants. Reporting requirements include: a schedule for the completion of these projects, including milestone dates to fund, design and construct the projects; and the mitigation funds raised to date and pollutant and flow reduction analyses prepared by project applicants that illustrate that the results are comparable to what would have been achieved by meeting the 5% EIA standard onsite.

Summary of Projected Need

As a first step, the potential extent of mitigation needs was estimated by developing countywide growth projections, estimating the volume of offsite mitigation needed, estimating the size of BMP structures needed, estimating the costs to design and build, and identifying interagency areas of influence. This estimate determined the need for offsite mitigation ranges from minimal in some municipalities down to nonexistent for offsite mitigation in other municipalities. A summary of projected new development and redevelopment acreage requiring offsite mitigation is provided in **Tables 1 and 2**. The projected need is an approximate estimate and is subject to alteration depending on zoning or General Plan modifications, and rate of and type of future new development and redevelopments. Additional details on the projected need are provided in **Attachment C**.

Table 1. Estimated Offsite Mitigation Need by 10-digit Hydrologic Unit Code (HUC)

10-Digit HUC	Mitigation Volume		
	ft3	ac-ft	gallons
Calleguas Creek	199,500	5	1,492,000
McGrath Lake-Frontal Pacific Ocean	85,900	2	642,400
Ventura River	19,000	0.4	141,900
Los Sauces Creek-Frontal Pacific Ocean	12,700	0.3	95,100
Lower Santa Clara River	7,800	0.2	58,600
Middle Santa Clara River	4,700	0.1	35,100
Malibu Creek	100	0.02	600
Upper Los Angeles River	0	0	0
Lower Piru Creek	0	0	0
Big Sycamore Canyon-Frontal Santa Monica Bay	0	0	0
Total	**329,700**	**8**	**2,465,700**

Table 2. Estimated Offsite Mitigation Need by Permittee

Permittee	Mitigation Volume		
	ft3	ac-ft	gallons
Simi Valley	149,300	3	1,116,500
Oxnard	73,100	2	547,100
Camarillo	44,800	1	335,000
Unincorporated County Urban Areas	18,900	0.4	141,300
Ventura City	11,100	0.3	82,800
Thousand Oaks	10,600	0.2	79,300
Ojai	8,300	0.2	62,100
Moorpark	4,300	0.1	32,100
Santa Paula	3,900	0.1	28,900

Permittee	Mitigation Volume		
	ft3	ac-ft	gallons
Port Hueneme	3,100	0.1	23,000
Fillmore	2,300	0.1	17,600
Total	**329,700**	**8**	**2,465,700**

These findings have several implications for the development of an offsite mitigation framework:

- The relatively small need projected for offsite mitigation diminishes the need for regional BMPs.
- It may be more cost effective and manageable for municipalities to meet the need with the implementation of just a few small offsite BMPs.
- The offsite mitigation framework should be flexible and adaptable enough to accommodate a variety of future growth scenarios.

Permit Provisions & Project Eligibility Criteria

Criteria for eligible offsite mitigation projects were recently developed by Permittees as part of a call for projects that solicited opportunities for regional offsite mitigation projects from interested stakeholders. The NPDES MS4 permit requirements guided the development of the eligibility criteria. The eligibility criteria combined with the estimated need is useful for identifying viable offsite mitigation options for Ventura County permittees. Relevant criteria for eligible projects include:

- Offsite projects must be located in Ventura County and within the same Hydrologic Unit Code (HUC).
- Offsite projects must be located such that the offsite mitigation project would achieve equivalent stormwater volume and pollutant load reduction as if the new development and redevelopment projects that will utilize the proposed alternative compliance project had complied with subparts 4.E.III.1.(a)-(d) of the permit. Project locations which can receive runoff from existing urban development meet this criteria.
- Offsite projects must be designed to retain and/or biofilter runoff from existing urbanized areas. In general, this should be accomplished via infiltration measures; however, stormwater harvesting and biofiltration will be considered on a site-specific basis. BMPs must be designed in accordance with the design guidance in the 2011 Technical Guidance Manual (TGM).
- Offsite mitigation projects may include green streets projects, parking lot retrofits, other site specific BMPs, and regional BMPs.
- Offsite mitigation projects must be able to be completed within 4 years of the certificate of occupancy for the first project that contributed funds toward the construction of the offsite mitigation project, unless a longer period is otherwise authorized by the Regional Water Board Executive Officer.

OVERVIEW OF PROJECT-SPECIFIC CHALLENGES

Several challenges exist that have the potential to constrain the type of offsite mitigation projects implemented by Permittees. One of the principle challenges in designing a funding mechanism for the proposed offsite facilities is the unpredictability of the timing of the need for the facilities. Several likely scenarios exist and are discussed below:

Scenario 1: Large Regional Facility

A large, regional multi-municipality facility, potentially involving multiple (roughly more than three) development projects, poses clear funding challenges and risks. Since development projects are difficult to predict in terms of size and timing, both the size and schedule for investment would be difficult to predict and manage, accordingly. In particular, permit requirements to achieve the minimum EIA technically feasible onsite combined with a small projected need are likely to limit the participation in regional facilities. The NPDES MS4 permit requires that offsite mitigation projects be completed “as soon as possible, and at the latest, within four years of the certificate of occupancy for the first project that contributed funds towards the construction of the offsite mitigation project.” The four year timeline makes the implementation of regional facilities challenging because it is likely that Permittees will have to construct a regional facility before a sufficient, “critical mass” of funds are received from developers.

It may take several years for a permittee to work with developers and accumulate the funds necessary for the design, construction and permitting of a regional facility. In addition to the uncertainty associated with funding, completing the construction of a regional facility in four years may be difficult given the length of time it takes to acquire necessary permits.

However, since there may be economic advantages resulting from the efficiencies of scale of a large, regional facility, this scenario, although not optimal, should not necessarily be discounted. A regional facility may be feasible if a permittee or a group of permittees felt that they could predict development size and timing and then build a facility to suit. As new development projects arose, and participated in the offsite mitigation, they could be required to pay their portion, plus interest, of the regional facility. In essence the municipalities would serve a developer/ bank, speculatively building the facility, but planning on recouping all of their investment from future development.

Water supply facilities are often set up using this approach in areas where development is predicted. The water supply agency designs and installs water treatment and piping capacity that is larger than needed, speculating that future development will occur, and can be tapped to reimburse the agency’s capital costs. Of course, this “build it and they will come” approach is particularly vulnerable to the risk that predicted future development does not occur, and the costs of the unused regional facility would be incurred by the Permittee.

Scenario 2 – Midsized Facility

Smaller, midsized facilities involving two or three developers may offer many of the offsite mitigation advantages without the same significant financial risk as regional facilities. Because of the smaller, more manageable number of participants, financing arrangements could be established and designed prior to design, construction and operations. This project would have to be completed within the four year window, as stipulated in the permit. As an example, a municipality may elect to construct a retrofit on public land (e.g., bioretention area in parking lot) that could provide offsite mitigation for two or three developers.

Scenario 3 - Small Development Project-Specific Facility

Individual, development project-specific would allow the maximum control and the least financial risk to the municipalities in terms of establishing a funding mechanism. The entire financing arrangement would be established and designed prior to design, construction and operations. The primary disadvantage of this scenario is that it potentially results in a relatively high implementation cost to the developer. Additionally, the small amount of mitigation volume that is likely to result on a per project basis may not warrant the creation of a standalone BMP such as an infiltration trench. However, given the right set of site conditions, it could support the implementation of a small BMP such as a tree-well filter in the right-of-way located in front of the development project. This is further discussed under the option, “Developer Mitigates Offsite.”

PROGRAMMATIC/ FUNDING APPROACHES

The following section explores several options available to Permittees for an offsite mitigation funding framework. A survey was conducted in November 2011 to get an idea of what each permittee is considering for an offsite mitigation framework. The results of this survey (see **Attachment B**) were used to help determine the offsite mitigation framework options. Additionally, a review of other offsite programs was conducted and summarized in **Attachment A**. These programs included non-stormwater offset programs already being conducted by Permittees (e.g., parks) and stormwater quality offsite mitigation programs located outside of Ventura County. Aspects of these programs were incorporated into the options described below.

A description, advantages, and disadvantages are described for each funding approach (O&M and tracking discussed separately in next section):

- Developer Mitigates Offsite
- Purchase Credits through Private Seller
- In-Lieu Fee
- Impact Fee
- Community Facilities District
- Effective Combinations
- Additional Considerations that Cross Multiple Options

Developer Mitigates Offsite

Under this option, the developer is responsible for constructing a stormwater BMP offsite that will retain or biofilter the mitigation volume. Two primary scenarios exist under this option.

Developer Builds Offsite Mitigation Project on Private Property

The primary advantage of this approach is that it results in a potentially reduced burden on the Permittee, particularly if the developer or another third party is responsible for operation and maintenance (O&M). Permittees will still have to ensure that the developer constructs a BMP that meets the intent of the permit and retains or biofilters the mitigation volume.

There are several disadvantages exist for this scenario. One disadvantage is that developers might have difficulty identifying a feasible offsite mitigation project within the municipality (or HUC). This could result in a high transaction cost for the developer and may introduce uncertainty into the project approval process and timeline. Additionally, since the offsite mitigation project is located on private land, the owner of the land must be willing to accept the liability and O&M associated with the project. Additional tracking is required to ensure that if the offsite location is redeveloped that the retained volume is not credited to the redevelopment.

Developer Builds Offsite Mitigation Project on Public Property

Under the second scenario, Permittees generate a list of options available to the developer on public land. The advantage of this scenario is that it reduces the burden on the Permittee and the developer (relative to other options). In this scenario, the developer takes on the responsibility of constructing the BMP, but their burden is reduced since they are not left with trying to find a viable retrofit opportunity. Permittees may provide the design and the location of the offsite mitigation project or just the location. This scenario is particularly desirable if the developer is able to implement a small BMP in the right-of-way such as a tree-well filter.

There are a few disadvantages to this scenario. Given the small offsite mitigation likely needed on a project-by-project basis it may not be technically or financially effective for each project to construct a standalone BMP such as an infiltration trench. It may also be undesirable if the public perceives this scenario as a donation of public land to developers (i.e., viewed as favoring certain developers). However, it is not uncommon for a municipality to dedicate land to developers for other public infrastructure projects such as parks or schools. Finally, the Permittee would likely be solely responsible for O&M costs. Additional options for O&M discussed under Program Administration.

Purchase Credits through Private Seller

This option requires a private company to take on the liability of mitigation, responsibility for O&M, and certify that offsite mitigation will be completed within four years of the certificate of occupancy and located within the same HUC. A private company can sell mitigation credits by either:

- Exceeding the volume they are required to retain onsite (i.e., they harvest and use more than the SQDV onsite)
- Retrofitting an unregulated site (i.e., currently has no stormwater quality management)

A private seller-oriented program would likely include the following steps:

- The developer proposing to purchase credits from a private seller documents the amount of mitigation volume needed and how it will be met using private mitigation (e.g., 120 street trees planted = 50 gallons mitigated). This documentation is included as part of the post-construction plan review submittals.
- The developer pays private company directly.
- The private company conducts mitigation (e.g., constructs retrofit).

- The private company reports to Permittee when the offsite mitigation project is completed.
- Permittee must verify that the BMP meets intent of permit provisions and has “credits” to sell.

The primary advantage of this approach is that the cost of the offsite mitigation project, including construction and O&M, is financed by private sector investors seeking to profit by selling credits. The credit system being considered by Washington DC is summarized in Attachment A.

There are several disadvantages to this approach. Given the small projected need for offsite mitigation, it is unlikely that it could support a marketplace of private sellers offering credits to developers within the HUC. Likewise, if this is the only option available to developers, Permittees may need to invest some time at the outset of the program to help foster an offsite mitigation credit marketplace (e.g., helping private sellers identify potential offsite mitigation opportunities). Additionally, an up-to-date tracking system would be necessary in order to ensure that available and used credits are accurately tracked to ensure that double-counting does not occur.

Reimbursement Agreement

Under this option, a developer that is eligible for offsite mitigation opts to construct an offsite mitigation facility that meets and exceeds their mitigation volume. Permittees may direct willing developers to a specific project that they have in mind. To facilitate cost sharing, the developer requests a reimbursement agreement with the City. When other developers eligible for offsite mitigation are identified by the permittee, the permittee collects and transfers an amount identified in the reimbursement agreement to the developer that entered into the reimbursement agreement. The amount should be in keeping with the facility’s available mitigation volume. This option is commonly used in Thousand Oaks for the extension of water and wastewater utilities.

The primary disadvantage of this approach is finding a developer willing to construct a facility that exceeds the required mitigation volume and who is willing to take on some uncertainty associated with payback. This option also does not create a straightforward mechanism for ensuring long-term O&M. One scenario may be to combine this option with a CFD tax that will cover O&M costs associated with the facility.

Negotiated Mitigation Agreement

A negotiated mitigation agreement (also commonly referred to as an in-lieu fee) between a developer and a public agency is a common and flexible approach to addressing mutual infrastructure and service needs. This approach, which may also be called a “mitigation fee”, “cash-out” involves the developer making a one-time payment associated with the mitigation, “in lieu” of meeting permit requirements onsite, or satisfying the associated financial obligation in some other way. Permittees collect and use these funds to identify, design and construct and manage offsite mitigation projects. These funds could also be used towards existing projects that currently retain more stormwater runoff volume than required or retrofit of an existing BMP to provide additional retention. To minimize local developer opposition or concerns from elected officials, the payment structure should be transparent and directly correspond to the costs associated with constructing and maintaining an offsite mitigation project.

A negotiated mitigation agreement/in-lieu fee is straightforward and usually accomplished by an ordinance (or modification to an existing ordinance) approved by a Council or Board of Supervisors. Recommendations for the adjustment or increase of a flat mitigation agreement will require approval by Council/Board of Supervisors. A nexus must also be created between the agreement and the Building or Grading permit. To reduce the frequency that the negotiated mitigation agreement/in-lieu fee must be adjusted via Council, calculation of the payment should include an inflation adjustment factor. Several existing mitigation fee programs within the County require that payment account for inflation using the construction cost index for Los Angeles as published by the Engineering News Record/McGraw-Hill Construction Weekly.

Two primary scenarios exist under this option:

- **Flat Mitigation Agreement/In-Lieu Fee:** Under this scenario, Permittees develop a flat dollar amount per gallon of stormwater runoff that could not be retained or biofiltered onsite. The majority of communities with stormwater offsite mitigation programs utilize this approach (Attachment A). Payment is set so that it encompasses a variety of likely design and BMP scenarios. To provide consistency and transparency, it may be desirable to determine a Countywide fee versus a Permittee-by-Permittee or project-by-project one. Preliminary cost estimates based on capital costs for an infiltration trench and infiltration basin were calculated as part of the Offsite Mitigation Need Memorandum (see Attachment C). The memo determined the cost by volume to be approximately $1.55 to $3.65/ gallon. These numbers for not include the cost of land acquisition which could vary widely by permittee.

  <u>Example: Use of Flat Mitigation Agreement to fund Capital Costs and O&M costs:</u>

  Assumptions:

Capital Costs Offsite Facilities	= $750,000 (generalized across BMP types)
# of Gallons Treated by Offsite Facility	= 150,000 (generalized)
Maintenance and Operations Costs	= $750,000 (10% of capital costs/ yearly for 10 yrs)

  Results:

Flat In-Lieu Fee	= (750,000+750,000)/155,000 = $10/gallon

- **Project Specific In-Lieu Fee:** This scenario is also known as a market driven model where Permittees design, construct, and maintain the offsite mitigation project and recoup the costs for the project from a negotiated mitigation agreement. Payment is determined on a project-by-project basis and will therefore vary for each project. Discussion with other mitigation fee programs located within the County indicated that offsite mitigation programs are less administratively burdensome when funds are directed towards a pre-identified project.

Example: Project Specific Negotiated Mitigation Agreement to fund Capital Costs and O&M costs:

Assumptions:	
Capital Costs Offsite Facilities	= $750,000 (actual cost of BMP)
# of Gallons Treated by Offsite Facility	= 150,000 (actual)
Maintenance and Operations Costs	= $750,000 (10% of capital costs/ yearly for 10 yrs)
Participating Developers	= 3 (assume equal need for offsite mitigation)
Results:	
Project Specific In-Lieu Fee	= (750,000+750,000)/155,000 = $10/gallon
Cost to each Developer	= $50,000 (5,000 gallons each at $10/gallon)

This approach has several advantages. This program allows funds to go to the Permittee which gives Permittees the ability to strategically direct retrofit efforts to priority areas (e.g., areas where infiltration is desirable). It also allows for the creative and flexible use of funds towards projects that work to reduce an equivalent volume of urban runoff. Options could include a street tree planting program or tax credits to homeowners that install LID practices on their property.

Additional advantages include reduced uncertainty from the developer's end. Once an agreement is determined, the developer's compliance is simple to calculate. Additionally, O&M responsibility is usually shifted to Permittee which provides certainty for the long-term function of the BMP.

The primary disadvantage of this option is that the administrative and long-term maintenance burden falls on the Permittee. A flat mitigation agreement/in-lieu fee is also challenging to identify and set so that it fairly recoups the costs associated with a wide range of projects. As an example, a Permittee may opt to implement an expensive harvest and reuse project or a modest infiltration project. The flat in-lieu fee must be able to cover the costs of both types of projects. In- lieu fees cannot be collected annually to support O&M so an established fee will have to incorporate the estimated future costs associated with O&M and inflation.

Additionally, some uncertainty exists for Permittees' ability to recoup the costs of BMP design, engineering, permitting, construction, and O&M for regional and midsized facilities. This is particularly true for offsite mitigation projects where construction is necessary prior to all the funds coming in from multiple developers.

Impact Fee

Similar to in-lieu fees, impact fees are one-time-only capital infusions. Impact fees are typically used to defray the cost of public facilities related to development projects (e.g., traffic impacts or affordable housing needs associated with commercial construction) versus a fee in-lieu of a development-specific requirement. These fees are often collected when the building permit is issued. The main disadvantage is that impact fees must adhere to Government Code Section 66000 (also known as the Mitigation Fee Act). This adds an additional layer of requirements including extensive public reporting.

Another disadvantage of implementing an impact fee is addressing any opposition from local developers and garnering support from the City Councils and/or Boards of Supervisors. However, since this impact fee would only affect a self-selected project, no resistance is expected from local developers nor elected officials so long as the fee bears a reasonable relationship to the offsite facility. Unfortunately, impact fees cannot be collected annually to support O&M so an established fee will have to incorporate the estimated future costs associated with O&M and inflation.

It should be noted that impact fees implemented by a municipality often serve as the basis for negotiations that result in an in-lieu fee, because of the preferred flexibility available of an in-lieu fee.

Example: Impact Fees to fund Capital Costs (in combination with a CFD to fund O&M costs):

Assumptions:

Capital Costs Offsite Facility	= $750,000		
Payback Period	= NA		
Maintenance and Operations Costs	= $10,000 per year		
Participating Developers	= 3 (assume equal need for offsite mitigation)		
Results:			
Impact Fee	= (750,000)/3	=	$250,000
Annual Rate CFD O&M Rate	= (10,000)/3	=	$ 3,333

Community Facilities District (CFD)

Ventura County currently has many localized special taxes, benefit assessments and fees (including the current funding mechanism for stormwater management) that fund the installation, maintenance and operations of various local infrastructure. These appear as "direct charges" on Ventura County property tax bills. The special taxes are primarily Community Facilities Districts (more commonly known as CFDs or Mello-Roos Districts), and the assessments are primarily Landscaping and Lighting Assessment Districts (LLADs). Both CFDs and LLADs are very effective and manageable, and are commonly used to fund maintenance of perimeter landscaping improvements for larger residential developments throughout the State. Most importantly, they are routinely established during the residential development phase, while the developer owns all of the property (and all the votes, accordingly), because they are politically challenging, requiring a balloting of all affected property owners, after the individual developed properties have been sold.

Since LLADs are more costly and difficult to set up, more limited in their use, and have greater legal risk than CFDs, they are not discussed further here. The only real advantage the LLADs have over CFDs is the arguably unfair negative reputation of Mello-Roos which arose during production house building in Southern California in the 1980 and 1990s; when homeowners felt duped by Mello-Roos charges as hidden costs. This should not be a factor regarding this offsite mitigation project.

CFDs can be set up by the Permittee, and are straightforward and well-proven. They require the development of a "Rate and Method of Apportionment" which documents the specific fee amount for a particular type of property and size; three resolutions, a tax report and ballot.

Properties can readily be annexed into a CFD and need not be contiguous – an important consideration for this project. Similar to in-lieu fees, they can include an option to adjust on an annual basis to reflect inflation and can include expiration dates called "sunset provisions" which corresponding to the payoff of capital costs.

In this case, a countywide or citywide "parent" CFD could be established which readily facilitates future annexations of specific development projects supporting specific BMP costs. On the other hand, specific CFDs could be setup for each specific development project. It typically takes about four months to implement the initial "parent" CFD and two months for each individual annexation.

Revenue from the CFDs can be used to pay back capital costs, as well as for O&M. A lien is placed on the propert(ies) subject to the CFD which helps ensure payment in the future, although the Permittee may have to finance the construction. Typically the rate is set to payback the capital component over a number of years in addition to maintenance. CFDs can be used as the underlying financial mechanisms to support the sale of bonds, although that is not likely in this case.

Although CFDs are highly reliable funding mechanisms, there are several disadvantages including the need for the Permittee to finance the proposed facility because the CFD tax will likely not generate enough revenue in the first year to pay for design, construction and permitting. The cost of establishing, and then annually managing the administration of the CFD tax, is not trivial, and may be several thousand dollars per year. These costs must be balanced against the cost of the annual maintenance which may be less. In any case, the annual administration can and should be included in the tax rate to ensure that all Permittee's costs are recovered. It is worth noting that many Permittees (e.g. Moorpark) within the County already manage multiple CFDs and/or LLAD districts, so these administration costs can be shared and reduced. Also, similar to several of the other proposed funding mechanisms, the Permittee is burdened with the responsibility of the design, construction and permitting and O&M of the facility.

Example: CFD to fund Capital and O&M costs:

Assumptions:

Capital Costs Offsite Facility	= $750,000
Payback Period	= 20 years
Maintenance and Operations Costs	= $10,000 per year
Participating Developers	= 3 (assume equal shares)

Results:

Annual Rate for Year 1 thru 20	= ((750,000/20) + (10,000))/3	=	$15,833
Annual Rate for year 21 +	= (10,000)/3	=	$ 3,333

Note: this simple example does not include financing costs

Effective Combinations

Permittees may want to consider combining several of the options presented above in order to maximize advantages and minimize the disadvantages. CFDs in particular can be combined with a number of the options presented above in order to provide a long-term source of funding for O&M. Impact fees and in-lieu fees can be used to collect funds from the developer to construct offsite facilities and supplemented with a CFD tax that provides funding for O&M via future property owners. This option is attractive to the Permittee since funding is received upfront for the construction of the facility (versus spreading it out over 20 years) and funding is provided over the long-term for O&M. Similarly, this option is likely to be attractive to developers since the cost of O&M is directed to future property owners.

Another option may be to combine the private seller option with the developer mitigates offsite option. In this case, a developer constructs a sizeable facility that exceeds the amount of mitigation required by their development site. The developer is then able to sell off credits to other developers for a profit (this is similar to the “Reimbursable Agreement” option).

PROGRAM ADMINISTRATION AND ACCOUNTING

Several options for administering the accounting and programmatic aspects of an offsite mitigation program are described below.

Program Administration

Administering an offsite mitigation program requires several considerations including whether or not projects will be allowed to go outside the municipality, how tracking and reporting will be handled, and who will be responsible for O&M. These aspects of program administration are discussed in further detail below. The most likely options include municipality-by-municipality operated program or a Joint Powers Authority (JPA). If municipalities opt to allow offsite mitigation projects to occur watershed-wide, but do not establish a JPA other mechanisms such as memorandums of understanding (MOUs) will be required to address exchange of funds, maintenance responsibilities, etc.

Cross-Municipality Coordination

Allowing offsite mitigation projects to go outside of the municipality (but stay within the HUC) can increase flexibility and the number of options available to developers and Permittees alike. It also fosters a countywide approach that creates a level playing field for developers seeking offsite mitigation throughout the County. If offsite mitigation projects are allowed to occur within the HUC, several programmatic aspects must be addressed including tracking, exchange of funds, liability, and O&M responsibility.

If in-lieu fees, impact fees and/or CFDs are used to provide funding for construction and/or O&M, the funds will have to be collected by the municipality in which the development project takes place and then transferred to the municipality where the mitigation occurs.

At a minimum, municipalities that are willing to coordinate offsite mitigation projects on a watershed-wide basis should establish a MOU that documents mutually acceptable arrangements. The Calleguas Creek watershed is one example where it may be beneficial for multiple municipalities to coordinate offsite mitigation efforts. Coordination and exchange of funds across municipalities may be best facilitated through the establishment of a JPA (discussed in further detail below). Additionally, a countywide tracking program should be established in order to track the amount of mitigation volume available for each project.

Joint Powers Authority (JPA)

A JPA is an entity permitted under California law where two or more municipalities operate collectively. A JPA has a separate Board of Directors and is given powers, including taxing and planning authority authorized by an agreement typically referred to as a joint powers agreement. The term, membership, and standing orders of the Board of the JPA must be specified in the agreement. The JPA may employ staff and establish policies independent from their participating jurisdiction. JPAs allow the pooling of resources between two or more municipalities that are working together to address an issue that transcends municipal boundaries.

JPAs offer several advantages to an offsite mitigation program. Under a JPA, municipalities located within the same HUC would be able to more easily combine in-lieu or impact fees, and CFD taxes received from developers and therefore reduce the uncertainty of recouping the funds necessary to construct an offsite mitigation project.

Tracking & Reporting

Some level of tracking will be necessary regardless of the offsite mitigation option selected in order to ensure that the mitigation volume needed is matched up with the mitigation volume provided. Tracking becomes particularly important if offsite mitigation projects are allowed to go outside of the municipality and/or if credits are available for purchase through a private seller. Both options require an up-to-date tracking system to ensure that available and used credits are accurately tracked to ensure that double-counting does not occur. In the case of cross-municipality offsite mitigation, a countywide (or watershed wide) tracking program may be necessary to track the amount of mitigation volume available for each project.

Administration Costs

Permittees should consider mechanisms to recover the costs associated with administering an offsite mitigation program. This includes additional plan review time, review and oversight of acceptable offsite mitigation projects, tracking offsite mitigation projects and available mitigation volume, and annual reporting. Permittees should consider either incorporating these costs into an in-lieu fee or as an administrative fee charged as part of the plan review process. If possible, these fees should include the cost associated with education and outreach as discussed under private O&M responsibility below. In cases where the developer mitigates offsite, allowances should be made for the Permittee to recoup administrative costs

Discussions with other mitigation fee programs located within the County indicated that plan review time is recouped by directly billing the developer the time spent reviewing each individual project (hourly rate * hours spent on review).

O&M Responsibility

Any selected option must take into account how the offsite mitigation project will maintain function over the long-term. O&M considerations apply to permittee maintained offsite mitigation projects, privately maintained projects, and projects that cross municipal boundaries.

Permittee Maintained

O&M responsibility with the Permittee provides the greatest certainty for BMP maintenance, but presents challenges when determining how to adequately recoup O&M costs from the developer and/or property owner. Permittees should incorporate the cost of O&M and associated inflation into any in-lieu fees and/or CFD taxes established for offsite mitigation projects. Generally, Permittees should anticipate performing maintenance for at least 10 years at a cost of approximately 10% of the offsite mitigation project construction costs.

Privately Maintained

Developer or property owner maintained offsite mitigation projects reduce burden to the Permittees but are more difficult to ensure adequate maintenance over the long-term particularly if responsible parties go bankrupt. In order to ensure O&M of the project, Permittees should consider requiring the responsible party to enter into an escrow agreement with the Permittee. As mentioned in the following section, the developer could be required to pay a set amount equal to some minimum percent (%) of the construction cost of the BMP into the escrow account. This amount could be used by the Permittee in the event that the developer and/or landowner go bankrupt. Permittees could also require the developer to establish the escrow and continue to replenish as it is drawn down for maintenance activities so that the account maintains a minimum level of funds. Additionally, Permittees may have the option of putting a tax lien on the property to pay for O&M or cloud the title. A title with a cloud essentially places a yellow flag on a title and will create cause for closer scrutiny creating difficulty for the property owner when or if they attempt to sell the property.

If O&M responsibility remains with private parties, permittees should consider implementing an education and outreach program that addresses proper BMP maintenance. Education and outreach should address what should be maintained and how often.

Accounting Mechanisms

Funds for offsite mitigation should be collected and deposited into a dedicated fund solely for the purposes of constructing and maintaining offsite mitigation projects. Funds should be restricted so that they cannot be used for other purposes. Options available to Permittees include an escrow account, enterprise funds, and/or a designated revenue account.

Escrow Account

Escrow Accounts are used to hold funds that do not necessarily belong to a given party. An escrow account could be established to provide additional security to the Permittee and/or the developer. The developer could place funds into an escrow account that are dedicated to the construction of an offsite mitigation facility. In this case, the Permittee would benefit from the security that developer has dedicated funds for the project, and are available even if the developer declares bankruptcy during the project. Similarly, the developer would benefit from the security of knowing that the funds are not co-mingled with other city funds. Most likely, an escrow account would only be beneficial if a negotiated funding approach is used in which the developer directly agrees to a certain level of investment. Conversely, if a legally structured approach such as a CFD or impact fee is used, the Permittee would simply place the funds in a dedicated internal account.

Enterprise Funds

Enterprise funds provide goods or services to the public for a fee that makes the entity self-supporting. Government-owned utilities (such as water or wastewater facilities) are examples of enterprise funds. An enterprise fund could be established to collect “fees” from the developer and spend the revenue on construction, O&M of the offsite mitigation funding. There may be advantages to this approach with increased transparency and convenience, especially if multiple municipalities are involved. However, these enterprise fund fees would be regulated by

Proposition 218 as “property-related fees” and would likely be subject to legal and balloting requirements that would severely limit their use.

Designated Revenue Account

Permittees can set up a designated revenue account solely for the purposes of accepting and holding funds from developers received through a in-lieu fee or impact fee programs or CFD taxes. Developers write checks which are then deposited into a designated revenue account where funds are restricted for the use of offsite mitigation projects.

Bridge Funding

If a funding approach is used in which the capital costs are not completely paid up front by the developer, financing will be required. In most cases, for the relatively small capital costs of the proposed facilities, the municipalities should consider self-financing where they pay the initial capital costs and the developer pays it back, plus interest, over time, perhaps through a CFD. If for some reason, self-financing is not available, the municipalities could consider the use of bonds, grants, or a third party approach as a financing tool.

Bonds

Bonds are debt instruments in which an investor loans money to an entity that borrows the funds for a defined period of time at a fixed interest rate. In this case, a Permittee would engage a Financial Advisor and/or Bond Counsel to arrange to sell bonds to raise the capital cost amount needed. The Permittee would then pay back the bond holders at an agreed interest rate and schedule. The Permittee would be paid back, in turn, by a funding mechanism such as a CFD in the amount and on the same schedule as the bond payments. Use of bonds to pay for capital improvements is quite common in California, but there are significant financing costs, which would be borne by the developers, that may make this approach less attractive. A similar approach using Certificates of Participation, (also known as COPs) should also be explored. The significant overhead cost of bonds most likely makes them infeasible given the predicted small need for offsite mitigation facilities.

Grants

State grants are typically awarded through a highly competitive process, often require matching local funds, tend to be focused on capital expenses, are often narrowly focused in terms of scope and services, and can have significant administrative overhead. In addition, most grants are seldom designed to fund the O&M. Nonetheless, the revenue opportunities provided by grants is significant enough that they could be considered a viable approach.

If State grants such as Proposition 84 are pursued, applications should be written to maximize flexibility in use of the funds so the grant award can contribute towards annual expenses. Coordinating with other affected permittees to put forth larger and potentially more competitive grant applications is advised.

Third Party Financing

Occasionally, third party entities have provided financing assistance for infrastructure. These could include private, for profit entities like banks, or not-for-profit entities like environmental organizations. Although the projected need does not seem to warrant the construction of regional facilities, multi-functional offsite mitigation projects may still be an attractive option for third parties such as municipal water districts.

CONCLUSIONS

A variety of options are available to Permittees for forming the basis of an offsite mitigation program. Each permittee should select an option(s) based on the factors that are of most concern to their community such as projected offsite mitigation need and consideration of burden to permittees and developers. The Developer Builds Offsite Mitigation Project on Public Property, Project-Specific In-Lieu Fee, and CFDs appear to be the most viable options based on need and consideration of burden to permittees and developers. **Table 3** summarizes offsite mitigation program options by responsible party. **Table 4** summarizes the options by several factors including permittee responsibility, permittee risk, developer responsibility, compatibility with projected need, and adaptability to changing need.

Table 3. Summary of Offsite Mitigation Options by Responsibility

Offsite Mitigation Option	Responsibility		
	Construction	Ownership	Maintenance
Developer Builds on Private Property	Developer	Developer/ Property Owner	Developer/ Property Owner
Developer Builds on Public Property	Developer	Permittee	Permittee
Purchase Credits through Private Seller	Private Seller	Private Seller	Private Seller
Reimbursement Agreement	Developer	Permittee	Permittee
Flat In-Lieu Fee	Permittee	Permittee	Permittee
Project Specific In-Lieu Fee	Permittee	Permittee	Permittee
Impact Fee	Permittee	Permittee	Permittee
CFD	Permittee	Permittee	Permittee

Table 4. Summary of Offsite Mitigation Options

Offsite Mitigation Option	Permittee Responsibility	Permittee Risk/Liability	Developer Responsibility*	Compatibility w/ Projected Need	Adaptability to Changing Need
Developer Builds on Private Property	Low. Permittee must verify that BMP fulfills mitigation volume requirements.	Low. Developer identifies site and constructs. May be difficult to guarantee private O&M of project.	High. Developer must identify and construct BMP offsite.	Low. Unlikely that the small mitigation volume supports construction of a new standalone BMP.	High. Developer builds what he/she needs; may be somewhat limited by space availability.
Developer Builds on Public Property	Medium. Permittee must find public property available and suitable for offsite mitigation.	Medium. Developer constructs but likely that Permittee takes over O&M of project; unknown liability if project is not properly constructed.	Medium. Developer must construct.	Medium to High. Developer may be able to implement small BMPs in right-of-way.	High. Developer builds what he/she needs; may be somewhat limited by space availability/ site constraints.
Purchase Credits through Private Seller	Medium. Permittee must verify private projects and keep accurate and up-to-date tracking of credits.	Medium. Risk that market for private seller will not exist or not enough to sustain over long-term.	Low. Developer pays third party; third party takes on liability of mitigation and O&M.	Low. Medium to high mitigation volume is needed in order to sustain.	Low. Realistically, a medium to high mitigation volume is needed in order to sustain.
Reimbursement Agreement	Medium. Permittee must verify private projects and keep accurate and up-to-date tracking of available mitigation volume.	Low. Developer identifies site and constructs. Need to identify mechanism to ensure funding for long-term O&M.	High. Developer must construct BMP offsite and get reimbursed as additional offsite needs come in.	Medium to High. Depends on whether or not the flat in-lieu fee will be used for regional, midsized, or project-specific facilities.	Medium. Program could be altered if growth projections change (e.g., could shift focus from midsized facilities to regional).
Flat Mitigation Agreement/ In-Lieu Fee	High. Permittee must identify, construct and maintain offsite mitigation projects.	Medium to High. Difficult to encompass cost of all scenarios under flat fee. Low guarantee that funds will cover regional facility. Guaranteed O&M since covered by Permittee.	Low. Developer makes payment to Permittee; Permittee takes on O&M.	Medium to High. Depends on whether or not funds will be used for regional, midsized, or project-specific facilities.	Medium. Program could be altered if growth projections change. A change in payment would have to go through Council.
Project Specific Negotiated Mitigation Agreement/ In-Lieu Fee	High. Permittee must identify, construct and maintain offsite mitigation projects.	Low to Medium. Fair share is allocated to developers. Low guarantee that enough developers come in to cover a regional facility. Guaranteed O&M since responsibility of Permittee.	Low. Developer makes payment to Permittee. Permittee takes on O&M.	Medium to High. Depends on whether or not funds will be used for regional, midsized, or project-specific facilities.	Medium. Program could be altered if growth projections change (e.g., could shift focus from midsized facilities to regional).
Impact Fee	Very High. Permittee must identify, construct and maintain offsite mitigation projects and adhere to Govt Code Sec 66000.	Medium to High. Difficult to encompass cost of all scenarios under flat fee. Low guarantee that fee will cover regional facility. Guaranteed O&M since covered by Permittee.	Low. Developer pays Impact fee to Permittee; Permittee takes on O&M.	Medium to High. Depends on whether or not the impact fee will be used for regional, midsized, or project-specific facilities.	Medium. Program could be altered if growth projections change. A change in fee would have to go through Council.
CFD	High. Permittee must set up and construct and maintain project.	Low to Medium. Fair share is allocated to developers. Low guarantee that enough developers come in to cover a regional facility. Guaranteed O&M since covered by CFD taxes.	Low. Developer sets up CFD which pays for capital costs and O&M.	Medium to High. Depends on whether or not the impact fee will be used for regional, midsized, or project-specific facilities.	Low. Once CFD tax rate is establishes, it cannot be easily modified other than annual CPI increase.

*Based on administrative, construction and O&M burden and generalized perceptions of option