Development and Implementation of Hydromodification Control Methodology

Literature Review

Submitted to:

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1. Introduction

Hydromodification has been defined in a variety of ways. For example, Webster's on-line dictionary (www.websters-dictionary-online.org) offers the following definition of hydromodification: "Alteration of the hydrologic characteristics of coastal and noncoastal waters, which in turn could cause degradation of water resources. In the case of a stream channel this is the process whereby a stream bank is eroded by flowing water. This typically results in the suspension of sediments in the water course." This definition has a split personality: It starts with the general topic of alteration of hydrologic characteristics but quickly focuses on stream channel erosion.

The two parts of this definition indeed represent broad and narrow perspectives on hydromodification. The first two sentences, representing the broader definition, come directly from USEPA's Office of Water (USEPA, 1993), which defines hydromodification as the "alteration of the hydrologic characteristics of coastal and non-coastal waters, which in turn could cause degradation of water resources." The second two sentences reflect a narrow perspective, focusing on whether "a stream bank is eroded by flowing water" and thus on the influence of changes in the hydrograph on channel form and sediment transport. This narrower approach has been taken by a variety of regulatory agencies in California and elsewhere across the nation, reflecting the dominant focus of scientific research and engineering practices over the past two decades. The distinction between the narrow and broad perspectives is significant, as it determines the type of hydromodification management plan that will ultimately result: a narrow perspective results in a focus on matching the pre-development hydrograph, while a broad perspective can lead to holistic management to preserve waterbody functions.

USEPA (2007) further refined their definition of hydromodification to include a variety of specific activities and processes that may impact the health of streams. These were grouped into three categories:

1. ***Channelization and channel modification***, which "include activities such as straightening, widening, deepening, and clearing channels of debris and sediment." This can include activities in streams that are being done to maintain the stream's conveyance capacity, such as removal of snags.
2. ***Dams***, defined as artificial barriers on waterbodies that impound or divert water for whatever purpose. This includes both larger regulatory dams, as defined in Title 33 of the Code of Federal Regulations, and smaller dams, such as those used to create farm ponds and authorized under the NRCS program.
3. ***Streambank and shoreline erosion***, the former of which "occurs when the force of flowing water in a river or stream exceeds the ability of soil and vegetation to hold the banks in place", and the latter occurring in open waterbodies due to the impact of waves.

Note that the narrow definition of hydromodification (i.e., changes in the hydrograph that affect channel geomorphology and sediment transport) falls entirely under item 3 in USEPA's (2007) list. None of these three categories, however, embraced the full range of human activities that can result in the "degradation of water resources" broadly defined in the earlier document. Thus, USEPA's Office of Research and Development (Mohamoud *et al.*, 2009) subsequently has proposed a yet broader definition of hydromodification that explicitly includes urbanization, climate change, water withdrawals, and inter-basin transfers. The stated intention "is to use the term for a wide range of anthropogenic watershed disturbances that alter natural flow regimes and degrade water quality," providing a basis for integrated management of multiple stressors. Under this definition, water-quality impairment caused by hydromodification includes increased sedimentation, higher water temperature, lower dissolved oxygen, degradation of aquatic habitat, and loss of fish and other aquatic populations. Hydromodification (as broadly defined by USEPA) may also include decreased water quality due to increased levels of nutrients, metals, hydrocarbons, bacteria, and other constituents.

The Central Coast Water Board has taken a broad perspective on hydromodification, with the overarching strategy of the hydromodification management approach to "maintain and restore key watershed processes" to meet both resource protection goals and regulatory requirements. This can only be accomplished by addressing the variety of changes in watershed functions and processes (physical, chemical, and biological) that result from urban development. In this way, hydromodification management becomes a key component in protecting and restoring watershed functions and maintaining appropriate beneficial uses—and not just a tool to address stream-channel stability.

The remainder of this document provides a review and acknowledgment of key relevant studies and approaches on assessing the impacts of hydromodification and developing hydromodification control criteria, including ongoing work in California and nationwide, with a focus on how this work can inform and provide a foundation for the Central Coast's watershed-based approach. Section 2 discusses the extensive literature on the narrow, stream-stability perspective on hydromodification, particularly examples from California. For the most part, this section presents summaries of the findings of the reviewed literature and does not provide opinions about whether or not the approaches are useful for the Central Coast Joint Effort. Instead, the entire approach is summarized and discussed in the context of the project in Section 2.5.

Section 3 then lays the foundation for the broad perspective approach. Because this approach has not yet been fully developed for hydromodification management in California, the papers reviewed in Section 3 emphasize underlying tools and methods rather than examples of direct application. The relevance for the Central Coast Joint Effort is typically provided at the end of many of the summaries. While much of the current work on hydromodification relates to assessment methods for determining watershed or stream "health," this section instead highlights those studies that have focused on the watershed processes that are integral to protecting and enhancing watershed health. The goal of this project is not to identify a comprehensive list of stressors and impacts; rather, it is to identify the specific relationships between watershed conditions and waterbody health. A better understanding of watershed processes and functions will ultimately inform the broader array of management options that provide flexibility in development planning, such as fee-in-lieu, mitigation banking, and other tools that may help balance land uses and avoid cumulative impacts. Management options that are based on sound watershed science are also less likely to result in adverse social, economic, or other environmental consequences.

2. Stream Stability—The "Narrow Perspective" on Hydromodification

As noted above, the narrow perspective on hydromodification focuses on stream-channel stability and related geomorphology issues. This is a subset of the broad perspective on hydromodification but is often one of the major sources of impact. Maintaining stream stability is commonly a necessary component of hydromodification management, but it is not alone sufficient to achieve the broader objectives for watershed management in the Central Coast Region. This section begins with a summary of literature and approaches from three regions/agencies, starting with seminal work done in the Pacific Northwest, followed by a review of literature used to support development of the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) Hydromodification Plan report, and finishing with literature and an assessment framework from the Southern California Coastal Water Research Project (SCCWRP). This section then concludes with a discussion of hydromodification control implementation in the San Francisco Bay Region, and a summary that provides a forward-looking view to the broad perspective on hydromodification, discussed in Section 3.

2.1. Literature and Management Approaches from the Pacific Northwest

The climate and topography of the Central Coast of California is much more akin to those of the San Francisco Bay Area and southern California than to the Pacific Northwest. However, studies of urbanization and channel stability in the Pacific Northwest and the resulting regulatory framework have a much longer history than farther south. They also have formed much of the foundation for subsequent work in California, with uneven recognition of the degree to which the results can (and cannot) be translated into a different geography. Some of the significant efforts are summarized below.

2.1.1. Oregon Watershed Assessment Manual

While the method developed for the Oregon Watershed Assessment Manual (1999) has a fish habitat focus, it was designed to address ecological health by including water quality. Its goals were to understand how both natural processes and human activities affect fish habitat and water quality within the context of the history of land management activities. Reach-scale information is used to classify streams into 15 channel habitat types and is applicable to the entire state. The classification system helps identify which streams are most sensitive to disturbance. Several existing stream classification systems were adapted to account for a variety of stream types across the state.

2.1.2. Flow control in western Washington and the 2005 Stormwater Manual

The use of flow-duration matching in pre- and post-development conditions to maintain channel stability was first suggested in 1989 in watershed plans being developed for the greater Seattle area. Although the analyses were supported by use of the HSPF hydrologic model, the broader development and engineering consulting community were familiar only with much more rudimentary predictive hydrologic tools (particularly those based on SCS curve-number methods) that did not yield flow-duration outputs. Regulatory application was therefore limited until a simplified version of HSPF was developed (the King County Runoff Time Series model, or KCRTS, a geographically limited precursor to the Western Washington Hydrology Model (WWHM), which incorporated additional pre- and post-processing software to address sizing of stormwater controls to meet HMP requirements (Booth and Jackson, 1997). The range of flows to be controlled was initially $0.5Q_2$ through Q_{100} (with the upper limit later reduced to Q_{50}, a concession to cost concerns over the size of facilities needed to manage very high-magnitude flows). The basis for $0.5Q_2$ as the lower threshold for control was an unpublished review (Booth, 1993) of six studies of sediment mobility in humid-region gravel-bedded rivers, for which a range of critical discharges for incipient motion averaged to this value but with significant variation about this mean (14 to 90 percent of Q_2).

Following this evaluation of the range of urban-influenced flows requiring control, the (in)stability of stream channels draining urban and urbanizing watersheds was investigated. Booth and Henshaw (2001) presented 11 years of repeat cross-sectional measurements on 21 channels in western Washington (a record later extended to 20 years; Booth *et al.*, 2008),, and Henshaw and Booth (2000) documented both the local conditions leading to channel instability and the period of time over which restabilization of those channels might be expected, given a static urban watershed land cover. They found that the rate of channel change (typically, incision and widening) in watersheds with some urban development was generally not well correlated with the absolute magnitude of that development (a result also found subsequently by SCCWRP), and that urban channels did tend to restabilize in the decade or so following urban build-out. However, they emphasized that “Restabilization does not imply a return of the channel to its natural state, and restabilization alone is not a sufficient goal for protecting aquatic communities.”

The current stormwater control manual for western Washington State (WADOE, 2005) explicitly recognizes this fundamental limitation of flow control:

> “The engineered stormwater conveyance, treatment, and detention systems advocated by this and other stormwater manuals can reduce the impacts of development to water quality and hydrology. But they cannot replicate the natural hydrologic functions of the natural watershed that existed before development, nor can they remove sufficient pollutants to replicate the water quality of pre-development conditions.” (p. 1-25)

Nevertheless, flow-control regulations in this manual were limited to the requirement for flow-duration control from $0.5Q_2$ through Q_{50} and include an exemption for channels draining long-urbanized watersheds (and thus presumably restabilized), suggesting that this cautionary note on the limitations of “channel stability” as a surrogate for waterbody protection was acknowledged but not embraced.

A recent ruling by the Washington State Pollution Control Hearings Board, however, overturned the narrow regulatory focus on flow-duration standards. Instead, it “require[s] non-structural preventive actions and source reduction approaches, including Low Impact Development Techniques (LID), to minimize the creation of impervious surfaces, and measures to minimize the disturbance of soils and vegetation where feasible.” (WAPCHB, 2008, p. 71) These measures will need to be included in the next round of NPDES permits across all of western Washington.

2.2. Literature Supporting the Santa Clara Valley Hydromodification Plan Report

SCVURPPP produced a Hydromodification Plan (HMP) report (SCVURPPP, 2005) to address NPDES permit requirements for managing changes in runoff response from new or redevelopment. SCVURPPP adopted the Bay Area Hydrologic Model (discussed in detail in Section 2.4) for meeting HMP goals; however, an extensive literature review was also conducted to support development of the HMP. The purposes of the review were threefold—to meet permit requirements, to present technical background for reference during plan preparation, and to provide an educational reference for staff and stakeholders. The literature review (published as Appendix B to the HMP, available at http://www.eoainc.com/hmp_final_draft/) is useful as background reading for detailed principles about hydromodification, primarily from the narrow perspective of stream stability but also with a nod to achieving a broader scope of watershed and waterbody health. The document also provides details for several stream-stability assessment approaches and tools. The authors favored sources from peer-reviewed journals and local/regional sources. They noted that most of the research was conducted outside of the Bay Area region (see Section 2.3), where the climate, geology, and physiography represented by the sources could deviate significantly from those of the Bay Area.

2.2.1. Overview of Hydromodification Processes and Issues

The authors provided a summary of the following:

- hydrologic processes and how they are affected by hydromodification;
- geomorphic processes and how they relate to hydromodification;
- the link between riparian ecology and hydromodification; and
- primary urbanization factors affecting channel stability.

Much of the information need not be summarized for this report, but readers seeking background information about hydromodification would likely benefit from a review of chapters 3–6 of Appendix B of the HMP. However, there are some key points worth noting as they relate to the Central Coast Region work.

- The Central Coast has a similar Mediterranean climate as the Santa Clara Basin, with a wet season from November to April and a pronounced dry season from May to October. Annual rainfall is also highly variable in both regions, ranging from less than 15 to over 50 inches per year. Short- and long-term droughts are common. As a result, riparian ecology is adapted to major fluctuations in water balance. Urbanization can change riparian ecology by upsetting the natural flow regime—not only due to erosive flows and unstable channels but also from constant baseflow during normally dry periods introduced by irrigation return flow.
- Disturbance events (i.e., fire, flood, and drought) are common in California and occur naturally. Plant communities are adapted to disruption, so some changes occurring in stream channels may result and are not always due to urbanization. Practitioners must take care to interpret data correctly in light of natural disturbance.
- Several studies are summarized where increases in peak flow were related to percent impervious area, and they generally all noted that the relative increase in peak flow and runoff volume is greater for events with shorter recurrence intervals (first documented more than three decades ago by Hollis, 1975). In other words, the percent increase in peak flow and runoff volume for the 2-year events is much greater than for the 5-year or 100-year events. This finding has important implications since the flows that do the most work for sediment transport are typically cited as ranging from the 1-year to the 2-year event.
- Urbanization can change the flow regime of receiving streams, often resulting in flashier events but longer aggregate durations of high flows over the course of a year Channels adapt with changes in width and depth to accommodate the additional flow. These changes may lead to catastrophic failures with channel incision and bank collapse. However, urbanization may also result in slower changes (quasi-equilibrium expansion) that are harder to detect; and with sufficient time under a stable urban land cover, channels may attain a true (re)stabilized form (Henshaw and Booth, 2000).
- The dynamics of a changing flow regime due to urbanization can lead to channel instability due to increases in peaks and the duration of erosive flow in channels. But changes in sediment supply can also affect channel stability. Excess sediment can lead to increased bank shear stress as flows are diverted around deposits. On the other hand, reducing sediment load can lead to channel degradation if the stream does not have a steady supply to move in dynamic equilibrium. Urbanization can cause both increases and decreases in sediment supply; the construction phase of development projects often results in upland sediment erosion, while an increase in impervious surface and conversion of headwater channels to culverts and drains can decrease overall sediment supply. Channel-crossing infrastructure (culverts and bridges) can also interrupt the downstream flux of (particularly coarse) sediment, leading to imbalances within the downstream channel without any net change in watershed sediment delivery at all.

- Stream bank erodibility remains difficult to predict when assessing channel stability. Bank erosion can result for many reasons. The review lists the following factors:

  "…undercutting, abrasion during flow, slumping from positive ground water pressure during waning flood flows, water forced into bank from obstructions such as boulders or large woody debris, and collapse of bank vegetation by wind throw, disease, fire, or floating large woody debris during high flows."

  By the same token, many factors contribute to bank stability:

  "…soil materials, stratigraphy, vegetation density, root strength and apparent cohesion, the amount of clay or cementing of the matrix particles, bank height and slope."

  The result is that it is difficult to develop quantitative measures of the risk of bank erosion. The review indicated that the most successful predictors of stream stability relate bank failure to degree of development, often measured as effective impervious area.
- Stream type is an important factor. The same changes in controlling variables on two different stream types may produce different results. The authors provide an example where flow increases for an armored bed with an erodible bank versus sand bed with resistant bank. The armored bed stream tends to widen, whereas the sand bed stream tends to incise (followed by bank failure).
- The response of riparian ecology to urbanization is complex and depends largely on both changes to the flow regime and changes to the channel itself. Channel erosion and siltation can alter aquatic ecosystems. Urban runoff and loss of bank vegetation can increase water temperatures. As noted previously, irrigation return flow can introduce flow during naturally dry seasons, thereby altering hydro-periods and plant/aquatic communities.

In summarizing the effects of urbanization on stream channel physical characteristics, the authors of the SCVURPPP HMP (2005) provided the following factors as having the greatest effect on stream stability:

- An increase in effective impervious area
- Increased drainage density resulting from addition of downspouts, curb and gutter, storm drains, and culverts
- Proximity of development to stream channels, and presence of stream buffers
- Extent of development in areas with sensitive soils (e.g., high infiltration rates)
- Changes in watershed vegetation affecting interception and evapotranspiration

2.2.2. Overview of Hydromodification Assessment Methods and Tools

In their review, the authors of SCVURPPP (2005) favored tools that assessed hydromodification from the stream-stability focus. They gave little attention to assessing hydromodification from a broader waterbody (or watershed) health perspective. Watershed-based assessments are tied to stream stability to develop causal relationships (e.g., correlation between contributing impervious area and channel erosion). This section summarizes their findings, with consideration of important factors for this project. Please note that the citations included here are as reported by the literature review report authors, and not all have been independently checked for this summary.

Stream Classification

Application of a stream classification system is important for grouping stream types and organizing an assessment system. The authors discussed the Montgomery and Buffington (1993) system and that of Rosgen (1996). Montgomery and Buffington classified streams by process-based characteristics, with a focus on understanding controlling variables and likely response to changes in the watershed, and thence for identifying protective management strategies. Their system used a set of classifications of decreasing scale:

1. Geomorphic Province – areas with similar climate, physiography, landforms, and erosion processes.
2. Watershed Scale – area bound by topographic highs; may have variable geomorphic provinces.
3. Valley Scale – describes fill material, sediment supply, and transport capacity. Valley segments are categorized by fluvial process—erosional zones, transport zones, and depositional zones.
4. Reach Scale – a segment of channel with similar characteristics. Six channel types are used (cascade, step-pool, plane bed, pool-riffle, dune-ripple, and braided channel). Further information is used to define seven types of possible change (width, depth, slope, sinuosity, bed surface grain size, roughness, and scour).

The recommended application of their method involves a combination of field work, soil maps and slope measurements, historical information about changes in channels, and comparison to reference reaches.

Rosgen's approach has some similarities to that of Montgomery and Buffington, but it used criteria based on channel form (rather than channel processes) to classify streams into 41 types, with a focus on evolution of stream types. His method has gained widespread appeal with practitioners of stream restoration projects. There are four levels in his system:

1. Geomorphic Characterization (Level 1) – integrates landform, valley and channel morphology incorporating climate and depositional history influences. Streams are classified into major types using entrenchment ratio, slope, cross section morphology, and sinuosity.
2. Morphological Description (Level 2) – subclasses of Level 1 based on channel materials and finer slope ranges, producing the 41 stream types.
3. Stream State or Condition (Level 3) – Uses several stream characteristics related to channel stability, response potential, and function
4. Verification (Level 4) – Direct field measurements used to support a comprehensive and detailed evaluation.

Discharge Thresholds for Channel Stability and Permissible Velocity Threshold

The authors of SCVURPPP (2005) cited several studies that relate storm event discharge to sediment transport, but results varied by location and were not conclusive. The authors noted that any attempt to match pre-development flow duration across the entire spectrum of discharges would be problematic, since development leads to an increase in the total runoff volume and so some flows must increase in their total duration to account for the extra total discharge.

Some of the earliest work in assessing risk of bank erosion was done in the 1920's to support irrigation canal design. The authors included a table showing soil material type, and corresponding maximum velocity and shear stress.

Bed Mobility Indices

Shields criterion is discussed in detail in Section 2.4. A limitation of the Shields method is that it was developed on uniform grain sizes, but it is commonly applied to mixed grain beds using D_{50} (the diameter of the median particle size) as "representative" of the entire bed. However, smaller particles tend to be located between and underneath larger particles and are therefore not exposed to the full force of the shear stress. For example, Andrews (1984) developed a modified measure that predicts variable shear stress by particle size:

$$\tau_i^* = \tau_{D_{50}}^* \cdot \left(\frac{D_i}{D_{50}} \right)^{\beta}$$

where τ_i^* is the critical shear stress for particle size *i* across a distribution of sizes, and β was determined by observations on natural rivers to fall between -0.8 and -0.9, accounting for selective transport by size *i*. These results, however, form but one of a host of empirical and theoretical results that provide broadly (but not entirely) consistent guidance (see Buffington and Montgomery [1997] for a comprehensive review of research on the subject through the mid-1990s).

Channel Stability Erosion Indices

Booth (1990) identified an empirical threshold of channel erosion based on unit stream power (Sp), defined as follows:

$$Sp = \frac{\rho g Q_W S}{w}$$

where ρ is the density of water, g is the gravitational constant, Q_w is the bankfull channel discharge, and w is the bankfull channel width. His analysis of streams in Washington State found that eroding versus non-eroding streams were well-discriminated by a value of Sp at bankfull discharge of 80 watts/m^2. Other authors have found that erosion indices can be improved with a measure of stream resistance, with D_{50} being a common choice. For example, Bledsoe and Watson (2001) provided a bed-mobility index derived from a study of 270 streams from worldwide locations:

$$S\sqrt{\frac{Q_W}{D_{50}}}$$

where Q_W is stream flow and S is slope (note that this research was summarized in the *Bed Mobility Indices* section of SCVURPPP [2005]). Their regression analysis discriminated "stable" from "unstable" streams with 80 percent accuracy. The index was developed using data of stream-bed sediment and thus is less applicable to systems with eroding stream banks or high vegetation density. While the index may be useful for predicting whether or not a stream is stable, it does not indicate the root cause of the problem. Bledsoe and Watson indicated that the method could be refined with more information, but that the parameterization should be related to local conditions and data.

MacRae (1993, 1996) contended that erodibility thresholds should reflect the most sensitive boundary material in the basal layer. MacRae developed a method called “Distributed Runoff Control”, a strategy that seeks to maintain the same sediment transport characteristics between pre-development and post-development conditions. The method uses a “time integrated” erosion index, which was adopted by the Ontario Ministry of the Environment and Energy:

$$Es = \frac{\sum \left(q_{\mathrm{s\,out}} - q_{\mathrm{s\,in}}\right)_{post} \cdot \Delta t}{\sum \left(q_{\mathrm{s\,out}} - q_{\mathrm{s\,in}}\right)_{pre} \cdot \Delta t} \qquad q_s = a \cdot \left(\tau_b - \tau^*\right)^b$$

where ($q_{s\,out} - q_{s\,in}$) represents the change in stream reach sediment storage (for pre- and post-developed conditions), τ^* is critical shear stress, τ_b is the bed shear stress, and a and b are empirical coefficients. The critical shear stress is based on the resistance of the bed and each stratigraphy layer in the banks.

Use of GIS Data and Spatial Analysis

The authors of SCVURPPP (2005) discussed concepts related to the use of GIS analysis for stream assessments and summarized the work of two researchers. It is important to note that the literature review was performed as early as 2002, so the science of using GIS analysis for stream assessment was not well developed at that time, and several of their source documents were prepared long before GIS came into common usage. For example, Booth (1990) was limited to site-scale observational data; he found that local geology, channel slope, topography, channel roughness, and flow were effective at identifying stream reaches at risk of (or already expressing) significant erosion, but he incorporated no spatial data sets beyond that of regionally mapped geology.

In contrast, Stein and Ambrose (2001) used GIS analysis with historic land-use change data and aerial photos, and demonstrated that the cumulative impacts from small development projects over time caused degradation of the entire stream system. This study suggests that watershed impacts are likely to be influenced by the history and nature of development in a watershed, and not simply correlated with current conditions or spatial data.

San Francisco Estuary Institute Watershed Science Approach

The San Francisco Estuary Institute (2000) developed their approach using data from several streams in the Bay Area. Their method relates changes in historic land use, hydrology, and sediment supply sources to instability in channel geomorphology. It uses a decision-tree analysis and streamline graphs to track channel condition by thalweg, right bank, and left bank. Initially developed using detailed field data, a modified approach requiring less data was created to address time and budget constraints. The method relies heavily on data that track sediment and sediment changes in the system. It also uses GIS-based analyses of geology, soils, slope, and land use, and tracks impacts from receding groundwater tables. Their approach demonstrates the importance of incorporating historical information in an assessment, because it provides information about likely response to hydromodification.

2.3. Literature from the Southern California Coastal Water Research Project

SCCWRP has recently published a number of reports related to hydromodification in southern California. Early work focused on assessing the link between development and channel morphology (Coleman *et al.*, 2005). A workshop was held as a venue for sharing knowledge and identifying knowledge gaps and future research direction (Stein and Zaleski, 2005). A literature review was published focusing on classification and mapping systems related to risk of hydromodification, with a southern California focus (Bledsoe, *et al.*, 2008). The work culminated in the development of a framework to support implementation of hydromodification management measures. The framework is made up of two complementary tools—one for GIS analysis of land cover, geology, and slope to assign sediment production potential (Booth *et al.*, 2010), and another field-scale screening tool for assessing risk of channel hydromodification (Bledsoe *et al.*, 2010a).

2.3.1. Coleman *et al.* (2005) – "Effect of increases in peak flows and imperviousness on the morphology of southern California streams"

The objectives of the study were to create a stream classification system applicable to southern California, to develop a predictive relationship between increase in impervious area and stream channel enlargement, and to produce a conceptual model of stream channel behavior that would support later development of a numerical model. To carry out the study, the researchers paired historic analyses with detailed field stream geomorphology data. Eleven sites were selected in eight watersheds in Los Angeles, Orange, and Ventura counties. The site catchments ranged in size from about 1 to 18 mi^2, targeting ephemeral and intermittent streams. Three conclusions were drawn from the study:

1. There is a predictable relationship between bankfull discharge and channel geometry measures, such as width and cross section area. This finding is consistent with the oft-noted observations (first recorded by Hammer, 1972) that urbanization, which normally increases discharge, typically also results in enlarged channels due to widening and/or downcutting.
2. Ephemeral and intermittent streams in southern California appear to be more sensitive to increase in impervious area than values typically cited from research. They estimated a response threshold of 2 percent to 3 percent impervious area, much lower than a range of 7–10 percent reported from some studies in other regions of the U.S. (although see Cuffney *et al.* [2010] for a more recent interpretation). They noted this conclusion applies to drainages of less than 5 mi^2.
3. The relatively undisturbed streams of their study sites displayed a measurable annual average decrease in channel elevation over the 3–18 years for which repeated cross-sectional surveys were available. These channels maintained their basin channel morphology, whereas streams in developing catchments showed instability in response to changes in both peak flow and duration.

Their stream classification system produced 84 possible designations, based on three catchment size classes, seven channel-form types, and four channel-resistance categories (i.e., resistant versus susceptible and bed versus bank). They provided three recommendations for stormwater management strategies for new development. First, disconnect impervious area to the extent possible to maintain effective impervious area below the 2 percent to 3 percent "threshold." Second, design the entire site with a goal of hydrograph matching for storms ranging from the 1- to the 10-year discharge. Finally, provide a sufficient stream buffer zone to allow for natural movement and migration, for which a corollary is that in-stream controls should be used only when necessary.

2.3.2. Stein and Zaleski (2005) – "Managing runoff to protect natural streams: the latest developments on investigation and management of hydromodification in California"

This summary of a two-day workshop provided a recap of information presented during the main session, which was focused on presenting approaches to managing hydromodification. It also summarized the findings of working groups for identifying knowledge and information gaps, and developing priorities for research and tool development. The report included a section on technical approaches for assessing hydromodification, including continuous simulation modeling, geomorphic metrics for representing physical processes, and risk-based modeling. Much of the thinking here was built on approaches discussed in the Santa Clara Valley literature review.

2.3.3. Bledsoe *et al.* (2008) – "Stream channel classification and mapping systems: implications for assessing susceptibility to hydromodification effects in southern California"

This literature review focused on geomorphic mapping and classification systems for assessing risk of stream hydromodification in southern California. Nine approaches were explored:

1. **Planform classifications and predictors**
   The narrative focuses on the issue of predictors that discriminate between braided and meandering streams. Braided planforms are common in southern California and should be managed differently than meandering planforms. The authors concluded that an approach detailed by Van den Berg (1995, as cited by Bledsoe *et al.*, 2008) provided a good framework for identifying geomorphic thresholds for meandering and braiding channels.
2. **Energy-based classifications of overall channel stability**
   The authors discussed several methods of relating stream power and other commonly used measures (slope, material size, drainage area, channel measures) to predictions of channel stability.
3. **General stability assessment procedures**
   While no field assessment protocols for channel stability were found that were developed for semi-arid climates, several systems were reviewed with promising elements for southern California streams. Examples of elements included bank angle/slope, vegetation/amount of protection, degree of bank wasting/failure, presence of obstructions that deflect or hold back flow, and bed-armoring/bed-material consolidation.
4. **Sand vs. gravel behavior/threshold vs. live-bed contrasts**
   Channels dominated by sand versus gravel exhibit starkly different geomorphic behavior. A key difference is that sand channels (live-beds) transport material even at low flows, while gravel beds require a higher flow event to initiate transport (threshold). Management implications pertinent to southern California streams were discussed in this section.
5. **Channel evolution models of incising channels**
   The science of channel evolution models (CEMs) was explored. CEMs describe predictable stages that channels undergo as a response to hydromodification. Understanding channel evolution concepts provides managers with a framework for choosing proper implementation measures when addressing unstable systems.
6. **Channel evolution models combining vertical and lateral adjustment trajectories**
   The CEMs discussed in the preceding section focused on vertical changes and bank collapse/mass wasting. The authors discussed CEMs that include factors to account for lateral change due to fluvial detachment. The utility of various systems was discussed; however, the authors concluded that channel form-based approaches are not appropriate for southern California streams since they do not account for the stream types or complex flow and sediment regimes found there.
7. **Equilibrium models of supply vs. transport-capacity / qualitative response**
   Researchers have developed various qualitative models that predict probable direction of stream response to changes in flow regime and sediment supply. However, these frameworks typically do not address the magnitude of change. Incorporating these concepts into a management framework is important, however, since actions should be tailored to the stream type. For instance, bedrock-controlled streams will response differently to urbanization than sand-bed streams. Changes in sediment supply have not been incorporated in the BAHM and Contra Costa approaches (discussed in Section 2.4)—doing so would greatly complicate the analyses.

8. **Bank instability classifications**
   Systems that assess and classify bank stability were briefly discussed. The best known is the Bank Erosion Hazard Index (BEHI) developed by Rosgen (2001).
9. **Hierarchical approaches to mapping using aerial photographs/geographic information system**
   The authors discussed examples of the use of GIS data to support analyses at large landscape extents. GIS is especially useful for screening-level analyses, since it can assess measures such as slope and riparian vegetation. For projects spanning large geographic areas, GIS could be used to develop various stream and landscape metrics; field data could then be used to correlate the metrics with risk of hydromodification susceptibility. Detailed assessments and management efforts could then be targeted areas with higher risk.

2.3.4. Bledsoe *et al.* (2010b) – "Hydromodification Screening Tools: Technical Basis for Development of a Field Screening Tool for Assessing Channel Susceptibility to Hydromodification"

SCCWRP developed a comprehensive approach to assessing channel susceptibility to hydromodification, which includes both a GIS component (see Section 2.3.5) and a field manual (Bledsoe *et al.*, 2010a).

The field tool uses a set of quantitative field indicators as inputs to a set of decision trees, allowing users to classify reaches as having Low, Medium, High, or Very High risk of hydromodification, with separate assignments for deepening versus widening. Some notable features include:

- Metrics were based on analysis of a large amount of local data and scientific literature
- Braiding/incision threshold were calibrated to regional data and based on surrogates for stream power and boundary resistance
- The tool is founded on a CEM that is based on observations of responses in southern California
- Critical decision points in the trees are supplemented with probabilistic diagrams and checklists.
- Many problematic or time-consuming field determinations are avoided, such as bankfull determination and cross section surveys
- The tool assesses risk of mass wasting
- Bank vegetation is not used, a conservative assumption given uncertainty in future root reinforcement

The most important geomorphic thresholds identified in the analyses that supported the development of the method were a criterion based on a screening index versus D_{50}, and the threshold based on bank height and angle. The ratings (Low through Very High) translate to low versus high ratios of disturbing to resisting forces, risk of exceeding geomorphic thresholds, rapid versus long relaxation time, low versus high potential for positive feedbacks/nonlinear response/sensitivity to initial conditions, and limited versus widespread spatial propagation.

2.3.5. Booth *et al.* (2010) – "Hydromodification Screening Tools: GIS-based catchment analyses of potential changes in runoff and sediment discharge"

The GIS-based screening tool presented in this report is designed to assess watershed conditions that may lead to downstream channel changes in the event of future urbanization, while the field screening tool (see Section 2.3.4) assesses the resistance of the channel to hydromodification. The tools can be used independently, or in combination, to address management concerns. Ideally, the GIS screening tool would be used to support land-use planning decisions at a watershed scale and highlight areas of potentially greater concern, while the field screening tool would provide information about specific reaches.

The GIS screening tool is broadly analogous to the concept of Hydrologic Response Units (HRUs), which are defined as units of land with relatively homogenous hydrologic properties (typically based on land cover, soil properties, and/or slope). This concept was modified to represent units of land with similar inferred levels of sediment production, called Geomorphic Landscape Units (GLUs) in previous applications in southern California (see, for example, Stillwater Sciences 2007). GLUs express the unique combinations of a limited number of geology types (e.g., shale, sandstone, and unconsolidated, which are related to erodibility), slope classes, and land cover. Using GIS, these are combined into Low, Medium, and High classes of relative sediment production based on observed erosion and mass-wasting processes typical to each GLU across watersheds of southern California. A change analysis of net sediment production can then be conducted by modifying the land cover to reflect future development, which normally tends to reduce the sediment contribution from hillslopes into stream channels. By the same token, current conditions can be compared to pre-development land cover to better understand historic changes in sediment delivery, providing insight into current geomorphic changes in the streams.

2.4. Hydromodification control implementation in the San Francisco Bay Region

Management approaches developed in the Pacific Northwest (see Section 2.1) provided the framework for much of the subsequent California work and model development, which was adapted to better address California conditions. As such, most of the early efforts at hydromodification management in California took the narrow perspective of focusing on stream stability. Key work in this area was driven by the San Francisco Bay Region Water Quality Control Board, which in 2001 issued amendments to municipal stormwater permits that contain requirements to implement hydromodification management plans. This work proceeded from the perspective that "hydromodification refers to the effects of urbanization on runoff and stream flows that in turn may cause erosion and/or sedimentation in the stream channels" (SCVURPPP, 2005, Appendix B)—which well describes the narrow perspective on hydromodification. The governing conceptual model is that urbanization increases the peak flow and volume of surface runoff by adding impervious surfaces and drainage facilities. This in turn increases stream flow energy imposed on the stream channel, causing erosion of the streambed and banks.

The hydromodification control standards for post-construction new and redevelopment established in the Bay Area municipal permits generally require that post-project runoff shall not exceed pre-project rates or durations over a defined range of storm event sizes from one-tenth of the 2-year recurrence flow up to the 10-year flow. The change in hydrology associated with development must be evaluated over a long timeframe using a continuous simulation hydrologic model. The results of the modeling are used to size control measures to match the pre-project flow duration patterns.

Several counties in the Bay Area (Alameda, Santa Clara, and San Mateo) developed the Bay Area Hydrologic Model (BAHM; Clear Creek Solutions, 2007) as a tool to meet hydromodification control requirements. BAHM is a version of WWHM (see Section 2.1.2), which in turn is an implementation of the continuous-simulation Hydrologic Simulation Program–Fortran (HSPF) model. Contra Costa County took a somewhat different approach to hydrograph matching and has developed sizing charts for Integrated Management Practices (IMP) to meet the requirements (Contra Costa, 2005), using pre-computed hydrographs that can be used for analysis of sizing requirements. Computation of the hydrographs in the Contra Costa approach was also done using HSPF. Thus, the BAHM and Contra Costa approaches both have applications of HSPF hydrograph modeling at their core; however, the results obtained by the two approaches differ.

Of the San Francisco Bay Area jurisdictions, Contra Costa offers the widest range of alternative approaches for demonstrating compliance with hydromodification control requirements:

1. No increase in impervious area.
2. Implementation of infiltration-based integrated management practices (IMPs) based on sizing factors described in the HMP.
3. Site-specific modeling to show that post-project runoff durations and peak flows do not exceed pre-project runoff durations and peak flows, using a continuous simulation model such as HSPF.
4. Detailed site-specific study to demonstrate that the project will not result in accelerated erosion of receiving stream reaches.

Option 3 in the Contra Costa HMP is similar to the “BAHM” approach as implemented in Alameda, Santa Clara, San Mateo counties, although Contra Costa does not specify use of a specific modeling package. For all such applications, however, post-project runoff durations are to be controlled for flows between one-tenth of the two-year peak flow ($0.1Q_2$) and the 10-year peak flow (Q_{10}). The lower end ($0.1Q_2$) is based on studies and data specific to Bay Area creeks, as discussed below.

Option 2 is expected to be employed for most of the smaller projects in Contra Costa County, and, as noted above, focuses on integrated onsite IMP controls. The Contra Costa Clean Water Program developed an IMP Sizing Calculator, which facilitates iterative calculations to make the design process faster and easier. Land development professionals report the IMP Sizing Calculator, and the design procedure in the Stormwater Guidebook, are straightforward and easy to use. Based on Contra Costa’s success, all 21 municipalities in San Diego County, working through the San Diego County Project Clean Water, have developed a similar design procedure and calculator to implement stormwater treatment and hydrograph modification management requirements (D. Cloak, P.E., Dan Cloak Environmental Consulting, personal communication, January 13, 2011). The sizing factors for the design of IMPs to control post-development hydrographs are calculated on flows ranging from $0.5Q_2$ up to Q_{10}, and thus they do not directly address the range from $0.1Q_2$ to $0.5Q_2$. The rationale is stated as follows in the cover letter to the 15 May 2005 submittal: “IMPs could be designed to provide even more control of outflows in the range of flows below $0.5Q_2$. This would be accomplished by reducing allowable underdrain outflow and increasing the sizing factors. The Program rejected this idea because (1) we believe the current sizing factors achieve the HMP standard, as evidenced by a comparison of the resulting runoff curves, and (2) it would make the IMPs less attractive to applicants, thereby undermining the advantages to be had by promoting the use of IMPs.”

A review of the flow-duration curves provided in the Contra Costa HMP shows that it is *not* always the case that the proposed sizing factors provided protection down to $0.1Q_2$. For this to be true, the post-development flow-duration curve calculated at the proposed sizing factor would need to remain at or below the pre-development flow-duration curve out to the $0.1Q_2$ flow. This appears to be true for some of the management devices analyzed (in-ground planter, infiltration trench, dry well, infiltration basin), but it is clearly not true for the flow-through planter (and unclear for several others).

It is worth commenting on the original specification of the range of flows to be controlled ($0.1Q_2 – Q_{10}$), particularly as it differs from recommendations for Western Washington (which has been $0.5Q_2 – Q_{50}$ since the mid-1990’s, as described below in Section 2.3). The origin of this range is GeoSyntec’s 2004 analysis of Thompson Creek in Santa Clara County (SCVURPPP, 2005, Technical Memorandum 4, *Evaluation of the Range of Storms for HMP Performance Criteria*), including calculation of effective work curves. Subsequent analyses were developed for Ross and San Tomas Creek, with “similar” results. The final justification in the Santa Clara HMP sets the upper limit at Q_{10} because 90-95 percent of the work on the stream was found to be accomplished at flows less than Q_{10}. The lower limit is set at $0.1Q_2$ based on an analysis of critical flow that initiates erosion of the bed or bank (individual cross sections in the three study sites had estimated critical flows that ranged from 2 to 18 percent of the Q_2 peak). “Critical flow” is defined as the flow corresponding to the critical shear stress, τ_C, that initiates erosion. The calculation of effective work also depends on the critical shear stress. Both the selection of the value of τ_C and the form used in the effective work calculation affect the range of flows that must be controlled.

To establish the lower limit for control, separate calculations were made for the bed and bank materials. For bed materials, GeoSyntec estimated τ_C from Shields' criterion, which establishes the inertial resistance that must be overcome to initiate movement of a particle of a given diameter. The method performs well for sand grains and gravel, but deviates from observations for clay and silt particles because cohesion between particles, which increases resistance to movement, is ignored (Hsu, 1989). For bank materials, τ_C was estimated from literature values listed in the ASCE Manual of Engineering Practice, No. 77. Testing of shear stress measurement by a jet test device in Alameda and Sacramento Counties in 2006 confirmed that the bank τ_C values provided by ASCE were appropriate to the region, although the minimum value of τ_C is usually determined by the movement of bed sediment (rather than the erosion of bank sediment) in Bay Area streams.

The upper limit for control is calculated from an effective work index, which integrates an estimate of bedload movement as a function of shear stress (and thus of flow) under the frequency distribution of sediment-transporting flows. The effective work index (*W*, in units of mass transport rate times velocity) is given as follows:

$$W = C \cdot \sum_{i=1}^{n} \left(\tau_{bi} - \tau_c\right)^{1.5} \cdot V \cdot \Delta t \, ,$$

where C is a constant coefficient, τ_{bi} is the effective shear stress at the boundary, τ_c is the critical shear stress for initial transport or erosion of the boundary material, *V* is the mid-channel velocity, *t* is time, and the summation is over all observed flows. The erosion potential, E_P, is then calculated as the ratio of *W* for post-development conditions to *W* for pre-development conditions. The goal cited in the BAHM development is to maintain E_P less than 1.0.

Although not cited in the document, the mass transport part of the effective work index is the generalized DuBoys equation for bedload transport. It is the oldest (and simplest) of many empirical relationships that have been developed for bedload transport. For example, the GeoTools suite (Bledsoe *et al.*, 2007) provides five different sediment transport options for calculating *W*. However, many of these have a similar form, differing primarily in the coefficient (which cancels out when calculating E_P.). These types of formulations are most applicable to stream systems with relatively large width-to-depth ratios and a limited amount of fine-grained cohesive material (i.e., clay and silt; Simons and Sentürk, 1992). They also provided results that commonly diverge from measured values by an order of magnitude or more (Gomez and Church, 1989).

Bedload transport equations are essentially empirical, and thus they are dependent on the specific data sets for which they were developed. Calculation of effective work also depends on the estimation of critical shear stress for the bank and bed material: because the calculation of the effective work index has a non-linear relationship to τ_c, errors in estimating τ_c will also affect the calculation of how much work is done at and above Q_{10}.

The estimate of τ_c directly determines the specification of the lower boundary of effective flows, because that specifies the flow at which bedload motion starts. Selection of the $0.1Q_2$ to Q_{10} range for hydromodification control appears likely to be protective of most stream channels in the Bay Area with sand and gravel beds. For streams where significant amounts of fine-grained material are present in the bed, however, the Shields approach may underestimate the lower range of flows that need to be controlled, and the upper range of flows that should be controlled might need to be higher than the Q_{10}.

It should be noted that the erosion potential concept approach depends on accurate selection of a representative stream reach, cross section, and bed and bank material to estimate the flow that will mobilize sediment. It also requires characterization of erosion in that reach to calibrate the model. Importantly, the approach cannot be applied meaningfully to streams that are already unstable and eroding – a condition that characterizes many streams in the Central Coast Region. The erosion potential concept is also incomplete without considering that reductions in upstream sediment load can lead to channel instability – channels may degrade without a source of sediment to replace the eroded material. This point was reviewed extensively during the preparation of the San Diego Hydromodification Management Plan (Brown and Caldwell, 2010).

2.5. Summary and Relevance to Watershed Goals for the Central Coast

The last twenty years of stormwater management in the Pacific Northwest has been shadowed by the more recent trajectory throughout much of California. Recognition of the inadequacies of historic stormwater-management goals and strategies were documented most fully through measurement of physical channel characteristics and their rates of change. More restrictive standards for stormwater release focused on those flows presumed to erode the channel boundaries, and new analytical techniques were developed that could express the appropriate hydrologic parameters in user-friendly software packages. But even as these criteria, approaches, and techniques were being refined, a growing scientific awareness was warning that “stream stability” (what we characterize in this report as the “narrow” focus of hydromodification) is an inadequate goal for the protection of beneficial uses and achievement of the goals of physical, chemical, and biological integrity of the Clean Water Act. In the state of Washington, this was freely acknowledged by the primary stormwater regulatory body (the Washington State Department of Ecology) without any corresponding change in regulatory focus; a broadening of regulatory goals has required the subsequent actions of a superior judiciary body.

In contrast, the regulatory bodies in California remain primarily or exclusively absorbed with the narrow focus of hydromodification control. The Central Coast Regional Water Quality Control Board is presently alone in articulating the broader goal of achieving “long-term watershed protection” through its HMPs. Although the Board is arguably a leader in the California regulatory arena, their goal is hardly unprecedented. The approach being taken in this project to analyze watershed conditions and identify the key watershed processes needing protection has a long history in the scientific literature, which we now review in Section 3.

3. Watershed Health—The “Broad Perspective” on Hydromodification

The broad perspective on hydromodification takes an integrated watershed approach to managing potential impacts resulting from human activities. Indeed, it may include flow control to protect stream stability (the “narrow perspective,” discussed in Section 2), but only as one aspect of a broader approach to hydromodification control, and only where this component is necessary for the protection of beneficial uses in a particular watershed setting. As the previous section makes clear, the applications of flow control has been largely focused on maintaining stable stream channels by limiting the aggregate erosional work done on the channel boundary by the post-development hydrologic regime. In some cases, this is the end goal itself; for others it has been recognized as simply an indicator of a broader suite of desired outcomes, albeit without any additional analyses identified.

For the present Central Coast Joint Effort, however, the explicit intent is to develop a framework that can be used to protect and maintain the full suite of beneficial uses and ecosystem services associated with the hydrologic network (“watershed health”) from adverse impacts associated with human activities. To develop such an approach it is first necessary to identify the key watershed processes (and their spatial distribution) across the region that will require protection if watershed health is to be maintained. This framework will guide effective control strategies to achieve this protection, and the methodology for determining appropriate hydromodification control criteria throughout the Central Coast Region. We note that these later “implementation” steps do not have much representation in the regulatory (or scientific) literature; their development is the primary goal of Phase 1 of the present Joint Effort. We also note that the process-based studies reviewed below do not, in and of themselves, provide any guidance or assessment of watershed “health.” Such assessments, ultimately necessary to evaluate the success of management actions, are widely available for physical, chemical, and biological attributes of (particularly) streams and lakes, and to a lesser extent for groundwater and nearshore areas. They will be invoked in subsequent phases of the Joint Effort but are not the focus of the present literature review.

Although recent efforts to develop hydromodification management plans in California provide little precedent for an overall watershed health approach, there is ample scientific precedent. In addition, such a broad approach is consistent with USEPA’s (1993, 2007) national guidance on hydromodification.

The tools needed to support the development of a “watershed-health approach” to hydromodification control are largely articulated in published scientific literature, and they focus on the spatial analysis of landscapes. Stratification of a landscape into discrete categories (and the identification, or presumption, of unique characteristics associated with each group) is a foundational principal of large-scale environmental studies. Identifying and grouping dominant landscape characteristics into discrete spatial units has been the foundation of soils and geologic mapping for hundreds of years. The use of such units in hydrological and geomorphological applications is more recent, however, although it too has been explored for more than 40 years (see below).

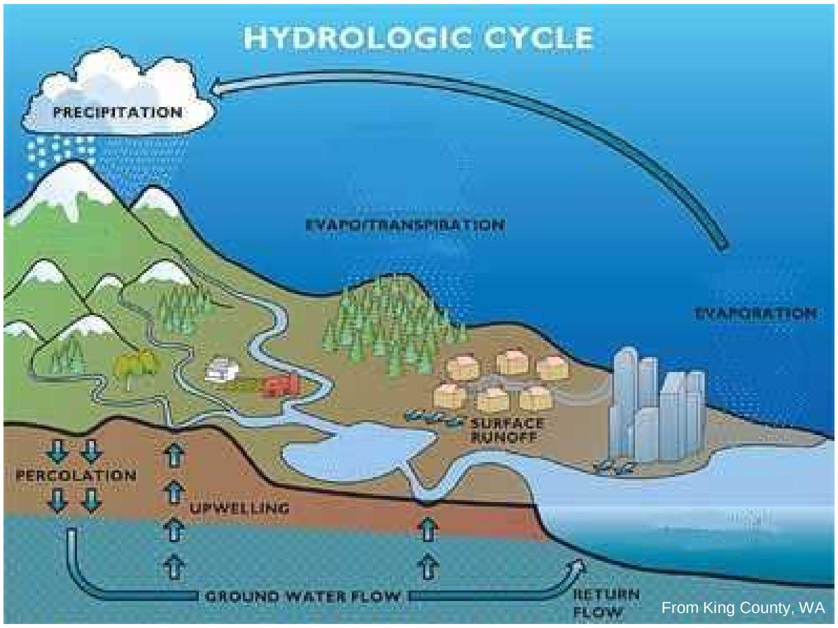
With the advent of more widely available spatial data sets, spatial analysis is now receiving progressively greater attention in both scientific studies and management applications. A variety of applications based on this general approach have been demonstrated to efficiently aid watershed researchers and management agencies in focusing their attention on the dominant physical processes present within a relatively small number of landscape areas, or “units,” which can then be extrapolated to units sharing similar characteristics across a larger area of interest. In effect, this “landscape-unit delineation” approach enables one to group spatially defined landscape components together (such as topography, land cover, and geology) that are expected to exhibit similar hydrologic or geomorphic characteristics in a given watershed. It can reduce the seemingly infinite complexity of a landscape into tractable groupings, and it can allow an analysis to focus on the most important processes that are active within each unit.

Once these units are established, specific watershed processes (whether hydrological, geomorphological, or ecological) can be qualitatively evaluated or selectively measured within a sampling of each unit type. These results can then be extrapolated to the greater population of common landscape units within the remainder of the watershed or region. Overall, this approach provides a useful, rapid framework to identify key watershed processes and, potentially to estimate their time-averaged rates under both undisturbed and human-influenced conditions. This can provide the basis to identify whether, and where, hydromodification control measures (in the broadest sense) may be needed.

To date, a range of peer-reviewed publications have developed or applied such watershed-process frameworks. Although many are not specific to southern California or the Central Coast Region, they provide both guidance for the present study and support for its application here.

3.1. Hydrological Processes

The delivery, movement, storage, and loss of water within a watershed constitute a set of key watershed processes that are most commonly represented by the hydrologic cycle.



Components of the hydrologic cycle constitute the fundamental hydrological processes that are active in any watershed: precipitation, surface runoff, infiltration, groundwater flow, return flow, surface-water storage, groundwater storage, evaporation and transpiration. Although present virtually everywhere across a watershed, these individual processes vary greatly in their importance to watershed health and functions. Recognizing their magnitude and spatial distribution has been a long-standing effort of landscape studies.

The term “Hydrologic Response Units” [HRUs] has more than four decades of use in the scientific and engineering literature. It first appeared in print in England and Holtan (1969) who noted “Soil properties significant to processes of infiltration, moisture storage, drainage, and the hydraulics of surface flow are related to topographic position. Areal and elevational distributions of soils provide a basis for interpretative grouping of soil mapping units in computations for watershed engineering…Profile characteristics, areal distribution, and relative elevation position of the units determine watershed response to storm rainfall.”

Thus, these authors were drawing a direct correlation between soil properties and the hydrologic response of a watershed, and they inferred those soil properties by assessment of their position on the landscape. They cited nearly 40 years of prior research that establish a basis for this inference, and they used this conceptual basis to define HRUs as landscape areas that “are internally homogeneous enough to be used as computational units in mathematical models simulating the hydrologic performance of agricultural watersheds.” This is the earliest, explicit statement of the approach that has seen continued development and refinement up through the present day. The studies described below all proceed from this common foundation.

3.1.1. Beighley *et al.* (2005) – “Understanding and modeling basin hydrology: interpreting the hydrogeological signature”

Beighley *et al.* (2005) presented an approach for modeling basin hydrology by determining the fundamental hydrologic components of a watershed and mapping areas that are expected to exhibit similar runoff mechanisms and runoff. The authors’ primary goal of developing this approach was to create a new rainfall-runoff model that could simulate both surface and subsurface runoff in a mixed rural and urban setting, which was subsequently applied to four gauged coastal watersheds near Santa Barbara, California to validate their modeling approach. The authors have essentially presented an enhanced approach to the hydrological response unit (HRU) method—a process of differentiating the landscape into discrete units possessing similar rainfall-runoff (i.e., surface) characteristics—by including hydrogeological interpretations to incorporate interflow and groundwater runoff sources, in addition to surface sources, to estimate streamflow at the outlet of a study watershed. This study is especially noteworthy relative to the Joint Effort since its field area is wholly contained within the Central Coast region.

In general, the HRU approach holds that landscapes possess an identifiable spatial structure (or “hydrogeological signature”), and that the corresponding patterns of runoff and stream chemistry are strongly influenced by climate, geology, and land use. The primary sources of spatial data used in their study were topography, drainage network (both natural streams and storm water systems), hydrologic soil characteristics, land use, and long-term precipitation; all of these datasets were freely available from state and local agencies. The authors applied the HRU approach along with their hydrogeological interpretation approach to simulate streamflow from three sources of runoff (i.e., surface, interflow, and groundwater) in their study watersheds. This was achieved by: (1) determining the fundamental hydrologic components of a watershed and mapping areas that are expected to exhibit similar runoff processes and pathways; and (2) developing, parameterizing, and calibrating a rainfall-runoff model using streamflow and suspended sediment concentration measurement data, which was also freely available from USGS stream gauging stations located throughout the study watersheds. The authors contend that by grouping the watershed into regions of similar runoff processes and considering only those active processes found to occur in each unit, they were able to reduce the parameterization and calibration of non-existent processes while providing physically meaningful, quantitative measures that aid in characterizing the inferred processes. Overall, this enhanced approach allowed for a more efficient hydrological modeling procedure which ultimately was found to produce reasonable streamflow predictions that agreed well with observed conditions (mean errors in peak discharge and runoff volume of <10%).

This study demonstrates an approach to landscape analysis that is entirely analogous to that contemplated for the Joint Effort—namely, analyzing specific landscape attributes that can be readily characterized in a GIS environment in order to infer the key watershed processes at every location across a region. This study, by virtue of its limited extent, not only applied such an analysis but also validated the results with measured streamflow data. It therefore provides a proof-of-concept for the approach, one that further supports the Joint Effort by virtue of being conducted within the same geographical area.

3.1.2. Shiels (2010) – "Implementing landscape indices to predict stream water quality in an agricultural setting: an assessment of the Lake and River Enhancement (LARE) protocol in the Mississinewa River watershed, east-central Indiana"

In this paper, Shiels (2010) sought to link landscape indices to stream water quality in a predominately agricultural landscape in central Indiana. The specific landscape indices consisted of three natural-area extent characteristics (e.g., land cover) and three natural-area disturbance characteristics (e.g., drained lands), while four water-quality variables were considered (i.e., total phosphorus, nitrate, *E. coli*, and macroinvertebrates). However, the author found that regressions were not found to be significant for any of the four water-quality variables. He suggested that the inability to capture relationships between the indices and response variables may have been based on the uniformity of the study landscape, where homogenous agricultural land cover (>80% row crop land use) likely prevented successful correlation of the landscape indices to water quality. The plausible finding of this study is that, unlike the flat, uniformly farmed landscape of the mid-west region of the United States, those landscapes with varied physical characteristics (such as the southern Coast Range province) are likely better suited for application of a landscape-unit methodology to predict local or regional water quantity and quality conditions. For the Joint Effort, however, it also provides a reminder that specific measures of "watershed health" (in this case, water-quality constituents) may not provide direct causal relationships. In this example, the authors found that relative modest differences in land cover do *not* produce a discernable signal in those health measures. This raises the potential that the sensitivity of the metrics may not always meet the needs of such an approach.

3.1.3. Wolock *et al.* (2004) – "Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses."

Wolock *et al.* explored the value of using geographic information system (GIS) tools and statistical analyses to identify and group similar landscape areas. They were applied to land-surface form, geologic texture (permeability of the soil and bedrock), and climate variables that describe the physical and climatic setting of 43,931 small (approximately 200 km^2) watersheds in the United States. They used variables of topography, geology, rainfall, and potential evapotranspiration to predict the dominant hydrologic runoff process (overland flow, shallow subsurface flow, and groundwater flow); they also explored correlations with several ecological and water-quality response variables.

Their "hydrologic-landscape regions" [HLRs] were compared to various physical and biological attributes from the entire area of the continental United States, grouped into (1) 19 square geometric regions (i.e., areas with no intrinsic "meaning" or internal similarities) and (2) the 21 U.S. Environmental Protection Agency level-II ecoregions. Hydrologic-landscape regions generally were better than ecoregions at delineating regions of distinct land-surface form and geologic texture. Hydrologic-landscape regions and ecoregions were equally effective at defining regions in terms of climate, land cover, and water-quality characteristics.

They note, "The approach used to define HLRs is objective in the sense that it is based on statistical methods applied to digital geospatial data. Subjective expert judgment, however, is required in making several choices required for the analysis: (1) the particular set of variables used, (2) details in the statistical analyses, and (3) details in the GIS analyses." Thus, it is not a fully automated process, and a different choice of criteria would result in a different suite of attributes and correlations—the outcomes (and, presumably, their utility) are dependent on the framework of the analysis. For the Joint Effort, the lesson here is that the method for grouping and analyzing watershed attributes is neither "automatic" nor obvious, but that a successful approach should provide significantly better discrimination and prediction of response variables (i.e., indicators of "watershed health") than simply assuming that all parts of the Region are equivalent and will respond identically to the same disturbance (or the same mitigation).

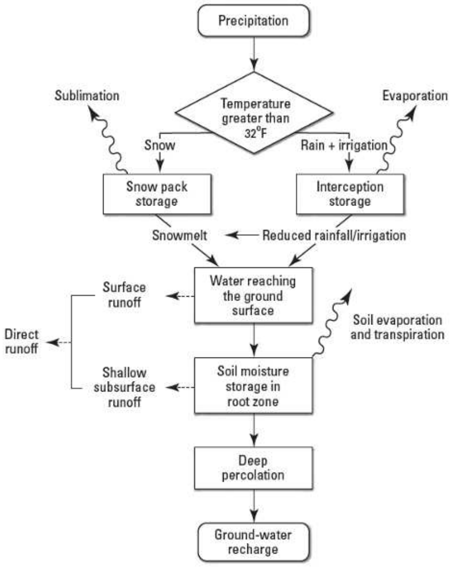
3.1.4. Carlisle *et al.* (2010) – "Predicting the natural flow regime: Models for assessing hydrological alteration in streams"

The objective of this study was to evaluate whether selected streamflow characteristics could be predicted at regional and national scales using geospatial data. Statistical models were developed to predict the value for a variety of streamflow metrics in undisturbed, gaged watersheds by using natural watershed characteristics. These characteristics were those that form the basis for ecoregions and for hydrologic-landscape regions [HLRs; Wolock *et al*. 2004], and they comprised attributes of basin topography and geographic location, climate (monthly and annual means), soil properties, and geology.

They compared the performance (i.e., bias and precision) of national- and regional-scale predictive models to that of models based on landscape classifications, including major river basins, ecoregions and HLRs. For all hydrologic metrics, landscape stratification models produced estimates that were less biased and more precise than a null model that accounted for no natural variability. Prediction error rates ranged from 15 to 40%, but were 25% for most metrics. They present three examples to show how the models accurately estimate predisturbance conditions and are sensitive to changes in streamflow variability associated with long-term land-use change, and how the models can be applied to predict expected natural flow characteristics at ungaged sites. Similar to the previous study, these results emphasize the value of discriminating different parts of the landscape—one size does *not* fit all.

3.1.5. Vacarro (2006) – "A deep percolation model for estimating ground-water recharge"

Although the primary focus of the preceding references is surface and near-surface flow, groundwater movement and aquifer recharge are important hydrologic processes in parts of the Central Coast region. Owing to the complexity (and obscurity) of most subsurface hydrologic systems, the development of watershed-process frameworks that explicitly include groundwater has lagged behind those of surface water. Those existing efforts either address a limited range of groundwater processes (typically, near-surface recharge rates only) or else embrace a level of complexity that is unlikely to be feasibly applied across a large and heterogeneous area.



Conceptual daily time-step routing of precipitation used in the Deep Percolation Model water-budget calculations. From Vacarro 2006

This figure displays the range of parameters that are used to characterize surface water–groundwater interactions in the US Geological Survey's "Deep Percolation Model," which is designed to estimate the potential quantity of recharge to an aquifer via the unsaturated zone. The modeled region, watershed, or area is subdivided using the same conceptual framework (and terminology) of several of the references previously discussed: Hydrologic Response Units (HRUs) are defined such that the hydrologic response is assumed to be similar over the entire area of an HRU, which is characterized by land use, land cover, and soil properties. Meteorological properties that are used to predict the delivery and near-surface movement of water are precipitation, temperature, and solar radiation.

Although this analytical approach is likely too detailed for regional application, it indicates the types of landscape-scale indicators that have been judged important for characterizing the magnitude (and, more qualitatively, the importance) of groundwater-related hydrological processes across a watershed. It also provides further affirmation that this overall framework for analyzing hydrological processes has a firm basis in the published scientific literature.

3.2. Geomorphological Processes

Geomorphological processes are a second set of watershed processes that strongly influence watershed health and function. They broadly refer to the movement or deposition of sediment, driven largely but not exclusively by the movement of water, that affect the land surface—in the Central Coast region, these primarily include erosion, landsliding and other mass wasting, and sediment transport and deposition in stream channels. Their magnitude and distribution across different landscapes has also been the focus of much scientific study, albeit for not nearly as long as for their hydrological counterparts.

3.2.1. Montgomery (1999) – “Process domains and the river continuum”

Much like the Hydrologic Response Units (HRUs,) Montgomery (1999) introduced the concepts of *process domains* and *lithotopo units* to provide a framework for analysis of complex landscapes. Although the author presented these concepts in the context of introducing an improved means to understand the linkages between geomorphic processes and the ecology of (specifically) mountain drainage basins, the framework described can also be applied to other physiographic provinces. Ultimately, the suite of landscape-forming processes that are distributed over a landscape, and that govern watershed characteristics and processes, are influenced by climate, geology, and topography. Within a given watershed or larger region of a given geomorphic province, the tectonic setting and climate history exerts a primary control over bedrock type, soil development, and topography. Geomorphic provinces discriminate areas having different physiography, bedrock type and structure, and climate. At a finer scale, lithotopo units define areas with similar geology (i.e., lithology) and topography. Finally, process domains define specific areas where distinct geomorphic process zones occur.

Overall, the Process Domain Concept (PDC) provides for a means to define and map domains within a watershed characterized by different geomorphic processes, disturbance regimes, response potential, and recovery time. The article presented an example of applying the PDC to a generic mountain drainage basin where: (1) the headwaters domain is characterized by convex planform hillslopes with hollows dominated by colluvial sediment production in which fire and wind are the dominant geomorphic disturbance processes; (2) the channel network domain situated down-gradient of the headwaters domain is characterized by steep, confined colluvial and alluvial channels dominated by scour by debris flows originating in upslope hollows; and (3) the fluvial lowland domain that represents the downstream portion of this conceptual watershed is characterized by low gradient alluvial channels that have built a laterally extensive floodplain and experience channel migration and avulsions driven primarily by large flood events. The article offers further support the PDC by showing several examples from other published studies that have shown strong spatial correspondence between landscape units and significant differences in landscape attributes, such as spatial patterns of landslides, soil moisture, and vegetation cover types (see also Hack and Goodlett 1960).

The relevance of this study to the Joint Effort lies in its promise that “domains,” where one or another geomorphic process is dominant, can be inferred and then mapped by reference to basic topographic and geologic information. This is the fundamental task of any effort at landscape stratification—given the great variability in local conditions and resulting processes, how can more general patterns be recognized in an efficient and meaningful fashion?

3.2.2. Warrick and Mertes (2009) – "Sediment yield from the tectonically active semiarid Western Transverse Ranges of California"

The principles of landscape stratification as described by Montgomery (1999) have been well-displayed in a local application by Warrick and Mertes (2009), who focused on estimating sediment yields from three major watershed regions that drain the Transverse Mountain ranges in southern California: Santa Clara River, Ventura River, and Santa Ynez Mountain drainages. Overall, this tectonically active, semiarid region exhibits high sediment yields in comparison to those in the surrounding areas of California—a product of relatively high uplift rates, steep drainages, weak lithologies, and (in many locations) intensive land-use impacts. The authors used statistical correlation methods to investigate whether combinations of certain landscape attributes relate to sediment yields from a given drainage. The authors contend that, in the absence of significant storage zones, sediment yield is generally greatest in areas with high relief, high rates of uplift, and intensive land use, whereas precipitation and other climatic factors have been found by other researchers to have nonlinear effects on sediment yield (e.g., Langbein and Schumm 1958, Molnar 2001). Their study area overlaps with that of the Central Coast region, and their results should be broadly applicable here as well. Their list of primary controls on the geomorphic processes in the region provide an excellent starting point for selecting indicators to characterize these processes within the Joint Effort.

Using available stream flow and sediment discharge data collected by the USGS at several locations throughout the authors' study watersheds, they were able to create mean annual water and suspended-sediment budgets. The results of their correlation analyses, which relied upon GIS-ready topography, precipitation, geology, and land-use data, revealed that sediment yield is variable in the study watersheds and is consistently correlated with lithologic and land-use characteristics of the watersheds. Specifically, the authors found that sediment yield was best correlated with the youngest marine sedimentary bedrock (i.e., the weakest rocks) and barren or human-modified land uses (i.e., minimal vegetation cover but not urbanized). Extensive large-scale mass wasting processes, including landslides and debris flows, are a ubiquitous feature on landscapes underlain by the young marine sedimentary formations, which also coincides with the regions of greatest reported uplift (>5 mm/yr) and are also highly correlated with barren lands. This is an important (though perhaps obvious) result, insofar as a dense vegetation coverage that would otherwise act to hinder erosion by binding soils and intercepting downward moving sediments cannot establish on highly erodible, steep surfaces.

In contrast, the authors found that landscapes underlain by older granitic and metamorphic formations exhibit the lowest sediment yields in the region. With respect to land-use effects, the authors cite the work of other researchers who have found that landscape denudation rates, and in turn sediment yields, are higher under grassland cover than under native chaparral (e.g., Gabet and Dunne 2002). The authors found other watershed characteristics to be statistically significantly related to measures of sediment discharge, including drainage basin area and slope, yet these were found to have only second-order effects across the study area.

In conclusion, the authors cautioned other researchers working in semiarid regions exhibiting high sediment yields against naïve extension of sediment-discharge results from one watershed to another using techniques such as uniform sediment yield or transferred sediment rating curves, because subtle differences in landscape characteristics or processes may significantly influence denudation rates. Therefore, one should consider simple process-based evaluations of landscape denudation to eliminate these localized errors. These findings are particularly relevant for the Joint Effort, because they emphasize the value of "simple" (yet relevant) characterization of landscape conditions to identify and quantify geomorphic processes. They also highlight the importance of choosing the correct scale for analysis. Detailed, site-specific data are likely to provide the best information for the site at hand but will also introduce unavoidable biases, suggesting high precision but not necessarily more accurate data for a region as a whole.

3.3. Integrated Landscape Processes

3.3.1. The Center for Watershed Protection (2003) – "Impacts of Impervious Cover on Aquatic Systems", and the use of biological indicators to assess watershed health

Although an admittedly simplified approach for analyzing the complexity of human impacts on watershed processes, the use of imperviousness can be recognized as a watershed-scale index for the impact of urban and suburban development (in particular) on a broad range of landscape processes. As summarized in National Research Council (2009), "The Impervious Cover Model (ICM) is a management tool that is useful for diagnosing the severity of future stream problems in a subwatershed. The ICM defines four categories of urban streams based on how much impervious cover exists in their subwatershed…the ICM is then used to develop specific quantitative or narrative predictions for stream indicators within each stream category. These predictions define the severity of current stream impacts and the prospects for their future restoration. Predictions are made for five kinds of urban stream impacts: changes in stream hydrology, alteration of the stream corridor, stream habitat degradation, declining water quality, and loss of aquatic diversity" (p. 190). The impact of urbanization on water quality should be emphasized, since it is often linked to declines in watershed health. Development usually leads to an increase in runoff volume and a change in land surface composition that increases pollutant loading and transport.

In other words, watershed imperviousness can be used as a simple-to-measure index of the variety of impacts to watershed processes; research both preceding and subsequent to the 2003 publication have emphasized its broad applicability, together with reminders of the variety of individual watersheds that do not match its predictions of waterbody conditions precisely. To test those predictions of watershed health, many of those studies have utilized biological indicators because of their similarly integrative expression of waterbody condition. As noted in the introduction, a complete exposition of their development and application is beyond the scope of this review, but the development of multimetric biological indices for such applications is described in Karr and Chu (1999); its application to urbanizing watersheds of the Pacific Northwest is reported (for example) in Morley and Karr (2000), and to southern California coastal streams by Ode *et al.* (2005).

3.3.2. Istanbulluoglu (2009) – "An eco-hydro-geomorphic perspective to modeling the role of climate in catchment evolution"

This review paper emphasized the importance of integrated ecological, hydrological, and geomorphological processes to the development of landscapes and their behavior under current and future climates. His Figure 1 (reproduced below) provides a worthwhile conceptual framework that embraces much of the multi-scalar aspects of Montgomery (1999). It also highlights a potential limitation of the present hydromodification study, namely that significant elements of his framework may *not* be included (particularly the full characterization of how ecological processes interact with the physical ones). Thus, it should provide a reminder of the limitations, as well as the opportunities, that the present approach may have.

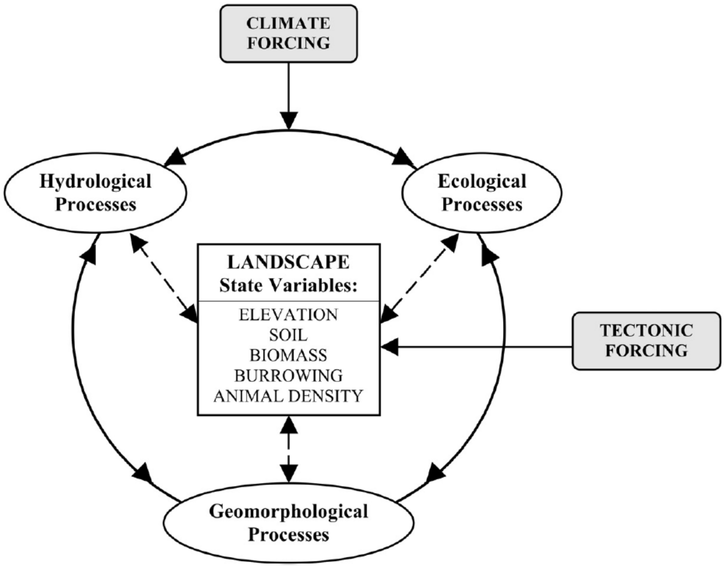


Fig. 1. A conceptual diagram depicting the interactions among biological and physical Earth surface processes in landscape evolution. Dashed lines represent the two-way interactions between landscape variables and processes.

He concluded, "To guide and promote field observations and modeling, an eco-hydro-geomorphic basin classification system, involving certain aspects of regional climate, hydrology, ecology, and geology, would be critical to advance this exciting new landscape system modeling endeavor (p. 1168)." Although this presently lies beyond our reach, it invokes the very approach, however incomplete, that our present study is pursuing.

3.3.3. Puget Sound Watershed Characterization Project

This ongoing project, a Washington State and USEPA-support project focused on the land area and watersheds draining to Puget Sound, has the overall goal of characterizing the key watershed processes in the region to assess their relative importance to aquatic resources and beneficial uses and to determine their relative impairment as a result of human activity. Its approach is to identify areas of the landscape that are important for maintaining specific watershed processes, with intended applications to land-use planning and prioritization of restoration projects and conservation acquisitions. It is executed entirely in a GIS environment, drawing on the following data sources:

- Geology and soils
- Topography and hydrography
- Climate
- Stream confinement
- Wetlands
- Land cover
- Fish distribution

To date (Stanley *et al.*, 2009), a complete "analysis module" has only been completed for one watershed process, namely water flow. It has been applied in several pilot projects for selected watersheds in both the north (ESA Adolfson, 2007) and south (see http://www.co.thurston.wa.us/stormwater/chara/chara-home.html) Puget Sound. The second phase of this project, which is running concurrently with the Central Coast Joint Effort and is scheduled for completion in June 2011, will add additional data sources and analysis modules to evaluate the watershed processes associated with water-quality conditions and, potentially, those influencing sediment movement and (important in the Pacific Northwest) the flux of large woody debris. The scale of this effort is driven by the analysis area (the Puget Sound watershed, about 6000 mi^2 which is comparable to the Central Coast region) and the “grain” of the component data layers (typically 10-m to 30-m pixels for the raster data). The data sets being used are broadly (and, in many cases, precisely) equivalent to those anticipated for the Joint Effort. However, the Puget Sound effort has a wider scope than even the “broad” definition of hydromodification (e.g., various water-quality constituents; delivery and movement of large woody debris). At the same time, its applications are explicitly limited to addressing planning-level decisions rather than seeking to meet a range of regulatory obligations.

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