FINAL REPORT

Development and Implementation of Hydromodification Control Methodology

The Linkage Analysis: Landscape Characterization, Receiving-Water Conditions, Watershed Processes, and Human Disturbance

Prepared for:

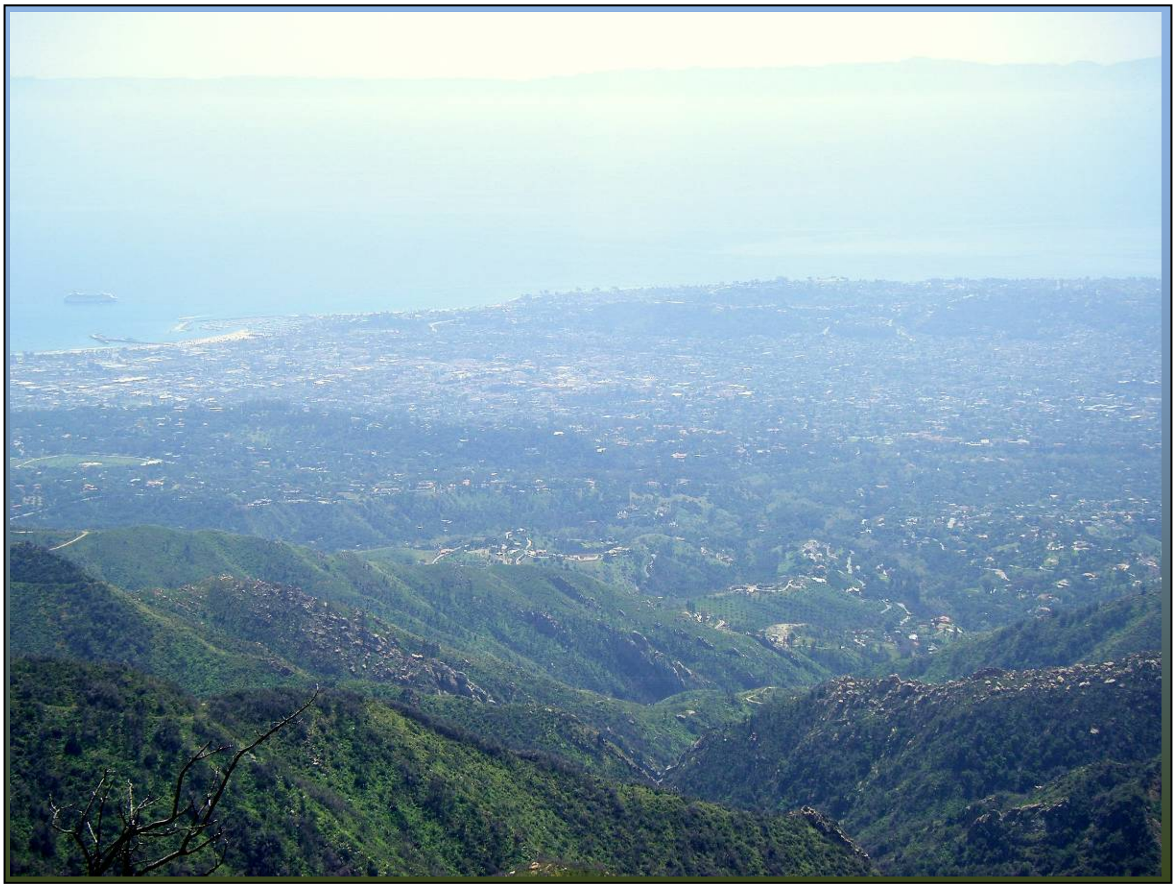
Central Coast Regional Water Quality Control Board
895 Aerovista Place, Suite 101
San Luis Obispo, CA 93401

Prepared by:

Stillwater Sciences
P.O. Box 904
Santa Barbara, CA 93102

Tetra Tech
301 Mentor Drive, Suite A
Santa Barbara, CA 93111

December 30, 2011



Frontispiece: View southeast across multiple "Physical Landscape Zones," from the steep bedrock in the foreground down to flat and geologically recent lowland terraces, now largely blanketed by urban development in the City of Santa Barbara.

Suggested citation:

Booth, D.B., E.A. Gilliam, S. Araya, and C. Helmle. 2011. The linkage analysis: landscape characterization, receiving-water conditions, watershed processes, and human disturbance. Prepared by Stillwater Sciences and TetraTech, Santa Barbara, California, for California State Central Coast Regional Water Quality Control Board, 62 pp.

EXECUTIVE SUMMARY

The Purpose of Task 4 of the Joint Effort is to identify the relationships between dominant watershed processes, disturbance, and receiving-water conditions. These relationships can provide the scientific basis for watershed management decisions, and they can be summarized in a simple conceptual model as follows:

IN AN UNDISTURBED ("INTACT") LANDSCAPE:

The Physical Landscape →
Watershed Processes →
Receiving Water Conditions

IN A DISTURBED (SPECIFICALLY, URBANIZED) LANDSCAPE:

The Physical Landscape →
Disturbance →
Disturbed Watershed Processes →
Disturbed Receiving Water Conditions

This framework implies two primary "linkages"—the first, the association of the attributes of the physical landscape with their associated key watershed processes; and the second, the relationship between those watershed processes and downstream receiving-water conditions. It also recognizes the importance of *disturbance* in those associations, which for the Joint Effort specifically focuses on areas and conditions affected by urbanization; and, subsequent to that understanding, the consequences of urbanization on receiving-water conditions.

The full Task 4 report is organized into four sections:

- Section 1 provides an introduction and a roadmap for the document.
- Section 2 summarizes the findings from Tasks 2 and 3 (prior reports from the Joint Effort), including an overview of the Central Coast Region's "Physical Landscape Zones" (PLZ's; originally termed "Watershed Management Zones" in the Task 3 report) and identifies the dominant watershed processes in the Central Coast Region and their typical distribution across both intact and disturbed watersheds.
- Section 3, the "Linkage Analysis," evaluates the observed and presumed relationships between dominant watershed processes, disturbance, and receiving-water conditions in the Central Coast Region.
- Section 4 offers a preview of work to be accomplished in Task 5 of the Joint Effort, scheduled for completion in early 2012.

From the conditions observed across the broadly undisturbed landscape areas of the Central Coast Region during Task 3 of the Joint Effort, fifteen landscape categories (plus "open water"), coarsely defined on the basis of lithology and hillslope gradient, provide a regional discrimination of landscape types and dominant watershed processes in undisturbed landscapes (Table 1 and

Figure 1). These categories were defined using just two factors—lithology (i.e., the underlying rock/sediment) and hillslope gradient—that both theory and observation suggest to be the primary determinants of watershed processes in the "natural" (i.e., undisturbed) landscape. Other factors of potential relevance, including the spatial variability of precipitation and the influence of different vegetation types in undisturbed watersheds (e.g., trees vs. shrubs vs. grasslands in progressively drier parts of the Region) are also assessed.

Table 1. PLZ areas as a proportion of the Central Coast Region. A summary description of the major PLZ's is provided in Appendix A, and their distribution is shown in Figure 1.

Physical Landscape Zone (based on lithology [geologic material] and hillslope gradient [% slope])	% of total area	
Franciscan mélange; 0–10%	0.5%	8%
Franciscan mélange; 10–40%	5%	
Franciscan mélange; >40%	2%	
Pre–Quaternary crystalline rocks; 0–10%	1%	23%
Pre–Quaternary crystalline rocks; 10–40%	11%	
Pre–Quaternary crystalline rocks; >40%	11%	
Early to Mid–Tertiary sedimentary; 0–10%	2%	30%
Early to Mid–Tertiary sedimentary; 10–40%	16%	
Early to Mid–Tertiary sedimentary; >40%	12%	
Late Tertiary sediments; 0–10%	1%	6%
Late Tertiary sediments; 10–40%	4%	
Late Tertiary sediments; >40%	2%	
Quaternary sedimentary deposits; 0–10%	18%	33%
Quaternary sedimentary deposits; 10–40%	14%	
Quaternary sedimentary deposits; >40%	1%	
Open water	0.4%	0.4%

By reference to Table 2, the primary changes to watershed processes as a result of urbanization can be summarized as follows:

Infiltration and groundwater recharge: These closely linked hydrologic processes are dominant across most intact landscapes of the Central Coast Region. Their widespread occurrence is expressed by the common absence of surface-water channels on even steep (undisturbed) hillslopes. Thus, on virtually any geologic material on all but the steepest slopes (or bare rock), infiltration of rainfall into the soil is inferred to be widespread, if not ubiquitous. With urbanization, changes to the process of infiltration are also quite simple to characterize: some (typically large) fraction of that once-infiltrating water is now converted to overland flow.

Overland flow: This process can be thought of as the inverse of infiltration; precipitation reaching the ground surface that does not immediately soak in must run over the land surface (thus, "overland" flow). It reflects the relative rates of rainfall intensity and the soil's infiltration capacity: wherever and whenever the rainfall intensity exceeds the soil's infiltration capacity, some overland flow will occur. Most uncompacted, vegetated soils have infiltration capacities of one to several inches per hour at the ground surface, which exceeds the rainfall intensity of even unusually intense storms of the Central Coast and so confirms the field observations of little to no overland flow reported in Task 3. In contrast, pavement and hard surfaces reduce the effective infiltration capacity of the ground surface to zero, ensuring overland flow regardless of the meteorological attributes of a storm, together with a much faster rate of runoff relative to vegetated surfaces.

Rilling and gullying: These hillslope processes are the geomorphological expression of the hydrologic process of overland flow, and so the pattern of these two sets of processes are similar. However, they can diverge in several, fairly common settings. First, overland flow across flat surfaces will generate little or no erosion simply because the energy of the water is too low to transport sediment. Second, areas of likely overland flow where the substrate is strong (e.g., bare rock outcrops) will not produce corresponding gullying; conversely, a weak substrate may show evidence of significant surface erosion with only modest levels of overland flow (as long as slopes are sufficiently steep).

Table 2. The association of watershed processes with PLZ's, highlighting the qualitative magnitude of anticipated change for each process as a result of urbanization. Red-shaded cells indicate the greatest anticipated change (e.g., a "Low" importance for overland flow in many PLZ's is anticipated to become "High" in an urban watershed). Note that this tabulation does not explicitly include the movement or delivery of organic material; these processes are associated most strongly with high overland flow and its associated hillslope process (rilling and gullying).

PHYSICAL LANDSCAPE ZONE		WATERSHED PROCESS (and anticipated direction of urban-induced change: + increase, – decrease)						
Slope class	Geology	Overland flow (incl. sheetwash) (+)	Infiltration (–)	Interflow (–)	Groundwater recharge (–)	Creep (+)	Rilling and gullying (+)	Landsliding (+)
0–10%	Franciscan mélange	M	L	L	L	L	L	L
	Pre-Quaternary crystalline	L	M	M	L	L	L	L
	Early to Mid-Tertiary sed.	L	H	M	H	L	L	L
	Late Tertiary sediments	L	H	M	H	L	L	L
	Quaternary deposits	L	H	M	H	L	L	L
10–40%	Franciscan mélange	M	L	L	L	M	M	M
	Pre-Quaternary crystalline	M	L	L	L	L	L	L
	Early to Mid-Tertiary sed.	L	M	M	M	L	L	L
	Late Tertiary sediments	L	H	M	H	M	M	L
	Quaternary deposits	L	H	M	H	M	H	M
>40%	Franciscan mélange	H	L	L	L	H	M	H
	Pre-Quaternary crystalline	M	L	L	L	L	M	L
	Early to Mid-Tertiary sed.	M	M	M	M	L	M	L
	Late Tertiary sediments	H	M	M	M	M	H	H
	Quaternary deposits	M	M	M	M	M	H	H

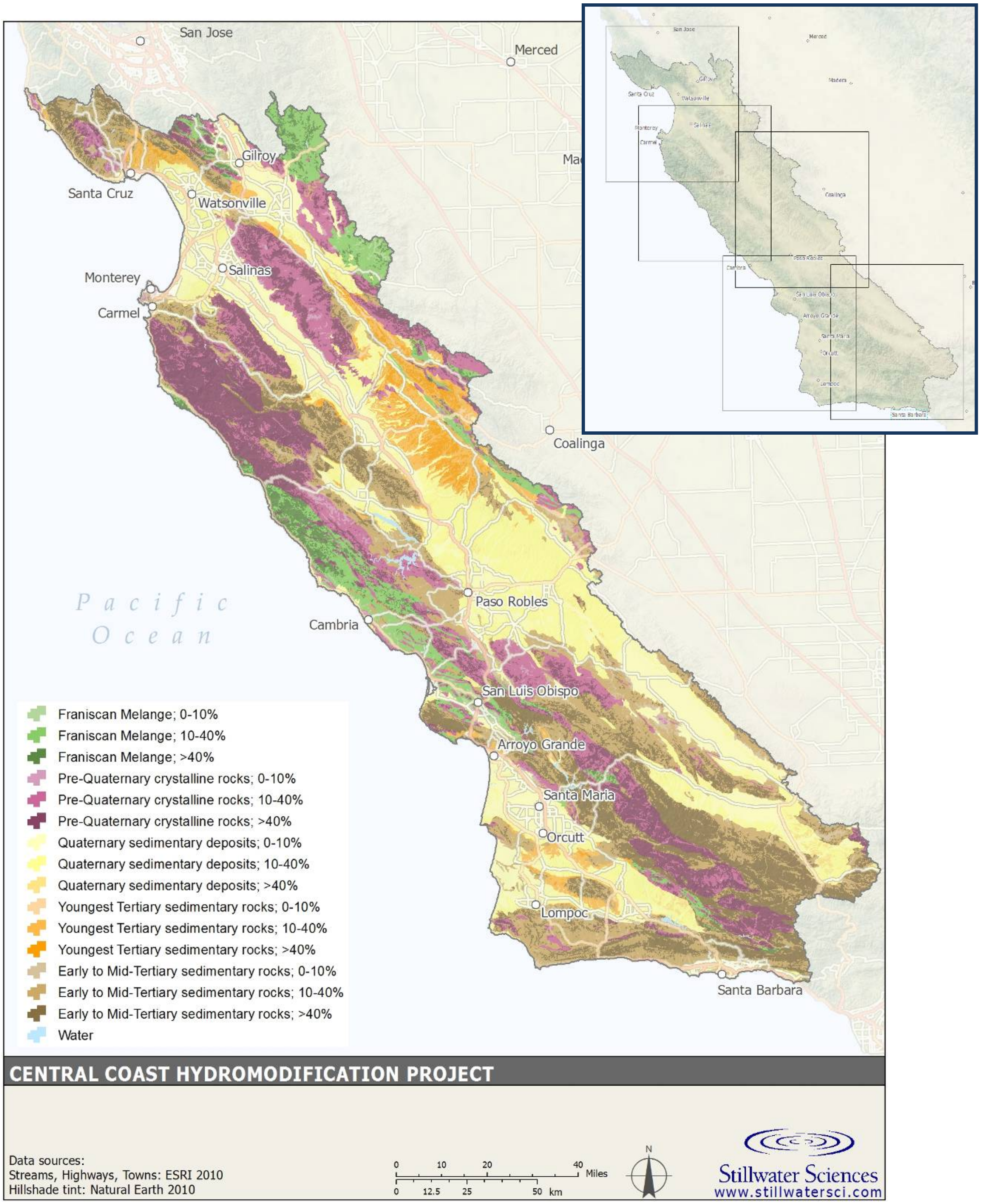


Figure 1. Final map of the Physical Landscape Zones, based on smoothed hillslope gradients and generalized geology units of Jennings et al. (1977), as developed from undisturbed watersheds with relatively intact vegetation cover. Detailed maps (inset) are reproduced in Appendix D at 1:750,000 scale (1″ ≈ 12 miles).

Receiving waters of the Central Coast are diverse, comprising streams, rivers, lakes, wetlands, marine nearshore, and groundwater aquifers. This report emphasizes *streams* and *stream channels* (as commonly defined, namely freshwater channels that flow at least episodically), because of their widespread distribution, readily expressed responses to disturbance, and availability of preexisting data. We recognize that the findings relating the condition of streams to watershed processes, and to their response to watershed disturbance, are relevant but not entirely transferrable to other types of receiving waters (Table 3).

Table 3. The major categories of receiving-water conditions (left column) and their applicability to evaluating the level of disturbance (or guiding the protection) of the various types of receiving waters.

CONDITIONS	RECEIVING WATER TYPE				
	Streams	**Large rivers**	**Lake/wetland**	**Marine nearshore**	**Groundwater aquifers**
Hydrology	X		X		X
Morphology and habitat structure	X	X			
Chemistry (water quality)	X	X	X	X	X
Biological health	X		X	X	

Stream conditions are assessed by reference to what is termed the "Classical Model"—the general characterization of how urbanization affects watersheds, watershed processes, and receiving waters developed over the past 50 years of scientific study. The Classical Model provides a variety of predictions for how receiving waters will respond to disturbance, which are largely supported by data from the Central Coast Region:

- Flows will be flashier, and with bigger peaks, in watersheds dominated by overland flow as a consequence of urbanization.
- Aquifer recharge from precipitation sources will decrease in response to decreased infiltration.
- Physical stream habitat will lose complexity in human-disturbed streams as a consequence of changes in runoff and sediment processes in the contributing watershed and/or loss of near-stream riparian vegetation.
- Water quality will decline in receiving waters draining urban and/or agricultural watersheds with the introduction of nutrients, pesticides, and toxics not present in the natural environment.
- Receiving waters will lose detrital material due to loss of upland and riparian vegetation.
- Instream biota will diverge from reference conditions in response to changes in biotic and abiotic processes in both the contributing watershed and the near-stream riparian zone.

Receiving waters are the products of their watersheds. In the Central Coast, observations and data on channel form, instream hydrology, and benthic macroinvertebrates paint a relatively consistent picture of the landscape and the nature of these receiving waters and their response to watershed disturbance, particularly the changes to watershed processes imposed by urbanization. These findings provide an important foundation for subsequent stages of the Joint Effort, whose explicit focus will be on the management of hydromodification in the Central Coast Region. In summary:

1. Infiltration and subsurface flow are the dominant hydrologic processes across all intact watersheds of the Region, regardless of the specific Physical Landscape Zone being considered. Different Physical Landscape Zones respond differently to the changes in watershed processes imposed by urbanization, but the shift from infiltration to surface flow is ubiquitous.
2. Geomorphology-based metrics of channel condition are not likely to provide clear guidance for evaluating biological health, and so hydromodification control plans based on meeting a particular geomorphic objective (e.g., "stable stream channels") is unlikely to achieve broader biological objectives. Stream-channel conditions can provide a useful diagnostic indicator of watershed disturbance, but managing to achieve a particular stream-channel form will not achieve other management objectives for the protection of receiving waters.
3. The consequences of urbanization on receiving waters other than streams is not well-documented and must be inferred, either by studies from other parts of the country or by extrapolation from stream-specific data. Much of the historical focus of hydromodification control on flow rates in small streams is (at most) marginally relevant, however, to the condition or health of other types of receiving waters. Conversely, certain water-quality constituents of limited concern in streams are critical to the health of non-flowing receiving waters, such as lakes, that lie at the downstream end of the channel network.
4. Linkages between hydrology, channel geomorphology, and biological health are undisputed, but the recovery of healthy watershed cannot be achieved by fine-tuning any particular flow attribute or reconstructing a desired geomorphic feature. Instead, it can only occur by restoring the degraded key watershed processes that can create and sustain these valued attributes.

Table of Contents

Tables

Figures

Appendices

1 INTRODUCTION

The goal of the Central Coast Joint Effort for Hydromodification Control is to protect or restore key watershed processes that otherwise would be (or have been) adversely affected by human activity. The Joint Effort is focused most immediately on defining hydromodification control strategies for new urban development and redevelopment, but the landscape characterization and analyses of this work can also provide a foundation for achieving broader objectives for the protection and restoration of aquatic resources. Because the natural balance of watershed processes in any area is dictated by the combination of intrinsic landscape attributes, climate, and disturbance, these are the three primary factors being carried forward throughout the individual tasks of the Joint Effort. Understanding the relationships between these factors, each of which varies across the Region, is judged to be essential for identifying and applying appropriate management strategies to protect and enhance the watersheds and receiving waters of the Central Coast. Describing these relationships is the primary goal of this report, which constitutes Task 4 of the overall Joint Effort.

To date, products of the Central Coast Joint Effort have included literature and data summaries (Task 1); a preliminary, GIS-based characterization of the landscape and watersheds of the Central Coast Region (Task 2); and the data- and field-supported identification of landscape attributes, watershed processes, receiving-water conditions, and primary disturbances present on that landscape (Task 3).

Task 4 comprises the analyses included herein. The primary elements are as follows:

- Section 2. Synthesis of findings from Tasks 2 and 3, including an overview of the Central Coast Region's "Physical Landscape Zones" (PLZ's; originally termed "Watershed Management Zones" in the Task 3 report), based on hillslope gradient and geologic material (Section 2.1); and identification of the dominant watershed processes in the Central Coast Region and their typical distribution across both intact and disturbed watersheds (Section 2.2). Also included in Section 2 are observations from the Central Coast that offer instructive exceptions to the typical interrelationships between processes, disturbances, and receiving-water conditions that are broadly observed here and elsewhere (Section 2.3).
- Section 3. Analysis of the observed, inferred, and (as necessary) presumed relationships between dominant watershed processes, disturbance, and receiving-water conditions in the Central Coast Region (in short, the "Linkage Analysis"). Stream systems are emphasized in this analysis because they provide the richest and most detailed expression of these linkages; once defined, however, the responses of streams also permit substantive inferences for the linkage of watershed processes to other receiving waters (e.g., lakes, groundwater aquifers, marine nearshore).
- Section 4. Outline of the work to be accomplished in Task 5, which will translate the scientific foundation of the Linkage Analysis into support of management actions. This will include: 1) identifying appropriate management strategies to sustain watershed processes; 2) stratifying known or presumed receiving-water conditions across the Region based on preexisting data, watershed land cover, and waterbody type; 3) providing a scientific basis for the selection of (and standards for) management strategies based on the type and condition of receiving waters; 4) summarizing existing numerical standards associated with hydromodification controls and their potential applicability to the Central Coast; and 5) documenting both the scientific approach and the implementation steps by

which a watershed or set of watersheds can be analyzed to achieve effective protection of its receiving waters.

Associated with this Task 4 report are several key products:

1. GIS-based maps of the Central Coast Region that displays a final set of PLZ's at the finest scale permitted by the resolution of the underlying data, including a description of the defining attributes of each PLZ.
2. A description of dominant watershed processes associated with each PLZ.
3. A description of observed stream conditions in response to disturbed watershed processes, and the inference of these findings to the broader array of Central Coast receiving water types (i.e., lakes, wetlands, groundwater aquifers, and the marine nearshore).

2 WATERSHED AND RECEIVING-WATER CONDITIONS IN THE CENTRAL COAST REGION

The Central Coast Region encompasses a magnificently diverse landscape that spans a tremendous range of physiographic and ecological terrains. It rises from the Santa Barbara Channel more than 4,000 feet to the top of Santa Ynez Peak in less than 6 miles; south of Big Sur the mountains rise almost 5,000 feet in less than 4 miles. In its interior, the semiarid Carrizo Plain only averages about 7 inches of annual rainfall; but the mountains along the coast above Santa Cruz see more than 60 inches. The Region covers fifteen Level IV ecoregions, primarily in the foothills and coastal mountain zones. Their primary distinguishing characteristics are a Mediterranean climate of hot, dry summers and cool, moist winters, giving rise to an associated vegetative cover comprising mainly chaparral and oak woodlands, with grasslands in some lower elevations and evergreen forests at higher elevations (the USEPA map of California ecoregions can be downloaded here).

Despite this diversity, our work in Task 3 revealed strong patterns in watershed processes and receiving-water conditions, which are summarized below.

2.1 Summary of Prior Findings from the Central Coast (Task 3 of the Joint Effort)

Task 3 of the Joint Effort, *Watershed Characterization Part 2: Watershed Management Zones and Receiving-Water Conditions* (Booth et al. 2011), conducted a comprehensive, largely qualitative assessment of the varied landscapes and receiving waters across the entire Central Coast Region. It emphasized (relatively) undisturbed, "intact" watersheds to best characterize the natural hydrologic and sediment processes that are most responsible for the movement of water and sediment from hillslopes to receiving waters. These same processes also deliver organic matter, originating from native vegetation, to receiving waters, thus providing the foundation for the aquatic food web. Additionally, vegetation in intact watersheds promotes interception, transpiration, and infiltration of precipitation that slow and decrease the volume of stormwater runoff. Soils in intact watersheds provide a functional role in the degradation, transformation, and attenuation of organic and inorganic constituents moving through the watershed. These processes, in total, are broadly recognized as responsible for the formation of habitat and the maintenance of healthy watersheds that are the overarching goals of hydromodification control plans everywhere.

Watershed processes in different parts of the Central Coast landscape were inferred from scientific understanding, with an initial framework that was either confirmed or modified wherever observations so indicated. Receiving waters, primarily streams, were evaluated less comprehensively in the field but their characterization was supplemented by extensive biological data and some stream gage data, which were incorporated into an overall picture of their condition.

2.1.1 The physical landscape—"Physical Landscape Zones" (PLZ's)

From the conditions observed across the broadly undisturbed landscape areas of the Central Coast Region during Task 3 of the Joint Effort, fifteen landscape categories (plus "open water"), coarsely defined on the basis of hillslope gradient and geologic substrate, provide a regional discrimination of landscape types and dominant watershed processes in undisturbed landscapes. These categories were termed "Watershed Management Zones," because they are expected to express internally consistent response(s) to disturbance, and to benefit from the same type(s) of management approaches to reducing the effects of urban development. To clarify the distinction between early tasks of the Joint Effort (including the current one) and the last task (Task 5, whose focus will be explicitly hydromodification management), these categories are herein referred to as "Physical Landscape Zones" but are otherwise unmodified from the WMZ's of the previous report (Booth et al. 2011). The relative proportion of these WMZ/PLZ's in the Central Coast Region as defined in Task 3 is tabulated in Table 2-1; their distribution across the Region is displayed in Figure 2-1.

These categories were defined using just two factors that both theory and observation guide us to judge are the primary determinants of watershed processes in the "natural" (i.e., undisturbed) landscape—hillslope gradient and the underlying geologic material. Other factors of potential relevance, including the spatial variability of precipitation and the influence of different vegetation types in undisturbed watersheds (e.g., trees vs. shrubs vs. grasslands in progressively drier parts of the Region) are assessed later in this document.

Table 2-1. PLZ areas as a proportion of the Central Coast Region. Summary descriptions of the major PLZ's are provided in Appendix A.

Symbol	Physical Landscape Zone (based on lithology [geologic material] and hillslope gradient [% slope])	% of total area	
F1	Franciscan mélange; 0–10%	0.5%	8%
F2	Franciscan mélange; 10–40%	5%	
F3	Franciscan mélange; >40%	2%	
pQ1	Pre–Quaternary crystalline rocks; 0–10%	1%	23%
pQ2	Pre–Quaternary crystalline rocks; 10–40%	11%	
pQ3	Pre–Quaternary crystalline rocks; >40%	11%	
ET1	Early to Mid–Tertiary sedimentary; 0–10%	2%	30%
ET2	Early to Mid–Tertiary sedimentary; 10–40%	16%	
ET3	Early to Mid–Tertiary sedimentary; >40%	12%	
LT1	Late Tertiary sediments; 0–10%	1%	6%
LT2	Late Tertiary sediments; 10–40%	4%	
LT3	Late Tertiary sediments; >40%	2%	
Q1	Quaternary sedimentary deposits; 0–10%	18%	33%
Q2	Quaternary sedimentary deposits; 10–40%	14%	
Q3	Quaternary sedimentary deposits; >40%	1%	
	Open water	0.4%	0.4%

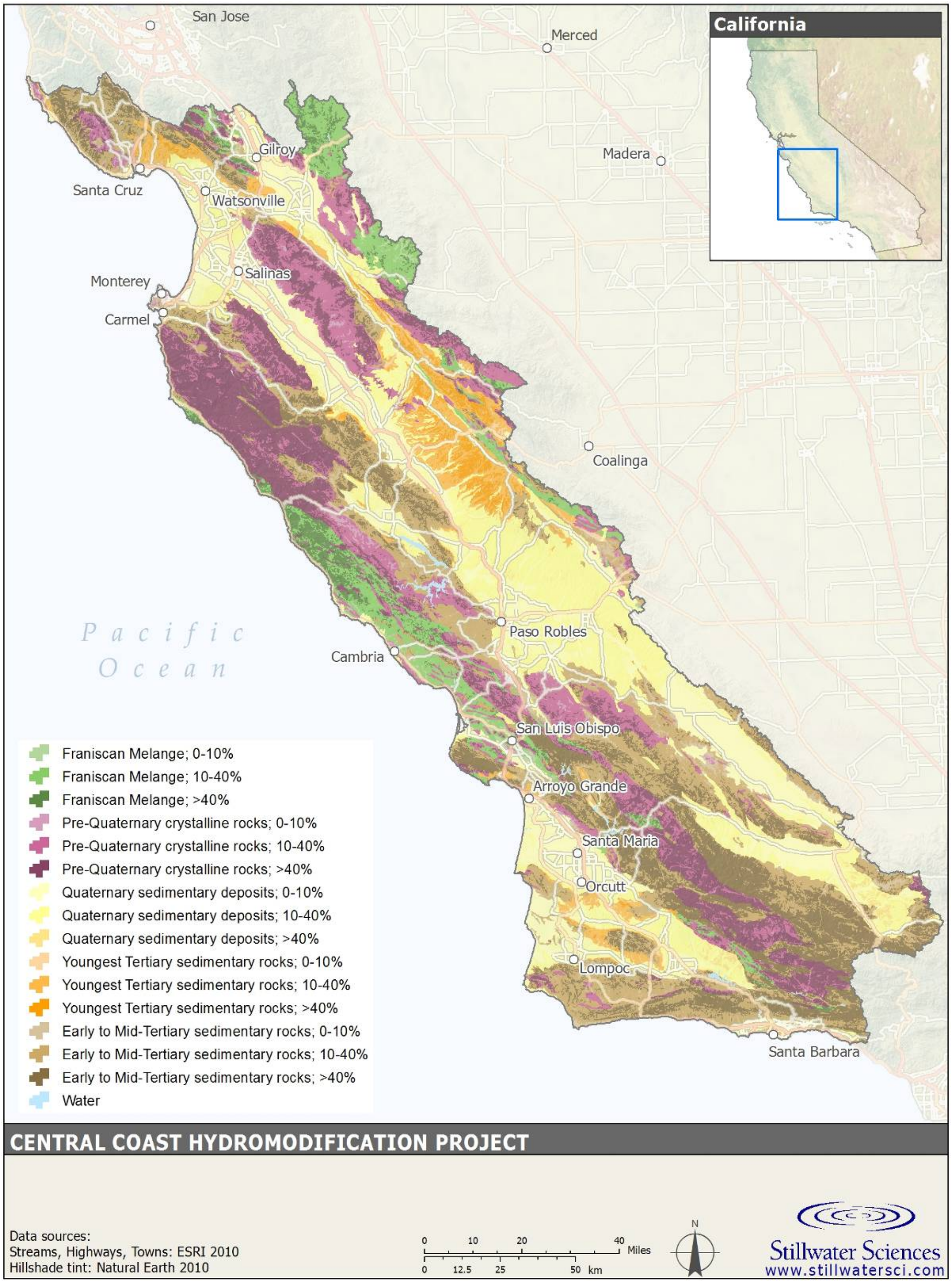


Figure 2-2-1. Final map of the Physical Landscape Zones, based on smoothed hillslope gradients and generalized geology units of Jennings et al. (1977) as developed from undisturbed watersheds with relatively intact vegetation cover. Detailed maps are reproduced in Appendix D at 1:750,000 scale (1″ ≈ 12 miles). Relative areas of each PLZ are tabulated in Table 2-1.

Although the watershed processes that dominate on any given hillside obviously will depend on more factors than simply "slope" and "geology," our observations confirm geomorphic theory that these are critical determinants of those processes (e.g., Montgomery 1999, Beighley et al. 2005, Warrick and Mertes 2009), and that a regional-scale stratification of the landscape based on these properties is a useful and defensible starting point for watershed management (Section 2.2).

2.1.2 Receiving waters

Receiving waters of the Central Coast are diverse, comprising streams, rivers, lakes, wetlands, marine nearshore, and groundwater aquifers. In the discussion that follows, particular emphasis has been placed on *streams* and *stream channels* (as commonly defined, namely freshwater channels that flow at least episodically). This emphasis is for the following reasons:

1. Distribution: Streams are found everywhere throughout the Central Coast Region; there are, literally, thousands of them across our landscape.
2. Response to disturbance: Streams express measurable (and commonly obvious) responses to many types of disturbance (hydrologic, chemical, physical). They are a sensitive indicator of degradation; as an "early warning" of such degradation, their data will likely reflect degradation first (whereas, in other types of receiving waters, potentially not at all).
3. Data availability: Relative to all other receiving waters, streams have the greatest amount and variety of previously collected physical, chemical, and biological data. Systematic evaluation of any other type(s) of receiving waters (i.e., marine nearshore, lakes and wetlands, groundwater) would therefore be much less complete, given limited and inconsistently compiled data.
4. Upstream indicator of downstream impacts: Streams provide a conduit by which altered conditions of water quality and biological health are passed to other receiving waters farther downstream.
5. Historical management: Streams have been a primary and/or sole focus of hydromodification control efforts throughout California and the West over the last several decades; however misguided this narrow focus, the relevance of alternative approaches to assessing and controlling hydromodification (such as the Joint Effort) must recognize and address this prominence .

Thus, we have emphasized "streams" in the following analyses for both scientific and pragmatic reasons. However, this emphasis does not restrict the applicability of the Joint Effort to this sole type of water body. We therefore expect these findings can provide valuable insight into the known or inferred condition of those other types of receiving waters that cannot be as directly measured or observed.

The receiving-water analyses for the Joint Effort utilized field observations and existing data to determine if linkages exist between observed processes (in both intact and disturbed watersheds) and receiving-water condition. Of the many thousands of streams, rivers, lakes, groundwater aquifers, and wetlands in the Central Coast Region, however, the Task 3 effort considered only a small subset. We field-visited less than 200 of them (overwhelmingly streams, owing to their prevalence and ease of observation), evaluated biological data (primarily benthic macroinvertebrate [BMI] data) at 153 unique sites, reviewed a comprehensive catalog of historical and current southern steelhead occurrence covering 150 streams in the Region (Becker and Reining 2008), and identified 36 USGS gage sites with high-quality flow records for the past

30 years. The goal of this investigation was not to characterize the water quality of individual receiving waters, but rather to evaluate broad trends in stream conditions, which (not surprisingly) are closely aligned with their watershed setting and land-use context, expressing relationships long-recognized and well-documented from other regions of the world.

Streams draining relatively undisturbed parts of the Region were the focus of Task 3 and are most common in the mid- to upper-elevation watersheds primarily in National Forest lands. In contrast, streams of the central valleys and coastal terraces of the Region are typically affected by near-ubiquitous grazing and/or more intensive agriculture or urban development, and they display abundant evidence of physical and biological degradation. As reported in most other parts of the world, urbanization appears to impose the most severe impacts of any land use on stream channels where it occurs. It is difficult to quantify the full magnitude or extent of these impacts, however; “developed” land occupies less than 8% of the Region’s total area, but the consequences of an urbanized watershed can extend far downstream past the boundaries of a city or town.

Streams draining disturbed parts of the Region also show systematic relationships between their watershed settings and their physical and biological conditions. Almost 20% of the Region’s land area constitutes flat valleys filled with Quaternary (i.e., the most recent geologic period, spanning the last 2.5 million years) sediment. These areas generally correspond both to identified groundwater basins and to areas of most extensive human activity. In them, the density of surface-water stream channels is low, and any drainage courses that do exist are distributed sparsely across these plains and are most commonly associated with agricultural or roadway drainage. Another watershed setting in the Region with some of the largest concentrations of cities, flat coastal plains that contain the downstream extension of steep mountain and foothill streams, is host to stream channels that exhibit marked downstream changes that reflect the combined influence of geology, topography, and land use. Channels of the southern Central Coast (e.g., Atascadero, Mission, and Carpinteria creeks), in particular, transition rapidly from cobble- and boulder-cascade morphologies with clean water and healthy benthic populations to lowland gullies (in some cases, concrete-encased) incised into their own debris fans, afflicted with heavy macrophyte growth and poor biological diversity.

2.2 Primary Observed Patterns of Conditions and Processes

Within almost any portion of the coastal United States, disturbance is ubiquitous. In the Central Coast Region, even the most remote upper-elevation mountain ridges of the National Forest have been affected by 19th century logging, human-influenced fire recurrences, and introduced exotic species. For purposes of this study, however, we have defined only two broad categories along the continuum of human disturbance. The first we term “intact,” describing landscapes that maintain a predominance of native vegetation with limited grazing or row agriculture, scattered (or altogether absent) rural residences, and minimal intrusion of roads into the stream corridor. The second, “disturbed,” has one or (more commonly) more of these listed land-use impacts over a substantial fraction of the watershed area. For purposes of the Joint Effort we have not endeavored to quantify any thresholds between these two broad categories, although such criteria are readily available in the literature (as a local example, see the quantitative definition of “reference sites” in Ode et al. 2005). Instead, we recognize that the Region’s “urban streams” (as commonly recognized) will all express the consequences of watershed disturbance, albeit each in their own way(s); and that to find good representatives of truly “intact” watersheds we need to look into some of the most remote parts of the Region. However, we also recognize a range of relatively undisrupted watershed *processes*, even in moderately disturbed watersheds, and we have made full use of these examples as well in the discussion that follows.

2.2.1 Intact watersheds of the Central Coast Region

The watersheds of the Central Coast span more than a vertical mile of elevation and a ten-fold variation in annual rainfall. The age and strength of the rocks range from ancient crystalline bedrock to recently uplifted marine sediments that are barely more cemented than the day they first washed into the ocean. Vegetation cover is as luxuriant as the redwood forests of the north-central coast, and as sparse as the near-desert scrub of the southeast interior; some streams flow year-round, and yet one of the largest rivers of the Region (the Santa Maria) can be entirely dry for more than three years at a stretch.

Despite this variability, we find an overall homogeneity of many of the conditions and processes expressed by the intact watersheds throughout the Region, and only a few systematic and readily recognized differences between them. Broadly, all but the steepest mountain ridges and the driest hillslopes are well-vegetated, whether by chaparral, coastal scrub, grasslands, oak woodlands, or evergreen forest. Most hillslopes are relatively ungullied, expressing a predominance of infiltration and subsurface movement of water after precipitation first falls on the ground surface.

The movement of sediment and plant detrital material largely follows the patterns set by these hydrologic processes. Sediment movement is driven by gravity and so is negligible on flat ground regardless of the geologic material. On slopes, surface erosion (rilling, gullying) occurs only in the presence of surface flow, and its expression is rare (in undisturbed areas) except in a few very weak rock types. Landslides (and other forms of mass wasting) are more dependent on rock strength, for which the Region has excellent examples at both the weak (Franciscan mélange) and strong (crystalline rocks) ends of the spectrum. Our observations and inferences of watershed processes and the Physical Landscape Zones in which they occur, from Task 3 of the Joint Effort, are summarized in Table 2-2.

Table 2-2. Tabular summary of observed and inferred watershed processes in undisturbed settings, as discriminated by Physical Landscape Zones. The assigned ratings (for "Low," "Medium," and "High") are relative and apply only to a particular column; so, for example, a "H" (high) rate of creep processes will not necessarily produce as much sediment as a high rating for rilling and gullying (indeed, the opposite will be true); but an "H" for creep will produce more sediment than an "L" for creep in a different zone. Compare to Table 2-3, which evaluates the effects of disturbance on these processes.

Slope class	Geologic unit	WATERSHED PROCESS						
		Overland flow (incl. sheetwash)	Infiltration	Interflow	Groundwater recharge	Creep	Rilling and gullying	Landsliding
0–10%	Franciscan mélange	M	L	L	L	L	L	L
	Pre-Quaternary crystalline	L	M	M	L	L	L	L
	Early to Mid-Tertiary sed.	L	H	M	H	L	L	L
	Late Tertiary sediments	L	H	M	H	L	L	L
	Quaternary deposits	L	H	M	H	L	L	L
10–40%	Franciscan mélange	M	L	L	L	M	M	M
	Pre-Quaternary crystalline	M	L	L	L	L	L	L
	Early to Mid-Tertiary sed.	L	M	M	M	L	L	L
	Late Tertiary sediments	L	H	M	H	M	M	L
	Quaternary deposits	L	H	M	H	M	H	M
>40%	Franciscan mélange	H	L	L	L	H	M	H
	Pre-Quaternary crystalline	M	L	L	L	L	M	L
	Early to Mid-Tertiary sed.	M	M	M	M	L	M	L
	Late Tertiary sediments	H	M	M	M	M	H	H
	Quaternary deposits	M	M	M	M	M	H	H

The streams draining relatively intact areas of the Region, notably the mid- to upper-elevation watersheds, typically exhibit stable morphology, episodically mobile sand-and-cobble beds, intact riparian areas, and varied populations of macroinvertebrates. Channels lower in the drainage network but still with a preponderance of undisturbed or only lightly disturbed watershed area tend towards wide, shallow channels with sandy beds and more active patterns of migration and local bank erosion, particularly in the drier eastern parts of the Region where these conditions of minimal watershed disturbance are more widespread. These channel attributes are typical of semiarid regions with episodically high sediment loads; they do not represent pervasively "degraded" channel morphology, despite their divergence from an idealized single-thread meandering river common to more humid regions (see Section 3).

The condition of these receiving waters also reflects their watershed setting and dominant watershed processes. Commonly, they receive baseflow for varying portions of the summer and fall (which, in the wetter parts of the region, can result in year-round flow). Flow during storms is a combination of shallow subsurface flow and some overland flow, delivered from saturated areas of the watershed and during periods of particularly intense rainfall. Across most of the Central Coast landscape, however, most of the annual water budget leaves the watersheds by a combination of evaporation, subsurface flow, and aquifer recharge (Figure 2-2). And, if the channel itself flows across a highly infiltrative basin, surface discharge can be absent altogether except during the largest storms (Figure 2-3).

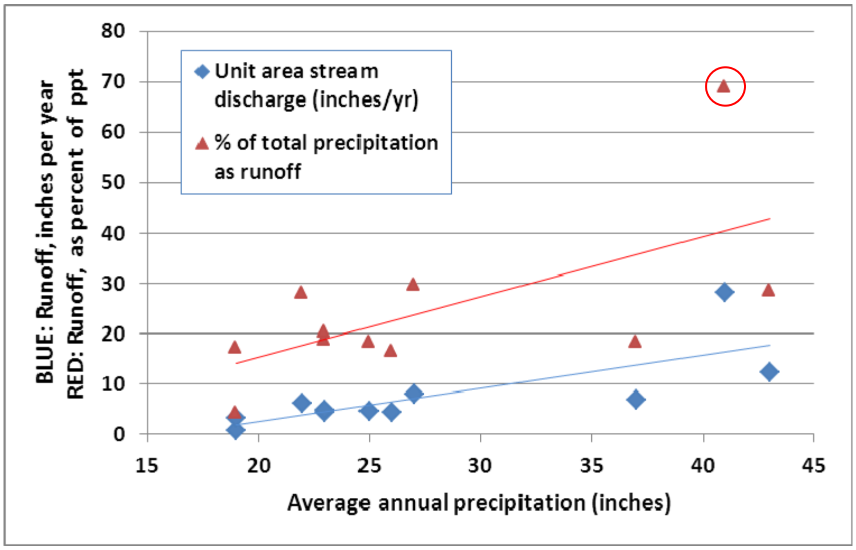


Figure 2-2. Comparison of the annual volume of precipitation (x axis) on 11 gaged watersheds with drainage areas <50 mi^2 (see Appendix C) with the annual volume of runoff (y axis), the latter expressed as both the inches of runoff from the watershed (blue diamonds) and as a percentage of the total rainfall volume (red triangles). With one exception (Big Sur River, circled red triangle), less than one-third of the water delivered by precipitation leaves each of these watersheds by surface flow.

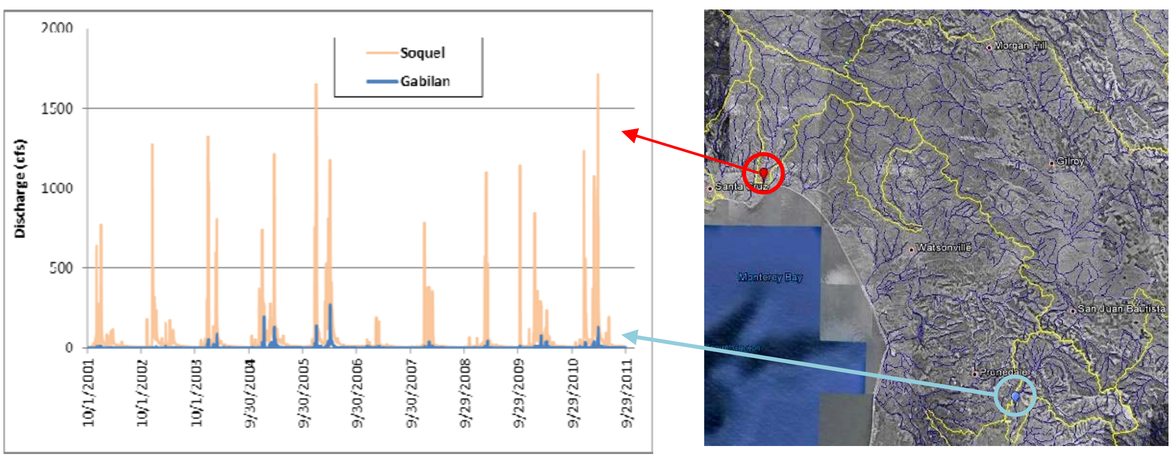


Figure 2-3. Illustrative, comparative 10-year hydrographs of Soquel and Gabilan creeks at USGS gages 1116000 and 11152600 (red and blue markers on the right-side map [from GoogleEarth], respectively). Sites are about 25 miles apart and drain watersheds of approximately equal size; although about twice as much annual rainfall falls over the Soquel watershed, net annual discharge is more than 15 times greater (0.91 cfs/mi^2 [equivalent to 12.3" of rainfall] for Soquel, 0.06 cfs/mi^2 [0.8"] for Gabilan). This reflects the highly infiltrative nature of the Gabilan Creek valley (entirely 0-10% Quaternary deposits [Q1], forming part of the Salinas Valley Groundwater Basin; CA Department of Water Resources 2003) in contrast to that of Soquel Creek (almost all 10–40% Early to Mid-Tertiary sediments [ET2]).

Systematic characterization of high instream "quality" across the Region, which typically requires intact (i.e., undisturbed) watersheds, is hampered by the paucity of sampling points for either biota, flow, or water chemistry in such locations. Most such data are collected relatively low in a watershed, with upstream land uses sufficiently diverse that some moderate (or extensive) degree of upstream human activity is virtually always present. The two streams with the best biological rating using the Southern California Index of Biotic Integrity (SCIBI; Ode et al. 2005), Arroyo Paredon Creek (east of Santa Barbara) and Big Sur River (south of Carmel), have minimal human intrusion into their respective watersheds and wide riparian buffers (Figure 2-4). Curiously, however, even these top scores for the Region place them only in the middle "fair" category of the SCIBI (i.e., neither "good" nor "very good"), a result that is explored in greater detail in Section 2.3.2.1.

Figure 2-4. Views of Arroyo Paredon Creek (left) and Big Sur River (right), channels with the highest SCIBI scores in the Central Coast Region.

2.2.2 Disturbed watersheds of the Central Coast Region

Present-day disturbance across the Region falls into three major categories, which in declining order of affected area are grazing, agriculture, and urbanization. The respective impacts of these disturbance types on watershed processes (and resulting receiving-water conditions) do not necessarily correspond to the size of their respective areas, however. In particular, the hydrologic effects of urbanization generally extend well beyond the limits of direct landscape disturbance, both to downstream surface-water bodies and to underlying aquifers. Similar downgradient effects also result from less intensive but more widespread agricultural activities, particularly relating to water-quality impacts. These multiple and far-reaching effects confound any simple assignment of causality (or, therefore, of corrective measures) in developing strategies to address the impacts of hydromodification, the primary goal of the Joint Effort.

Despite the complexities of watershed disturbance and receiving-water response, the basic characterization of urban watersheds has been well-described for more than half a century (e.g., Leopold 1968, Paul and Meyer 2001, Walsh et al. 2005). We will call this characterization the "Classical Model" of watersheds and urbanization, and we embrace it as a general principal with widespread applicability to the Central Coast Region. Specific elements of the Classical Model include the following:

- Intact watersheds emphasize subsurface flow paths for the delivery of precipitation from hillslopes to stream channels (left side of Figure 2-5); disturbed (and, in particular, urbanized watersheds) create large areas of overland flow (right side of Figure 2-5). This is the **fundamental** change that accompanies urbanization, although it is commonly accompanied by other changes, both *abiotic* (e.g., bank armoring) and *biotic* (e.g., riparian and upland vegetation clearing and replacement).

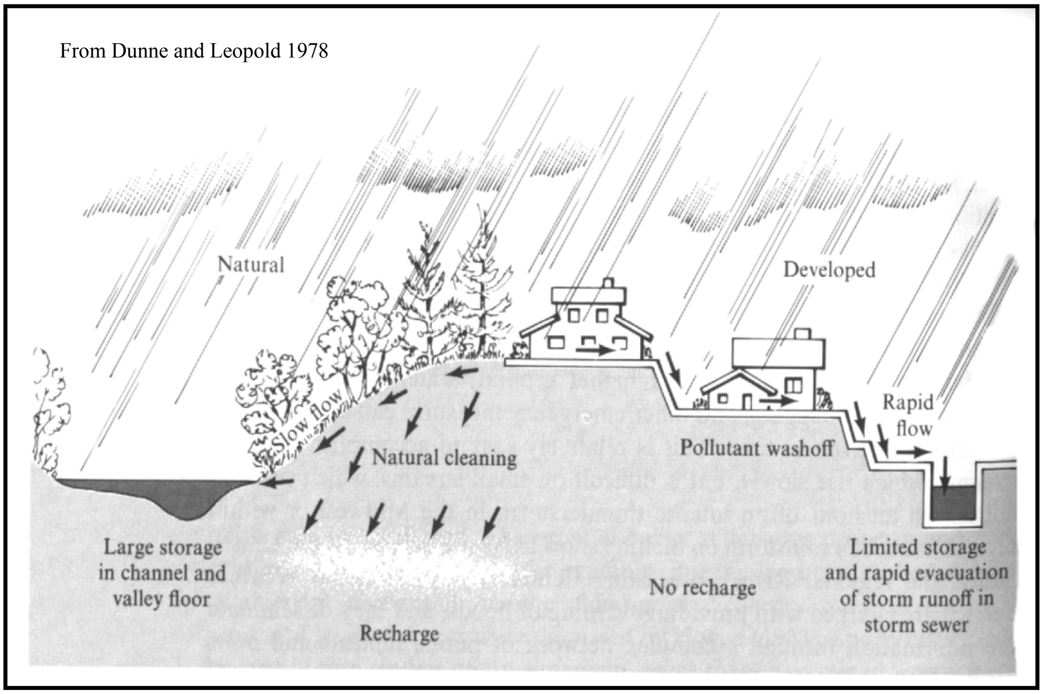


Figure 2-5. Schematic of intact (left) and urban (right) patterns of runoff, water storage, and conveyance. From Dunne and Leopold (1978, their Figure 11-14).

- Watershed urbanization simplifies watershed and receiving-water structure and processes, reducing or eliminating altogether heterogeneity and diversity (both physical and biological).
- Urban streams share many common attributes with each other, best summarized as "flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biotic richness, with increased dominance of tolerant species" (Walsh et al. 2005). Instream conditions tend to reflect the combined influence(s) of both the whole contributing watershed and the local/riparian zone.

Although we most commonly evaluate the physical and/or biological condition of receiving waters to assess the consequences of urbanization and to determine whether mitigation is needed, the focus of the Joint Effort is on protecting and restoring *watershed processes*, reflecting the scientific understanding that receiving-water conditions are a direct reflection of the condition of those processes. We therefore begin with a summary of our findings on these processes.

2.2.2.1 Effects of disturbance on watershed processes

The Classical Model can be usefully framed in "watershed process" terms:

- Urbanization results in less infiltration and more overland flow;
- Urbanization results in faster delivery of surface runoff from the upland to the receiving water
- Urbanization results in less upland sediment delivery from stabilized hillslopes;

- Urbanization results in reduced biotic activity and biological processes, such as delivery of coarse organic debris to streams or biological uptake/breakdown of nutrients or pollutants in soil or waterbodies; and
- Urbanization results in greater in-channel erosion, independent of any (additional) direct channel modification.

As an integrated consequence of these changes, urbanization reduces the natural differences between the diverse expression of watershed processes in a natural landscape, moving all landscapes towards a uniform set of watershed processes dominated by (and driven by) overland flow as its overriding feature. This change has the additional consequences of altering the flow regime of surface waters, which results in greater flow volumes and higher peak-flow magnitudes; reduced magnitude of infiltrated water to shallow and deep aquifers (a reduction, however, that may be partly or fully offset by "outside" water imported for irrigation or other human uses); and increased rate of in-channel erosion from systematically greater discharges.

These changes can be summarized in tabular form by reference to the primary Physical Landscape Zones identified for the Central Coast Region in Task 3 (Table 2-3). Colored shading indicates the relative magnitude of anticipated change for each process in an urban or urbanizing watershed—red for a change judged "major" (e.g., the loss of infiltration in a high-recharge area due to impervious surfaces), yellow for "moderate," and unshaded for those judged minor or absent altogether, based on both the guidance of the Classical Model and our field observations during Task 3.

Table 2-3. The association of watershed processes with PLZ's (reproduced from Table 2-2), highlighting the qualitative magnitude of anticipated change for each process as a result of urbanization. Red-shaded cells indicate the greatest anticipated change (e.g., a "Low" importance for overland flow in many PLZ's is anticipated to become "High" in an urban watershed). Note that this tabulation does not explicitly include the movement or delivery of organic material; changes to these processes can be inferred by their strong association with overland flow (and its associated hillslope processes of rilling and gullying).

PHYSICAL LANDSCAPE ZONE		WATERSHED PROCESS (and anticipated direction of urban-induced change: + increase, – decrease)						
Slope class	Geology	Overland flow (incl. sheetwash) (+)	Infiltration (–)	Interflow (–)	Groundwater recharge (–)	Creep (+)	Rilling and gullying (+)	Landsliding (+)
0–10%	Franciscan mélange	M	L	L	L	L	L	L
	Pre-Quaternary crystalline	L	M	M	L	L	L	L
	Early to Mid-Tertiary sed.	L	H	M	H	L	L	L
	Late Tertiary sediments	L	H	M	H	L	L	L
	Quaternary deposits	L	H	M	H	L	L	L
10–40%	Franciscan mélange	M	L	L	L	M	M	M
	Pre-Quaternary crystalline	M	L	L	L	L	L	L
	Early to Mid-Tertiary sed.	L	M	M	M	L	L	L
	Late Tertiary sediments	L	H	M	H	M	M	L
	Quaternary deposits	L	H	M	H	M	H	M
>40%	Franciscan mélange	H	L	L	L	H	M	H
	Pre-Quaternary crystalline	M	L	L	L	L	M	L
	Early to Mid-Tertiary sed.	M	M	M	M	L	M	L
	Late Tertiary sediments	H	M	M	M	M	H	H
	Quaternary deposits	M	M	M	M	M	H	H

By inspection of these tabulated predictions of changes, specific PLZ's appear to have particular "sensitivity" to urbanization:

Most sensitive to disturbance (i.e., greatest number of large changes)

- Early to Mid-Tertiary sediments, 0–10% (ET1)
- Late Tertiary sediments, 0–10% and 10–40% (LT1 and LT2)
- Quaternary deposits, 0–10% and 10–40% (Q1 and Q2)

Moderately sensitive to disturbance

- Pre-Quaternary crystalline rocks, 0–10% (pQ1)
- Early to Mid-Tertiary sediments, 10–40% (ET2)
- Late Tertiary sediments, >40% (LT3)
- Quaternary deposits, >40% (Q3)

Note that these relative rankings identify the sensitivity to *change* in the magnitude of the watershed process, not its intrinsic magnitude. For example, steep (i.e., >40%) rocks of the Franciscan mélange are highly susceptible to landsliding, regardless of the degree of watershed disturbance. Human intervention may further increase that activity, but mitigation or avoidance of these landscape areas may be advisable whether or not planned activities may further alter this process.

These associations are explored in greater detail in Section 3 (The Linkage Analysis).

2.2.2.2 Effects of disturbance on receiving waters

Prior studies, both within and far from the Central Coast, have shown that high percentages of disturbed land all-but-assures poor receiving-water conditions regardless of other watershed attributes (an expression of the "Classical Model"); but, conversely, a low percentage of disturbed land upstream does *not* guarantee high-quality biological conditions. Our review of receiving waters in Task 3 affirmed both of these principles, particularly widespread degradation as streams pass through urban areas. We also noted common occurrences of slightly-to-moderately degraded in-channel conditions without upstream watershed urbanization. In some locations this could be traced to other types of landscape disturbance (e.g., extensive grazing or intensive agriculture), but not everywhere.

In our evaluation of degradation and its expression in receiving waters in the Central Coast Region, we did not explore in detail those systems conforming to the Classical Model, because it was not the goal of the Joint Effort to add yet another example to the extensive literature on the topic. Instead, we tried to identify any exceptions to the general patterns under the assumption that a divergence from "expected" results would point to heretofore unrecognized factors, or the overriding influence of particular attributes, that could inform subsequent efforts at mitigating urban impacts.

The Classical Model provides a variety of predictions for how receiving waters will respond to disturbance. Not all could (or need to be) verified under the time and resource constraints of the Joint Effort, but existing data do provide a range of opportunities to evaluate the Model and its predictions:

- Flows will be flashier, and with bigger peaks, in watersheds dominated by overland flow as a consequence of urbanization.
- Aquifer recharge from precipitation sources will decrease in response to decreased infiltration.
- Physical stream habitat will lose complexity in human-disturbed streams as a consequence of changes in runoff and sediment processes in the contributing watershed and/or loss of near-stream riparian area.
- Water quality will decline in receiving waters draining urban and/or agricultural watersheds with the introduction of nutrients, pesticides, and toxics not present in the natural environment.
- Receiving waters will lose detrital material due to loss of upland and riparian vegetation.
- Instream biota will diverge from reference conditions, in response to changes in biotic and abiotic processes in both the contributing watershed and the near-stream riparian zone.

2.2.2.3 Hydrology

Through the hydrologic data collection and analysis of Task 3, we found very little basis to question or reevaluate the gross hydrologic predictions of the Classical Model. The relationship between urbanization and flashiness, the fundamental prediction of the Classical Model, is well-supported by hydrologic data from the Central Coast Region, but challenges in applying our chosen (indeed, any) index of hydrologic flashiness preclude a more nuanced evaluation (see

Section 3.2.2). As suggested by Figure 2.2, the dominant feature of the hydrologic regime of streams in the Central Coast is how little of the annual water budget is actually contained in stream channels as surface runoff; and although this is true in urban and non-urban catchments alike, it also means that even a seemingly "small" increase in the amount of surface runoff can constitute a dramatic change in the magnitude of this process.

2.2.2.4 Instream biota

As part of Task 3, we compiled an extensive collection of biological data across the rivers and streams of the Central Coast Region. The most comprehensive, namely the tabulation of more than 600 unique events where (and when) benthic macroinvertebrates (BMI's) have been collected and analyzed, is compiled and maintained by staff of the Regional Board. It includes data collected as part of the State's Surface Water Ambient Monitoring Program (SWAMP) and other data developed by the Regional Board. Other, more local reports of BMI data are available from the City and County of Santa Barbara for the South Coast streams (e.g., Ecology Consultants 2011; available at http://www.sbprojectcleanwater.org/waterquality.aspx?id=66#bioassess; accessed December 27, 2011), and for Santa Rosa Creek (Central Coast Salmon Enhancement, 2010). Referenced data also included individual project reports, evaluations using CRAM (California Rapid Assessment Methodology; http://www.cramwetlands.org/, accessed December 27, 2011), and a regional assessment of past and present fish utilization south of the San Francisco Bay (including all of the Central Coast Region; Becker and Reining 2008).

Our objective in this element of the Joint Effort was not to create a comprehensive catalog of biological data across the Region, but instead to seek patterns in the existing data that could inform the broader goals of the project. We therefore narrowed our focus to a homogenous data set, namely BMI analyses that could be converted into a single, recognized "score" of biological quality. For this application the Southern California Index of Biotic Integrity ("SCIBI"; Ode et al. 2005) was judged to be the best such indicator, insofar as the Central Coast Region was almost entirely covered by the set of streams used to develop the index (Ode et al's Figure 1). We created a spreadsheet tool to convert raw BMI data from the various sources across the Central Coast into a SCIBI score where not already provided by the original study authors. The results of this inventory and metric calculation are presented in Figure 2-6 below (see also Appendix B, which includes a tabulation of the Region's stream systems for which data were reviewed).

We focused our evaluation on two types of conditions that evaluated the location and results of sample sites relative to upstream urban land cover:

1. "Typical" patterns of biological response to urbanization, namely high-quality conditions upstream of urban development that progressively degrade through and downstream of developed areas (this section); and
2. "Atypical" patterns, which are either poor biological conditions without significant upstream urbanization, or biological conditions below urban areas that do not show a significant downstream decline (Section 2.3.2).

The first condition needs little exposition in this report, insofar as its recognition and characterization has been the subject of scientific literature for many decades (for some recent summaries, see Paul and Meyer 2001, or Center for Watershed Protection 2003). We include below a brief description of one such system from the Central Coast Region, but the pattern of downstream decline in biological quality through a progressively more urban watershed is clearly as ubiquitous here in this region as it is across the rest of the planet.

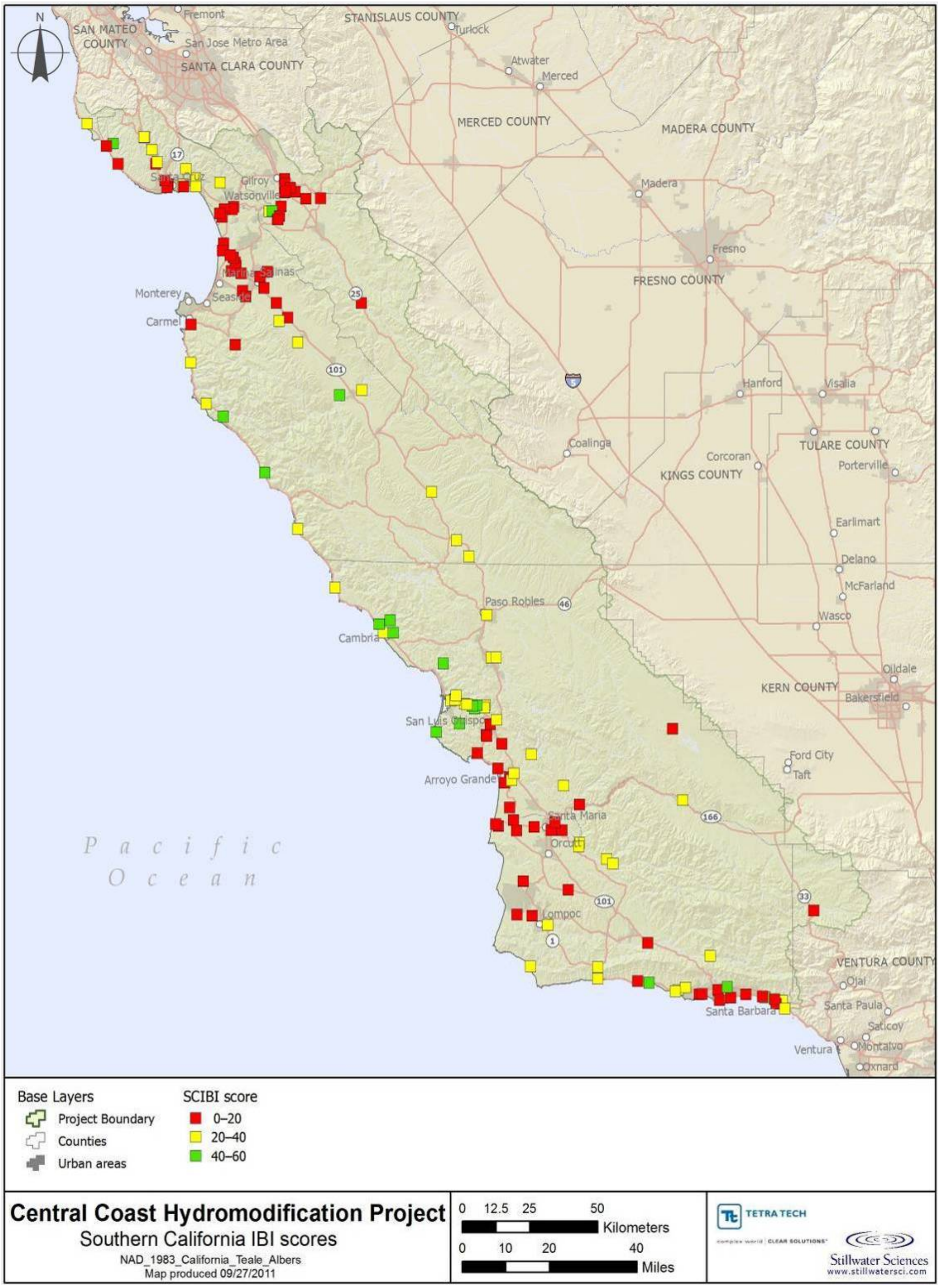


Figure 2-6. Calculated Southern California Index of Biotic Integrity (SCIBI; Ode et al. 2005) scores from BMI data in the Central Coast Region. 149 unique sampling locations are displayed here, of which most represent the average score from two to six annual sampling events. SCIBI scores can range from 0 to 100, but no site in the Central Coast region had a multi-year average greater than 60. In the lexicon of the SCIBI, 0-20 = "very poor", 20-40 = "poor", and 40-60 = "fair" (in addition, 60-80 = "good" and 80-100 = "very good").

The Region is host to many urbanized areas, which constitute the primary focus of this task of the Joint Effort. The majority of these urban areas lie near the coast and nearly all have one or more streams draining from undisturbed or agricultural uplands that pass through them on their path downstream. These areas have been the focus of much of the BMI monitoring over the past decade, and so there are several tens of stream systems with multiple up- and downstream measurement sites. Not surprisingly, the very highest scoring sites have virtually no urban development in their contributing watershed— Arroyo Paredon Creek, about three miles WNW of the town of Carpinteria on the southern Central Coast, has the highest reported SCIBI scores of any in the region and drains a primarily forested watershed, with some adjacent orchards but with broad (50–100 feet or more), intact vegetated riparian buffers throughout the channel network. The other "best" site lies just upstream of the campground at Pfeiffer Big Sur and with a protected State Park as its headwaters (Figure 2-4).

At the other end of this spectrum lies the majority of other monitored streams in the Region. As an example, Carpinteria Creek (Figure 2-7) drains forest- and chaparral-covered mountainous headwaters just a few miles east of Arroyo Paredon Creek, and with the same underlying geology, slope distribution, and rainfall. Orchards are also present in the midslope portions of the Carpinteria Creek watershed, but they display much narrower (and commonly nonexistent) vegetative buffers. The upper BMI site, below about half of the agricultural area of the watershed but above most of the urban development and all of the major arterial roads and highways, has a SCIBI score of 36 (out of 100, indicating degraded "poor" conditions even upstream of urbanization). Downstream less than two miles, the creek picks up drainage from additional residential development, a trailer park, an industrial nursery, and US Highway 101, and the resulting SCIBI score shows a statistically significant reduction to 14 ("very poor"). Equivalently (very) poor scores are displayed by every other monitored creek draining the urban areas west through Montecito, Santa Barbara, and Goleta. Mission Creek, for example, traversing an even stronger urban gradient 12 miles west of Carpinteria Creek, displays a commensurately stronger biological decline (from a "fair" 43 to a "very poor" 8) as it leaves the suburban foothills and passes through downtown Santa Barbara.

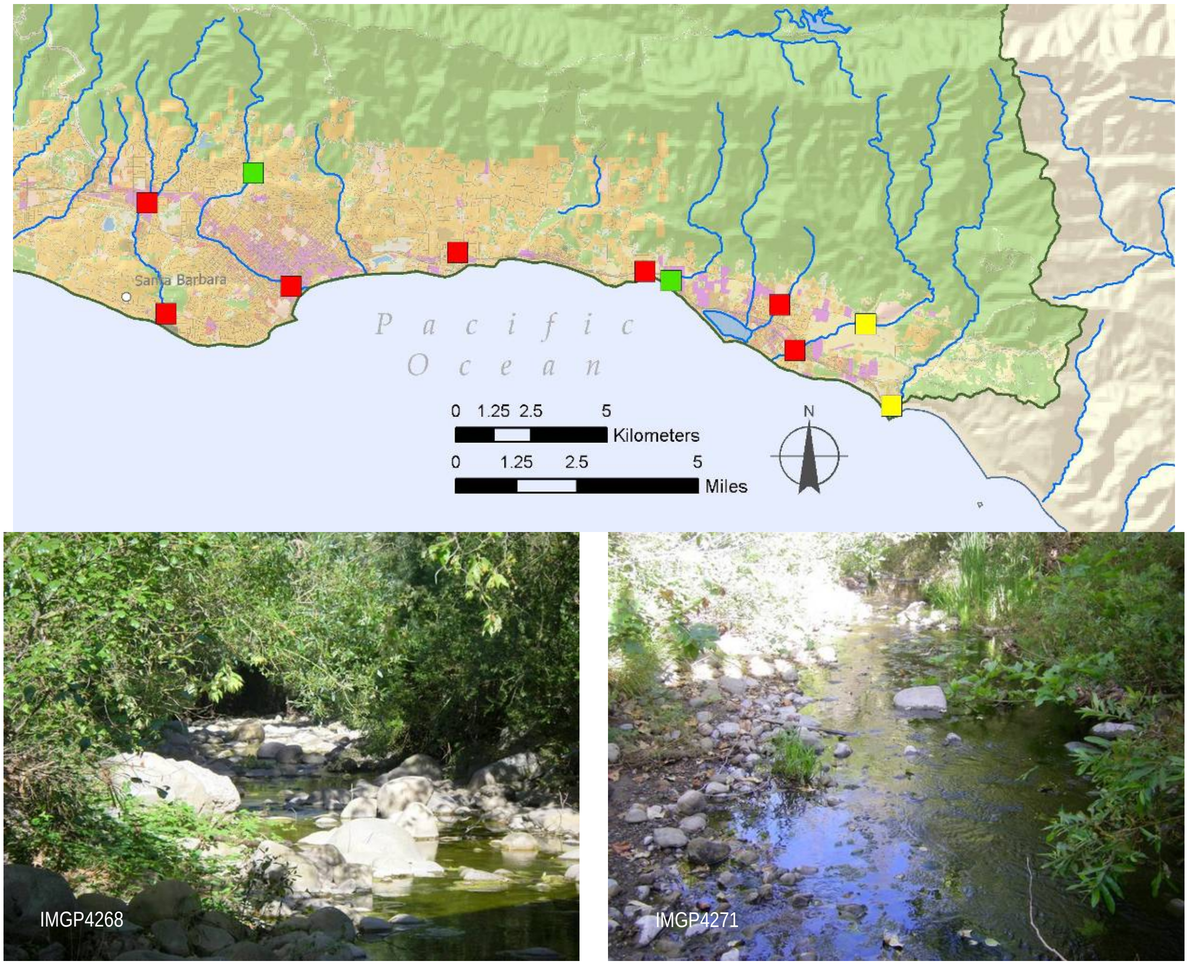


Figure 2-7. Top pane: SCIBI sampling locations (red = 0–20, yellow = 21–40, green = 41–60) for streams of the southern Central Coast. Arroyo Paredon is the one “green” site at the coast; upper Mission Creek, due north of Santa Barbara, is the other green site on this map. The base map shows simplified land cover: green = vegetated; orange/tan = low-density residential and agriculture; red/purple = commercial, industrial, and high-density residential. Carpinteria Creek is the channel with a “yellow” sampling site about 1.5 miles upstream of the coast (lower left photo) and a “red” site near the coast (lower right photo).

We also explored biological data on southern steelhead abundance, using a compilation of both systematic and anecdotal evidence produced by the Center for Ecosystem Management and Restoration (CEMAR) (Becker and Reining, 2008). The report does not provide an organized list of streams with the highest quality habitat or most resilient steelhead populations, but it does provide evidence of systems that have been impacted over time. We reviewed their notes of all 153 major rivers in the Central Coast Region to identify those systems that have historical and current steelhead populations, have adequate information to suggest actual observations were made to support inferences of fish use, and that have not shown significant (recognized) downward trends through time. Only five streams meet these criteria (Little Sur River and Big Creek in Monterey County; Islay Creek and See Canyon in San Luis Obispo County; and South Fork Sisquoc River in Santa Barbara County). All are in largely undisturbed (or protected) watersheds; and although none have corresponding BMI sites, their watershed setting is fully consistent with the typical association of high-quality conditions with undisturbed watersheds.

2.3 Exceptions to the Dominant Patterns of Conditions and Processes

In any broad-scale characterization of a landscape, general patterns of conditions and responses will tend to overwhelm minor variations within broad categories, and ignore uncommon exceptions or outright contradictions. Obviously, if these exceptions are numerous they can undermine the overall utility of the characterization. Even if overall trends are confirmed, however, these exceptions can have great value—they can show where the conceptual model or underlying assumptions are flawed, where the model is correct but the available data provide misleading indicators, or where accurate description of relevant conditions depends on data that are at too fine a scale or are otherwise simply not included in a broad-scale approach (such as that being used for the Joint Effort).

2.3.1 Variations in the dominant patterns of watershed processes

Although our work in Task 3 demonstrated broad commonalities in the overall conditions and dominant watershed processes for the Physical Landscape Zones (Figure 2-1 and Table 2-2), not every location followed these patterns exactly. Our initial analysis also was intentionally parsimonious (see Booth et al. 2011), using just two known determinants of watershed processes (geology and hillslope gradient) and evaluating the utility of a third (hydrologic soil type). However, other credible drivers of watershed process (specifically, vegetation type and rainfall amount and intensity) were acknowledged but deferred until this stage of our analysis. A variety of rainfall parameters were evaluated during Task 2 of the Joint Effort, with a final focus on the spatial variability of two: average annual precipitation and intensity of the 85th percentile storm (Figure 2-8).

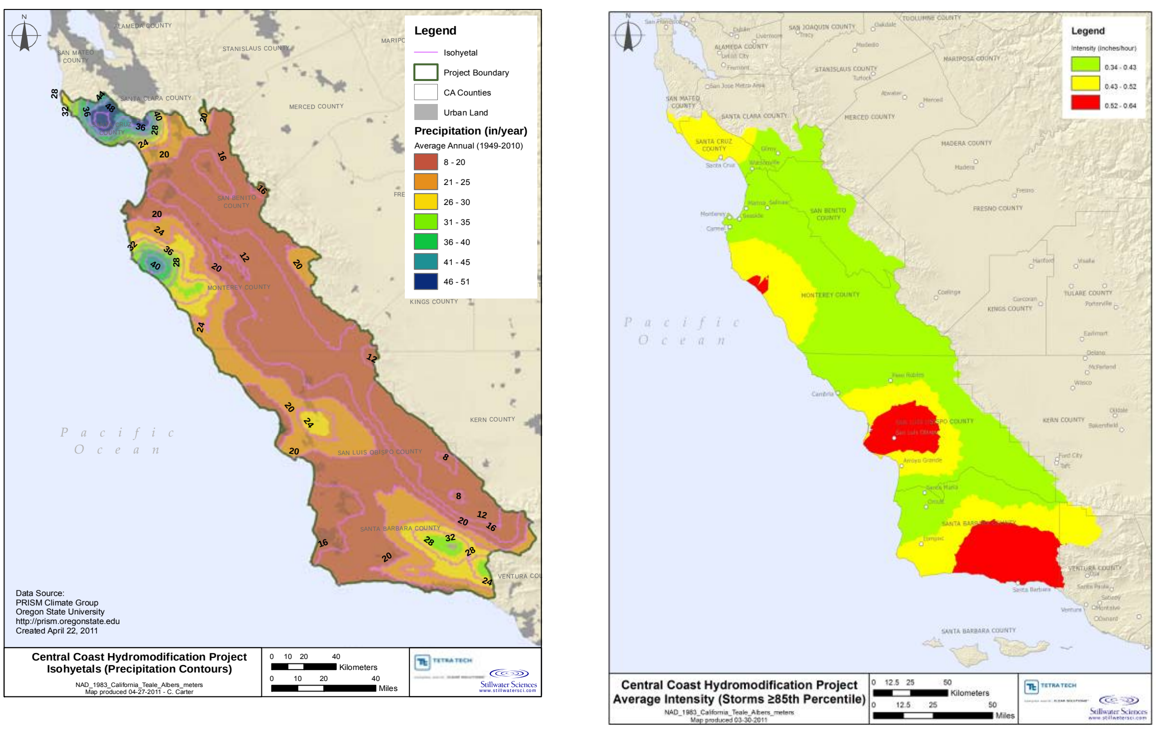


Figure 2-8. Left panel: average annual precipitation isohyetal map for PRISM rainfall volumes (water years 1950–2010; from http://www.prism.oregonstate.edu/). Right panel: Categories of rainfall intensity for the largest storms (≥85th percentile of total

storm volume) for the Central Coast (reproduced from the Task 2 report of the Joint Effort).

Two elements of these maps are particularly useful for evaluating the potential for having (or, more importantly, recognizing) any fundamental influence of precipitation on watershed processes. First, the spatial pattern on each map is different; so, for example, a strong gradient in total rainfall is present in the southern part of the Region from the coastline to the ridgetops (Figure 2-8, left panel), but a corresponding difference in intensity (right panel) is not present. Similar patterns are also expressed in the Santa Cruz area. Second, the overall range in the two parameters is very different—average annual precipitation varies by nearly 10-fold, but intensity by less than two. This suggests that any landscape-scale expressions of precipitation differences are more likely to be a result of the former than of the latter.

In undisturbed watersheds of the Central Coast Region, strong differences in vegetation are also present. The National Land-Cover Database categories of “Herbaceous” (i.e., grasslands), “scrub-shrub” (i.e., chaparral), and “forest” (both evergreen and mixed) are the three dominant land covers in the Region (covering 29%, 32%, and 21% of the total area, respectively). Three primary hydrologic processes are associated with vegetation—interception, transpiration, and infiltration—and they each can affect the amount and timing of stormwater runoff. Recent studies, primarily related to trees, have documented the effects of loss of vegetation as well as benefits when vegetation such as trees are added to the landscape. For example, results from Davis, California found that a single oak tree intercepted approximately 27% of the gross precipitation during 38 storm events in the winter of 1997-1998. The subsequent slowing of water as it moved through the structure of the tree, as well as associated evaporation from branches and leaves, can be significant processes that affect the overall volume and timing of stormwater runoff on a landscape (see also Dunne a Leopold 1978, Reid and Dunne 1996).

The three major vegetation types of the Region (grasslands, chaparral, and forest) are not evenly distributed. Forest is overwhelmingly found only in those areas with moderate to high annual precipitation and makes up 70–80% of the total vegetation cover in those parts of the Region with more than 40” of annual precipitation (Figure 2-9).

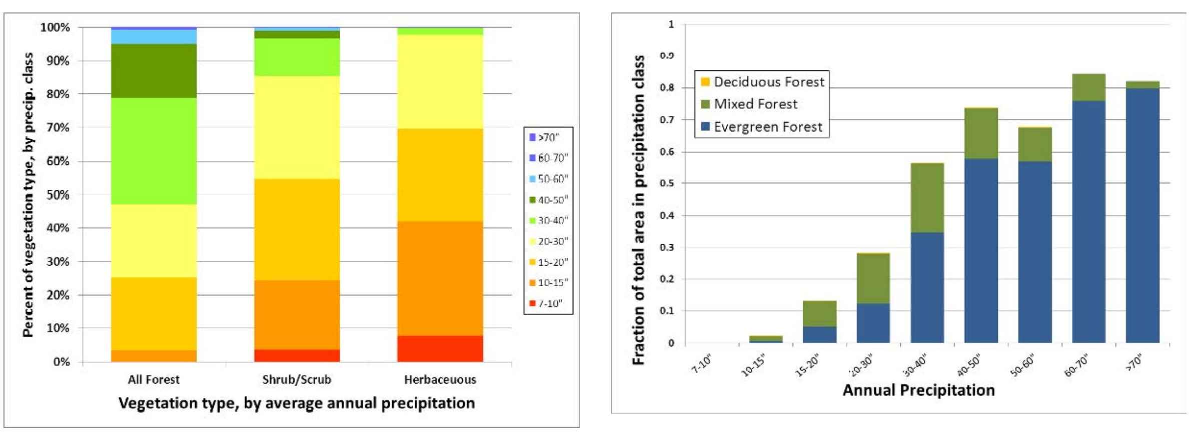


Figure 2-9. Variation of vegetation type with annual precipitation. Left panel, “forest” land cover is uncommon in areas with less than about 20″ annual precipitation; “herbaceous” cover is virtually absent above 30″. Right panel, in the higher precipitation zones (i.e., >40″ per year), forest is the dominant land cover. The “missing” fraction of the total area above each bar is occupied by all other land-cover types (primarily other vegetation types, along with all nonvegetated land cover).

Because of the strong correlation between vegetation cover and precipitation, any discernible influence of one of these factors on the type or magnitude of watershed processes cannot be discriminated from the other. We therefore focused our evaluation on differences in precipitation, because these parameters form more spatially coherent patterns (Figure 2-8) across the Region, whose influence (if any) will be easier to assess.

Watershed science leads us to expect that two conditions of rainfall are most likely to be associated with systematic differences in watershed processes. If significant over the range of conditions present in the Region, either could result in proportionally greater surface runoff, expressed by a high incidence of rills and gullies. These two conditions are (1) low vegetation cover in dry regions, promoting lower infiltration capacity and more easily erodible surface soils; and/or (2) high rainfall intensities, which can potentially increase the fraction of rainfall that exceeds the infiltration capacity of the soil and so result in surface runoff. Although we have not made a systematic catalog of the incidence of observed rilling, its presence is in fact quite rare across the undisturbed parts of the Central Coast. It is completely absent (indeed, no surface soil is visible at all) in the wet, well-vegetated areas, regardless of slope or geology (Figure 2-10, upper left). It is relatively uncommon even where the vegetation cover is sparse, particularly where the underlying rock is strong (Figure 2-10, upper right). Where rainfall intensity is high, but disturbance is absent and total rainfall is sufficient to promote abundant vegetation, competent bedrock and continuous vegetation appear to be sufficient to eliminate any potential effects of high rainfall intensity on surface runoff (Figure 2-10, lower left). Only where the area is dry (and so vegetation is sparse) *and* the geologic materials are weak do we see a systematic shift in watershed processes towards surface runoff and erosion (Figure 2-10, lower right). These conditions are common in the upper Cuyama River valley and environs in the southeast corner of the Region, providing a particularly large (and largely “natural”) sediment load to the tributaries and mainstem of the Cuyama River. For these processes to occur, the magnitude of rainfall intensity (it is low to moderate here) does not appear to matter.

Figure 2-10. Examples of hillslopes displaying various combinations of rock strength, total annual precipitation (and corresponding vegetative cover), and rainfall intensity. Upper left, Tertiary sandstone in the high-precipitation region north of Santa Cruz (and moderate rainfall intensity). Upper right, similar geology in the very low-precipitation (and low-intensity) region just west of the Carrizo Plain. Lower left, similar geology forming the slopes of the Santa Ynez Mountains near Lake Cachuma, in the center of the southern zone of highest rainfall intensity of Figure 2-8. Lower right, severely eroded young Tertiary sediments along an upper tributary of the Cuyama River, in a zone of low-to-moderate rainfall intensity but very low (<20″) annual precipitation.

This example also provides an unrelated, but important, reminder of the limitations of the underlying data compiled for the Joint Effort. On the state-wide compilation of geology (Jennings et al. 1977) used to produce the map of Physical Landscape Zones (Figure 2-1), the rocks shown in the lower right panel of Figure 2-10 are mapped in the class of "Early to Mid-Tertiary sedimentary rocks." However, a more detailed geologic map of this part of the Region is available (Kellogg et al. 2008) at more than seven times the spatial resolution, and it clearly shows that these rocks are a band of younger sediments, assigned to the much less competent Quatal Formation of Late Tertiary age. It provides a reminder that the application of regional-scale data to specific localities always includes potential errors, either with imprecise geographic placement or the loss of detail that may be "insignificant" at a regional scale but quite relevant on a particular hillslope of interest.

2.3.2 "Atypical" patterns of biological response to watershed disturbance

Atypical patterns in biological response were a focus of our assessments in this Task but have yielded only limited results—virtually all of the streams in the Region follow the predictions and expectations of the Classical Model. We have recognized two types of divergence, however. The first such divergence, namely poor biological conditions in streams draining nonurban watersheds, in part reflects the impacts of nonurban land disturbance (e.g., grazing or agriculture), but several examples also demonstrate that a reference-based biological scoring method (such as the SCIBI) is limited by the original population of reference sites—if the sampled location is simply too "different," it will score poorly regardless of the underlying level of disturbance.

The second type of anomaly, namely "high" (or at least not declining) conditions in and below urban areas, is simply very, very rare—we have identified only two locales with even a suggestion of such uncharacteristic patterns within the entire Central Coast Region, and they are discussed below. Regrettably, such a limited population suggests that, at best, we have not yet implemented successful strategies for restoration or mitigation of the effects of urbanization on downstream receiving waters.

2.3.2.1 Biological health and "reference" conditions

Divergences from the typical transition from upstream quality to downstream degradation are difficult to find in the Region (indeed, anywhere). In the Central Coast Region, our investigation of the first category of "atypical" findings, namely low SCIBI scores within relatively undisturbed watersheds, shows that most are a consequence of inappropriate site selection for these purposes. For example, Waddell Creek drains a nearly fully forested watershed within Big Basin State Park at the extreme northwest edge of the Region; it is host to only a few paved roads, a few tens of acres of cleared fields, and almost no structures. However, its SCIBI score is 2 ("very poor"), amongst the very lowest of the entire Region. Similarly, Scott Creek, 5 miles south along the coast, drains a similarly low-disturbance watershed yet sports a SCIBI score of just 6 (also "very poor"). The explanation in both of these cases is the choice of site—a coastal lagoon rather than a free-flowing stream, for which the reference conditions identified for the SCIBI (Ode et al. 2005, who specify sampling at riffles or other "fast-water habitat") are entirely inappropriate (Figure 2-11).

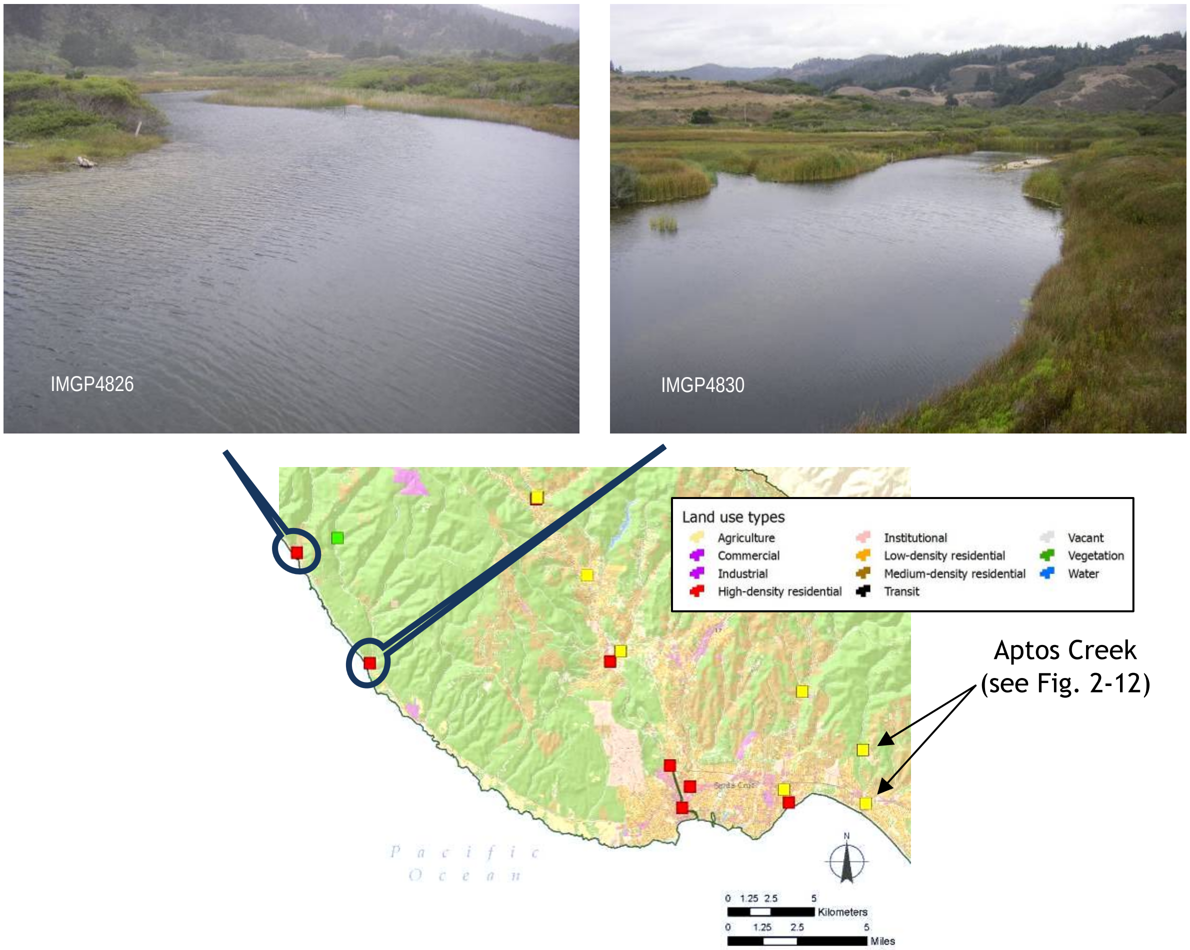


Figure 2-11. SCIBI sites and land use in the northern-most part of the Region. Upper left, lower Waddell Creek; upper right, lower Scott Creek. Both drain nearly undisturbed watersheds but the BMI sampling locations return anomalously low SCIBI scores, likely a consequence of sampling in an estuarine habitat. Base map shows simplified land cover: green = vegetated; orange/tan = low-density residential and agriculture; red/purple = commercial, industrial, and high-density residential.

A similarly inappropriate application of the SCIBI is suggested by the results from two sites in the driest, southeastern part of the Region. A BMI station on the upper Cuyama River at the Highway 33 crossing, lying downstream of a few hundred acres of agricultural fields and many tens of thousands of acres of undisturbed dryland mountains, has an SCIBI score of 18 ("very poor"). Similarly, an inflowing tributary to Soda Lake in the Carrizo Plain, in the driest (<10″ average annual rainfall) part of the Region and with only very low-density rangeland grazing and a flat infiltrative landscape with almost no overland flow, has an SCIBI score of 14. Although beyond the scope of this study to evaluate the reasons for this seeming disparity, it is suggestive that none of the reference or validation sites for the SCIBI (Ode et al. 2005, their Figure 1) lie this far into the low-rainfall interior of the Region—presumably, the criteria for "healthy biology" in these types of environments is simply different, and so the direct application of the SCIBI reference conditions does not accurately reflect the degree of divergence of these dryland sites from a natural state.

2.3.2.2 High-quality streams in disturbed landscapes

Of particular interest to the goals of the Joint Effort are those streams for which passage through an area of urban or urbanizing land use does not result in a monotonic decline in biological conditions. Along the entire Central Coast Region, however, we have found only two such examples, and even here the lessons are somewhat ambiguous.

Aptos Creek drains a largely forested watershed within the Forest of Nisene Marks State Park, about seven miles east of Santa Cruz. Although the upper watershed was almost entirely clearcut about 100 years ago, it has since developed a mature second-growth canopy throughout the riparian zone and upland areas. The upper BMI site (Figure 2-12) lies upstream of all recent development, save a single unpaved access road; it has been sampled twice and returned SCIBI scores of 42 ("fair"; in 2005) and 21 ("poor"; in 2006). The downstream BMI site is located beneath Highway 1, below where the channel has passed through about 3,500 feet of moderate-intensity residential and some commercial development. It has been sampled repeatedly with SCIBI scores averaged by year of 18 (2001), 33 (2004), 36 (2005), 24 (2006), and 21 (2007).

These results do not present a strong picture of an "urban-unaffected" trend, but at least one year (2007) showed no downstream decline with the paired upstream data, and the conditions in two other years (2004 and 2005) were better than at most other sites within urban to semi-urban parts of the Central Coast. The tributary channels have 100-foot vegetative buffers (or more) throughout nearly all of the upstream residential and commercial areas through which they pass; and the majority of the watershed is almost entirely undeveloped. These two attributes, long-recognized as key elements of a healthy stream, likely provide the explanation for the lack of a strong downstream decline in the quality of this stream.

Figure 2-12. Left panel: Aptos Creek at the lower BMI site, beneath the Highway 1 overpass. At right, index map of the two sampling locations (circled) superimposed on a GoogleEarth view, which also suggests the modest degree of upstream and adjacent development at the lower sampling site (bottom red marker).

Santa Rosa Creek drains 48 mi^2 of the Central Coast in northern San Luis Obispo County, with predominantly grazed uplands and cultivated valley bottoms in its contributing watershed, together with the town of Cambria flanking the lowermost two miles of the channel before reaching the Pacific Ocean. It was the subject of an extensive geomorphological study (Stillwater Sciences 2010) and has had multiple BMI samples taken over the past decade. The most useful were those taken in 2010 as part of the development of a watershed plan (Central Coast Salmon

Enhancement [CCSE] 2010), because they provide a systematic downstream characterization of biological indicators using the same sampling and analytical methods at the same time. The results of that study, presented below (Figure 2-13; from CCSE 2010, their Figure 2.1 and Table 4.5), show the classic downstream decline but with a nearly unprecedented recovery at the last site (“Windsor”).

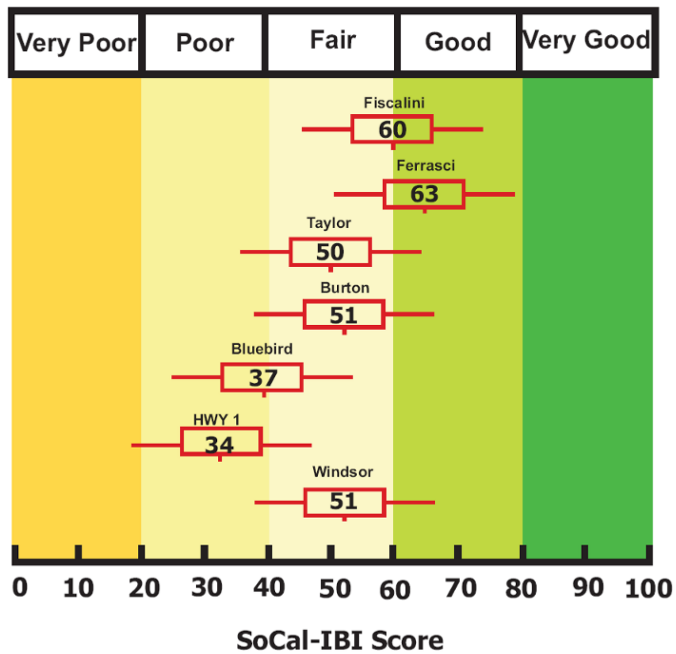


Figure 2-13. Top, aerial view of the lower six sampling sites of Santa Rosa Creek in 2010 (Site 7, Fiscalini, lies an additional 4 miles upstream of Site 6); at right, the graphically plotted SCIBI scores at all seven sites. Little urban development exists upstream of Site 5 (“Taylor”).

Previous BMI sampling along Santa Rosa Creek was conducted under the SWAMP program from 2001–2005 (Table 2-4) but at only two of the 2010 sites—Site 6 and Site 1. These two locations are too widely spaced to capture the “dip” in downstream ratings at Sites 2 and 3 of CCSE (2010); had these 2001–2005 data been the only available, then Santa Rosa Creek would simply be another example of “downstream urban degradation.” The addition of four intermediate sites in 2010, however, provides a finer discrimination and the suggestion of partial biological recovery, an encouraging finding for future efforts to improve urban streams.

Table 2-4. Results of BMI sampling, and calculated SCIBI scores, at the two sites covered by 2001-2005 data compiled by the Regional Board (#6 and #1 of CCSE 2010).

UPSTREAM SITE ("FERRASCI")							
Site		310SRU	310SRU				
Collection Date		3/29/02	3/25/03				May 2010
Collection Method		CSBP	CSBP				CCSE 2010
EPT Taxa		8	9				
Number Coleoptera Taxa		1	4				
Number Predator Taxa		12	16				
Percent Intolerant		0.04	0.18				
Percent Tolerant Taxa (8-10)		0.26	0.22				
Percent CF + CG Individuals		0.37	0.45				
Percent Non-Insecta Taxa		0.33	0.30				
SCORE:		**34**	**47**				**63**
DOWNSTREAM SITE ("WINDSOR")							
Site	310SRO	310SRO	310SRO	310SRO	310SRO	310SRO	
Collection Date	5/1/01	3/29/02	3/25/03	4/8/2004	4/1/2005	4/1/2005	May 2010
Collection Method	CSBP	CSBP	CSBP	CSBP	MCM	MH	CCSE 2010
EPT Taxa	8	1	4	9	2	2	
Number Coleoptera Taxa	5	3	3	3	1	2	
Number Predator Taxa	15	9	12	11	4	9	
Percent Intolerant	0.09	0.00	0.02	0.04	0.00	0.00	
Percent Tolerant Taxa (8-10)	0.19	0.38	0.38	0.27	0.18	0.33	
Percent CF + CG Individuals	0.52	0.49	0.37	0.64	0.95	0.98	
Percent Non-Insecta Taxa	0.31	0.57	0.42	0.40	0.27	0.44	
SCORE:	**45**	**21**	**29**	**33**	**16**	**14**	**51**

The reason(s) for this modest improvement in SCIBI scores are not readily apparent. The only systematic change in channel conditions identified by Stillwater Sciences (2010) was the reduction in confinement downstream of Highway 1 (between sites 1 and 2), accompanied by a significant widening of the riparian zone (from under 50′ to over 100′ along, each side of the channel) that is clearly visible on Figure 2.13 above. As of 2001, the "Developed" land-cover category covered about 10% of the watershed area (Stillwater Sciences 2010), suggesting the near-certainty of some urban impacts but not an overwhelming influence. As with Aptos Creek, the presence of a relatively wide riparian zone and an unconstrained area for in-channel and near-channel processes is favorable for biological conditions (Segura and Booth 2010), and this is distinctly different from the channel geomorphology immediately upstream with lower biological scores.

What is *not* indicated from these data is any particular stormwater management strategy, implemented to date, that has any causal relationship with instream conditions. However, these findings may point to alternative approaches, based on riparian-zone management and channel–floodplain connectivity, for mitigating at least some of the effects of hydromodification.

3 THE LINKAGE ANALYSIS

In the terminology of the Joint Effort, the "Linkage Analysis" is our characterization of the relationships between disturbance, dominant watershed processes, and receiving-water conditions, following the conceptual framework of Figure 3-1.

IN AN UNDISTURBED ("INTACT") LANDSCAPE:

PLZ →
Watershed Processes →
Receiving Water Conditions

IN A DISTURBED (SPECIFICALLY, URBANIZED) LANDSCAPE:

PLZ →
Disturbance →
Disturbed Watershed Processes →
Disturbed Receiving Water Conditions

Figure 3-1. Conceptual framework of the Linkage Analysis, tracing the physical attributes of a Physical Landscape Zone (PLZ) to the watershed processes that control the movement and storage of water, sediment, and organic matter; and finally to the resulting conditions of downstream (or, for aquifers, downgradient) receiving waters. Disturbance to those PLZ's can result in a new set of controlling watershed processes (red text), which in turn result in alterations to the conditions of receiving waters.

This framework implies two primary "linkages"—the first, the association of specific PLZ's with their associated key watershed processes; and the second, the relationship between those watershed processes and downstream receiving-water conditions. It also recognizes the importance of *disturbance* in those associations, which for the Joint Effort specifically focuses on areas and conditions affected by urbanization; and, subsequent to that understanding, the consequences of urbanization on receiving-water conditions.

We therefore offer a two-part discussion of linkages: those between PLZ's and key watershed processes, in both intact and disturbed environments (Section 3.1); and those between watershed processes and the resulting conditions in downstream (or downgradient) receiving waters (Section 3.2).

3.1 Linking Physical Landscape Zones and their Key Watershed Processes

The foundation of this relationship is rooted in the scientific investigation of watersheds for more than a century, whose broad framework was outlined in Task 3 (Booth et al. 2011) and the variety of references cited therein. Of central importance to the Joint Effort is the effects of disturbance, specifically urbanization, and for this we begin with the "Classical Model," described in Section 2.2.2 of this report as the presumptive description of how urbanization affects watersheds. However, a central tenet of the Joint Effort is the need to evaluate and potentially modify these general principles to align with the actual conditions of the Central Coast Region. We therefore have drawn on our observations and analyses to date in creating and applying the current framework, discussed below and summarized in Table 3-1. Relationships between watershed processes and each of the specific PLZ's are of necessity qualitative, because there are insufficient data (and overly complex interactions) to derive quantitative relationships. Nonetheless, the results are abundantly supported by the broader scientific literature and are well-documented throughout the Region.

Table 3-1. Summary tables of the relative importance (which, if relevant, are indicated by one or more X's) and magnitude of change (colored shading) of selected watershed processes, as stratified by PLZ and presence/absence of disturbance, specifically urbanization. Note that Table 2-3 provides an alternative representation of the same information. The tally of X's within each table is a *qualitative* assessment of the influence of the specified watershed process; color intensity reflects the magnitude of change in that process's importance between intact and disturbed conditions. Both broad patterns and exceptions to those patterns are discussed in the text below.

A. **INFILTRATION AND GROUNDWATER RECHARGE**	INTACT WATERSHEDS			DISTURBED WATERSHEDS		
	Hillslope gradient class			Hillslope gradient class		
	0–10%	10–40%	>40%	0–10%	10–40%	>40%
Franciscan mélange						
Pre-Quaternary crystalline						
Early to Mid-Tertiary sed.	XX	X	X			
Late Tertiary sediments	XX	XX	X	X		
Quaternary deposits	XX	XX	X	X		

B. **OVERLAND FLOW**	INTACT WATERSHEDS			DISTURBED WATERSHEDS		
	Hillslope gradient class			Hillslope gradient class		
	0–10%	10–40%	>40%	0–10%	10–40%	>40%
Franciscan mélange	X	X	XX	XX	XX	XX
Pre-Quaternary crystalline		X	X	XX	XX	XX
Early to Mid-Tertiary sed.		X	X	X	XX	XX
Late Tertiary sediments			XX	XX	XX	XX
Quaternary deposits			XX	XX	XX	XX

C. **RILLING AND GULLYING**	INTACT WATERSHEDS			DISTURBED WATERSHEDS		
	Hillslope gradient class			Hillslope gradient class		
	0–10%	10–40%	>40%	0–10%	10–40%	>40%
Franciscan mélange		X	X		X	X
Pre-Quaternary crystalline			X			X
Early to Mid-Tertiary sed.			X		X	X
Late Tertiary sediments		X	XX		XX	XXX
Quaternary deposits		XX	XX		XXX	XXX

The qualitative tabulations of Table 3-1 display the primary watershed processes and their typical response(s) to disturbance, specifically urbanization. They reflect both the presumptions of the "Classical Model" (Section 2.2.2) and our observations of these PLZ's across the varied landscapes of the Central Coast Region; and although they cannot capture every response in every locality, they do express the most important and widely observed attributes.

An example of the use of these summary results follows a brief discussion of each table.

Infiltration and groundwater recharge (Table 3-1A): These closely linked hydrologic processes are dominant across most intact landscapes of the Central Coast Region. Their widespread occurrence is expressed by the common absence of surface-water channels on even steep (undisturbed) hillslopes. Thus, on virtually any geologic material lying on all but the steepest slopes or bare rock, infiltration of rainfall into the soil is inferred to be widespread if not ubiquitous. With urbanization, changes to the process of infiltration are also quite simple to characterize: some (typically large) fraction of that once-infiltrating water is now converted to overland flow.

For infiltrating water to reach deeper aquifers, however, a geologic substrate is required that maintains infiltration at depth, which includes the Tertiary and Quaternary sedimentary deposits that, in total, cover more than two-thirds of the Central Coast Region. On these deposits, urbanization not only substitutes overland flow for the shallow subsurface water ("interflow") that occurs in virtually every PLZ, but also reduces or eliminates altogether the access that water once had to deeper groundwater aquifers.

Reduction of infiltration and groundwater recharge is the dominant alteration to hydrologic processes caused by urbanization (changes to the rate evapotranspiration surely occur and may be significant, but they are presumed to be of substantially smaller magnitude). Most generally, these losses will be greatest over those watershed areas where infiltration and recharge have been most active, and this is reflected in the table above. Observations of urbanized areas, however, suggest that some recharge commonly still occurs over highly infiltrative deposits. This presumed attribute of the most broadly infiltrative deposits in the region (Late Tertiary and Quaternary sediments) is also acknowledged in the table above.

Overland flow (Table 3-1B): This process can be thought of as the inverse of infiltration: precipitation reaching the ground surface that does not immediately soak in must run over the land surface (thus, "overland" flow). It reflects the relative rates of rainfall intensity and the soil's infiltration capacity: in particular, wherever and whenever the rainfall intensity exceeds the soil's infiltration capacity, some overland flow will occur. Most uncompacted, vegetated soils have infiltration capacities that are of one to several inches per hour at the ground surface, which exceeds the rainfall intensity of even unusually intense storms of the Central Coast (Figure 2-7) and so confirms the field observations of little to no overland flow reported in Task 3 (Booth et al. 2011). In contrast, pavement and hard surfaces reduce the effective infiltration capacity of the ground surface to zero, ensuring overland flow regardless of the meteorological attributes of a storm, together with a much faster rate of runoff relative to vegetated surfaces.

Our qualitative assessment of overland flow in the PLZ's of the Central Coast Region (Table 3-1B, above) is therefore the near-inverse of that for infiltration and groundwater recharge. This process is most important over steep and low-permeable deposits, and absent altogether on those surfaces where infiltration is dominant. We have observed, or otherwise anticipate, only a few exceptions to this general pattern:

- The presence or absence of overland flow on the low-gradient, older deposits is unknown because their actual presence on the landscape is uncertain. Although regions of low-gradient (i.e., 0–10%) pre-Quaternary rocks are mapped by Jennings et al. (1977), the map scale is so coarse (and the outcrops so poor) that many such areas are likely covered with a layer of much younger but unrecognized Quaternary alluvium. Any "true" pre-Quaternary crystalline rocks probably would support overland flow at any slope (and this property is tabulated accordingly above), but its actual occurrence on the landscape is dubious (and as mapped this PLZ only covers 1% of the Region).

- Although the Late Tertiary and Quaternary deposits, as a group, are highly infiltrative on any slope, we have observed a strong propensity for these deposits on steep exposures to display rills and gullies (recall Figure 2-9; see below), geomorphic features that require overland flow for their formation and maintenance. Many of these slopes are disturbed, and they should constitute some of the highest priority for stormwater management in the Region. However, many of these slopes have naturally sparse vegetation cover, particularly in the low-rainfall areas in the southeast part of the Region, and the (naturally) unprotected geologic deposit is simply too weak to maintain an intact, ungullied surface, even though we still anticipate a significant fraction of the total precipitation being infiltrated. For these deposits, therefore, Table 3-1A and 3-1B express the counterintuitive condition of a highly infiltrative deposit nonetheless supporting a recognizable level of overland flow.
- Analogous to groundwater recharge, urbanization imposes a uniform tendency towards overland flow, but even extensive pavement will likely not result in complete conversion to this hydrologic process (particularly on low-gradient hillslopes over infiltrative deposits). For this reason we expect that *some* infiltration will still occur in urbanized PLZ's with low-gradient, permeable sedimentary deposits. Nonetheless, the resulting degree of overland flow will still represent a dramatic increase in this runoff process in such urban areas.

Rilling and gullying (Table 3-1C): These hillslope processes are the geomorphological expression of the hydrologic process of overland flow, and so the pattern of these two sets of processes are similar (Table 3-1B and 3-1C). However, these two processes can diverge in several common settings. First, overland flow across flat surfaces will generate little or no erosion simply because the energy of the water is too low to transport sediment. Second, areas of overland flow where the substrate is strong (e.g., bare rock outcrops) will not produce corresponding gullying. Third, a weak substrate may show evidence of significant surface erosion with only modest levels of overland flow (as long as slopes are sufficiently steep).

As an integrated example, consider the anticipated processes and response(s) to disturbance of the three PLZ's associated with "Late Tertiary sediments" (i.e., with the three hillslope gradient classes 0–10%, 10–40%, and >40%). In intact watersheds, these PLZ's express a suite of processes dominated by infiltration on all but the steepest of slopes ("XX" on Table 3-1A), and with a virtual absence of overland flow and rilling on flat slopes (blanks on Table 3-1B and C), with an increasing incidence of these processes in the steepest terrain. In "disturbed" (i.e., urbanized) watersheds, overland flow will be prominent everywhere ("XX" on Table 3-1B, right side) but will induce rill erosion only where the ground is not flat (Table 3-1C, right side). Qualitatively, we judge the loss of infiltration to be significant on any gradient but particularly on moderate slopes where infiltration was still dominant on intact hillslopes but likely captured altogether with constructed conveyances (dark red block, Table 3-1A); indeed, the incidence of overland flow in disturbed landscapes where it never previously occurred (dark red blocks, Table 3-1B) is one of the most severe consequences of watershed urbanization observed anywhere.

In summary, these results support the following general principles regarding the linkages between intact and disturbed watersheds of the Central Coast Region and their key watershed process:

1. The dominant change imposed by urbanization is the replacement of infiltration with overland flow; the PLZ's most sensitive to disturbance are those that display the greatest level of (undisturbed) infiltration. This sensitivity also largely corresponds to the inferred magnitude of undisturbed groundwater recharge.
2. Conversely, the PLZ's with a suite of watershed processes least sensitive to change from urbanization are those of the older (and stronger) pre-Quaternary rocks on the steepest slopes.
3. The youngest rocks (Late Tertiary and Quaternary deposits) are naturally erosive and very susceptible to further disturbance.
4. Flat rocks have low susceptibility to surface erosion, regardless of disturbance, but urban-induced changes in infiltration are significant for the granular rocks regardless of hillslope gradient.
5. By reference to Tables 2-1 and 3-1, our qualitative judgment of the PLZ's with the greatest sensitivity to change (ET1, LT1 and LT2, Q1 and Q2) cover nearly 40% of the Region. Those with the least sensitivity to change (F3, pQ3, ET3) cover 25%. The balance, which includes most of the forested, chaparral-covered and grazed foothills of the Central Coast Region, displays varying responses amongst its key watershed processes.

3.2 Linking Watershed Processes and Receiving Waters

Receiving waters are the products of their watersheds. For example, the form of rivers expresses the processes that control the movement, storage, and delivery of water and sediment from their surrounding hillslopes, and the interaction of those physical processes and conditions with the biological agents that they support. The variety of receiving waters that are found across the world is almost unimaginably wide, because watershed processes are themselves so diverse in their rates, their magnitude, and their very nature. Within a suitably limited geographic region, however, we can recognize a more limited and tractable range of processes, and thus their expression in the receiving waters that they create and sustain. The Central Coast is such a region.

Receiving waters are commonly classified first by type: stream, river, wetland, lake, marine nearshore, or groundwater aquifer. Each such type can be subdivided with ever-increasing detail and specificity, and from a variety of physical and/or biological perspectives; thus, for example, we have lakes discriminated by nutrient levels (oligotrophic, mesotrophic or eutrophic) or by frequency of vertical mixing (amixis, meromixis, holomixis); wetlands are discriminated by their landscape position or dominant source of water; and aquifers are discriminated by whether they are completely or only partially filled with water. For the Joint Effort we have used (and will continue to use) *streams* as our "focal" receiving water, for the reasons stated in Section 2.1.2: they are widespread across the Central Coast, they are the source of much preexisting data, they are well-recognized to respond to disturbances in their contributing watersheds, and they are particularly efficient at passing the effects of disturbance farther downstream. For these reasons, they are a useful surrogate for the full range of receiving waters, as well as being critical watershed features in their own right.

Streams are classified most commonly by either their geomorphic form (e.g., Leopold et al., 1964; Montgomery and Buffington, 1997) or their hydrologic regime (Poff and Ward, 1989). Both aspects are expressions of two fundamental drivers: geology and climate. In the Central Coast Region, these two drivers display a wide but manageable range, permitting us to develop a necessarily generalized, but inclusive, description of the watershed drivers and stream-channel conditions here. We also explore their relationships to in-stream biological conditions across the Region, in both their intact and urban-altered states.

3.2.1 Watershed processes and receiving waters: the geomorphic form of stream channels

The Joint Effort has focused on "key watershed processes" as the determinants of receiving-water conditions. In Task 3 we assembled systematic data on hydrologic and biological expression of such processes; here we expand our consideration of receiving-water conditions to the geomorphic *form* of stream channels, because that form can be one of the most direct expressions of altered watershed processes: urban-induced changes in runoff processes, for example, can lead to rapid and very diagnostic changes in channel morphology (e.g., Booth 1990). Furthermore, this attribute has received much attention in prior and current hydromodification control plans.

The existing conceptual framework for linking watershed processes to stream-channel geomorphology has existed for many decades (Mollard 1973, Kellerhas and Church 1989, Montgomery and Buffington 1997) and is analogous to that being applied by the Joint Effort to a broader suite of watershed conditions. It begins with the interrelated primary "drivers" of any temperate-latitude landscape—topography, geology, climate, land use, and fire (Figure 3-2). For the Joint Effort, our basic approach has focused on just topography and geology; "climate" is important but it imposes only modest variability in stream-channel conditions across the Region. We have not considered fire explicitly because its influence is ubiquitous across the Region, although specific fires have undoubtedly influenced some of the local, short-term data used in our analyses. "Land use" is, of course, key to this entire effort and is explicitly addressed in the discussion that follows.

The list of "Watershed Attributes and Processes" of Figure 3-2 recognizes the importance of the key water and sediment processes of the Region that are the focus of the Joint Effort. It also acknowledges two other attributes that are particularly important for determining channel form, *valley form* and *riparian/instream vegetation*. These do not receive as much attention in the following discussion, however: valley form is not normally amenable to management intervention (although watershed disturbance can alter it); and vegetation is normally a consequence of a wide range of natural processes and human activities, even though it can itself influence in-stream conditions. Their explicit inclusion in this framework, however, reminds us that their status does influence receiving-water conditions, and their management or rehabilitation may also be an appropriate element of an overall strategy for hydromodification control.

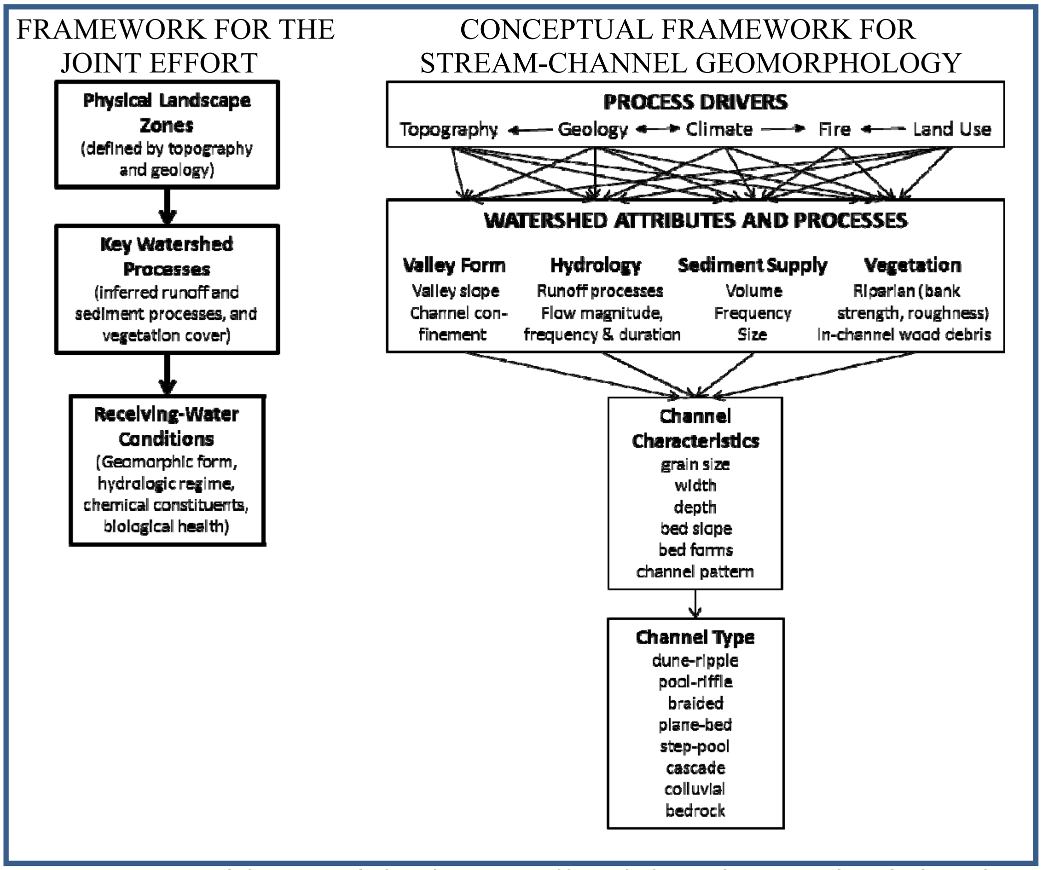


Figure 3-2. Conceptual framework for the Joint Effort (left) and a more detailed rendering specifically applied to stream-channel geomorphology (right; modified from Buffington et al. 2003, their Figure 1). Note that multiple interrelated attributes (right side, upper boxes) combine in multiple ways to form a relatively small number of discrete "channel types." Thus, a known set of watershed processes may indicate what channel type is most likely to result, but the answer to the inverse problem—inferring watershed processes from channel form—is less well constrained, because the same channel form can be the product of many alternative combinations of interacting processes.

The mutual adjustment of channel characteristics for different combinations of imposed watershed conditions gives rise to different reach-scale channel types (Buffington et al. 2003; the lowermost box in Figure 3-2). These channel types differ greatly in their response to disturbance, their rate and magnitude of change(s) that can impinge on adjacent land uses, and their habitat value for a wide range of organisms. We therefore explore their anticipated and observed distribution across the Central Coast Region, together with their primary attributes and likely response(s) to urbanization. This linkage between watershed disturbance and stream-channel form has been the focus of most prior hydromodification control plans (if only in the guise of "stream stability"), which is why we give it an otherwise disproportionate degree of attention here.

For undisturbed parts of the Region, the "Process Drivers" in the uppermost right-hand box of Figure 3-2 are largely expressed by the attributes and distribution of our 15 PLZ's (with the acknowledgment that any climatological differences are not included in defining these zones). The list of "Watershed Attributes and Processes" provides a reminder that not only the delivery of water and sediment (our "key watershed processes" of the Joint Effort) but also the variety of valley form and riparian vegetation can influence the characteristics of stream channels. We will evaluate the importance of these additional factors in the course of exploring the linkages between watershed processes and receiving waters, specifically stream-channel form.

The many thousands of stream channels of the Central Coast Region are each unique in detail, but they share broad commonalities that reflect the interplay of the landscape elements that form their watersheds. We organize the following discussion of stream-channel types and watershed processes using intuitive landscape categories, based primarily on gross physiography, and then describe how these align with the PLZ's defined in Task 3 and the stream channels that originate within them and flow across them (the lowermost box of Figure 3-2).

3.2.1.1 In the mountains

The Central Coast Region is mountainous terrain (Figure 3-3). A quarter of the land area lies on gradients steeper than 40%, and over three-quarters is at least 10%. Because of this broad physiography, most of the Region's stream channels begin in steeplands, and they flow down progressively flatter slopes until reaching the Pacific Ocean. Some of these channels traverse steep topography for only a few miles before reaching flatter ground, but those that originate high in the interior ranges persist for many tens of miles in this landscape before emerging from the rangefront onto the adjacent valleys. Within this extensive physiographic region, we recognize five primary channel types (Table 3-2).

Figure 3-3. Mountainous terrain of the Central Coast Region, here in the interior Santa Ynez Mountains in the southeast part of the Region.

Table 3-2. Mountainous-area **c**hannel types of the Central Coast Region, with their common attributes and typical Physical Landscape Zones in which they are found (for abbreviations of PLZ's see Appendix A).

Channel type	Process domain[1]	Key attributes	Typical settings	Typical Physical Landscape Zone(s)
Colluvial (Fig. 3-4a)	Hillslope erosion	Sediment delivery overwhelms fluvial processes	Moderate to steep hillsides, thick soils, little vegetation, minimal drainage area	>40% (all)
Gully (Fig. 3-4b)	Hillslope erosion	Rapid sediment delivery and evacuation	Moderate to steep hillsides, thick soils, little vegetation, greater runoff	>40% Q, all T (esp. drylands)
Bedrock (Fig. 3-4c–d)	Bedrock	Channel scoured to bedrock	Steep topography, confined valley, low sediment supply	>40% F >40% pre-Q >40% ET
Cascade and step-pool (Fig. 3-4e–f)	Alluvial	Self-formed channel; energy dissipation by vertical flow; typ. channel slope 4–20+% (cascade), 2–8% (step-pool)	Moderate to steep, confined to semi-confined valley, low sediment supply	10–40%, >40% pre-Q 10–40%, >40% ET
Plane bed and pool-riffle (Fig. 3-4g–h)	Alluvial	Self-formed channel; energy dissipation by lateral flow and channel roughness; channel slope <4%.	Moderate to steep, confined to semi-confined valley, low to moderate sediment supply. Low channel gradient makes this type uncommon in this terrain	10–40% (all, but uncommon)

[1] Term used as defined by Buffington et al. (2003); reflects a combination of hillslope processes and the resulting channel type. In the "Alluvial" process domain, channels are largely self-formed by the flow they carry, carved into the sediment that they have previously transported (and presumably can carry again under suitable discharges). In contrast, the "Bedrock" process domain is host to channels that are *non*-alluvial, that is, the current flow regime is ineffective at rapidly modifying the channel form in response to changes in discharge or sediment load.

Figure 3-4. Channel types in mountainous terrain of the Central Coast Region (for abbreviations of PLZ's see Table 2-1).

3.2.1.2 At the rangefront and through the foothills

As stream channels emerge from the mountains at the rangefront and flow across the topographic transition from steep terrain to much flatter ground (Figure 3-5), a variety of systematic changes commonly occur to stream-channel form. Most importantly, the channel gradient decreases and so the sediment-transporting ability of the flow declines as well. If that flow is carrying a high sediment load, it will create a distinctive landform (an alluvial fan) out of the now-excess sediment at this transition. This physiographic setting is also prone to deposition of *debris flows*: sediment-rich deposits that move rapidly down steep channels during periods of exceptionally high flow and sediment transport, coming to rest only where the channel gradient flattens. This sediment is not moved by the "normal" fluvial process of grain-by-grain transport by flowing water, but as a slurry that moves under its own weight. Once it comes to rest it can be eroded only slowly, if at all, by the stream under more typical flow conditions, and so the bulk of the deposit will remain to encase the channel as it exits the rangefront.

Figure 3-5. Physiographic transition from mountains to coastal terrace, here looking southeast towards the city of Santa Cruz.

Finally, if the valley-bottom sediment is highly infiltrative (or the alluvial-fan deposit is voluminous relative to water flow during non-storm conditions), water may disappear into the subsurface altogether, reappearing only during periods of high discharge or only far downvalley in a lower channel. Although a condition of low flow and high infiltration can result in such ephemeral channels anywhere in the landscape, this physiographic setting is a particularly common location for its expression.

Within this physiographic region, we therefore recognize three unique channel types (Table 3-3 and Figure 3-6), acknowledging that it is a transitional zone where channels can also express forms common to either their upstream mountainous counterparts (Figure 3-4) or (particularly) their downstream lowland valley channels (Figure 3-8).

Table 3-3. Transitional, foothill-region channel types of the Central Coast Region, with their common attributes and typical Physical Landscape Zones in which they are found. These are not the only channel types found here, only those that are most commonly restricted to this physiographic setting.

Channel type	Process domain	Key attributes	Typical settings	Typical Physical Landscape Zone(s)
Debris-flow impacted (Fig. 3-6a, b)	Semi-alluvial	Alluvial channel inset within rarely to never-transported sediment	Valley/terrace channels adjacent to episodic debris-flow-generating upper watershed	0–10% Q (with steeper source terrain, esp. 10-40% ET)
Alluvial fan (Fig. 3-6c)	Alluvial	Distributary channel system with rangefront sediment deposition	Rangefront flattening, high sediment load from erosive contributing watershed	0–10% L T, 0–10% Q (with steeper source terrain, esp. 10-40% LT & Q)
Ephemeral (Fig. 3-6d)	Non-alluvial	Unconfined, commonly indistinct channels	Small, dryland contributing watershed	0–10% Q

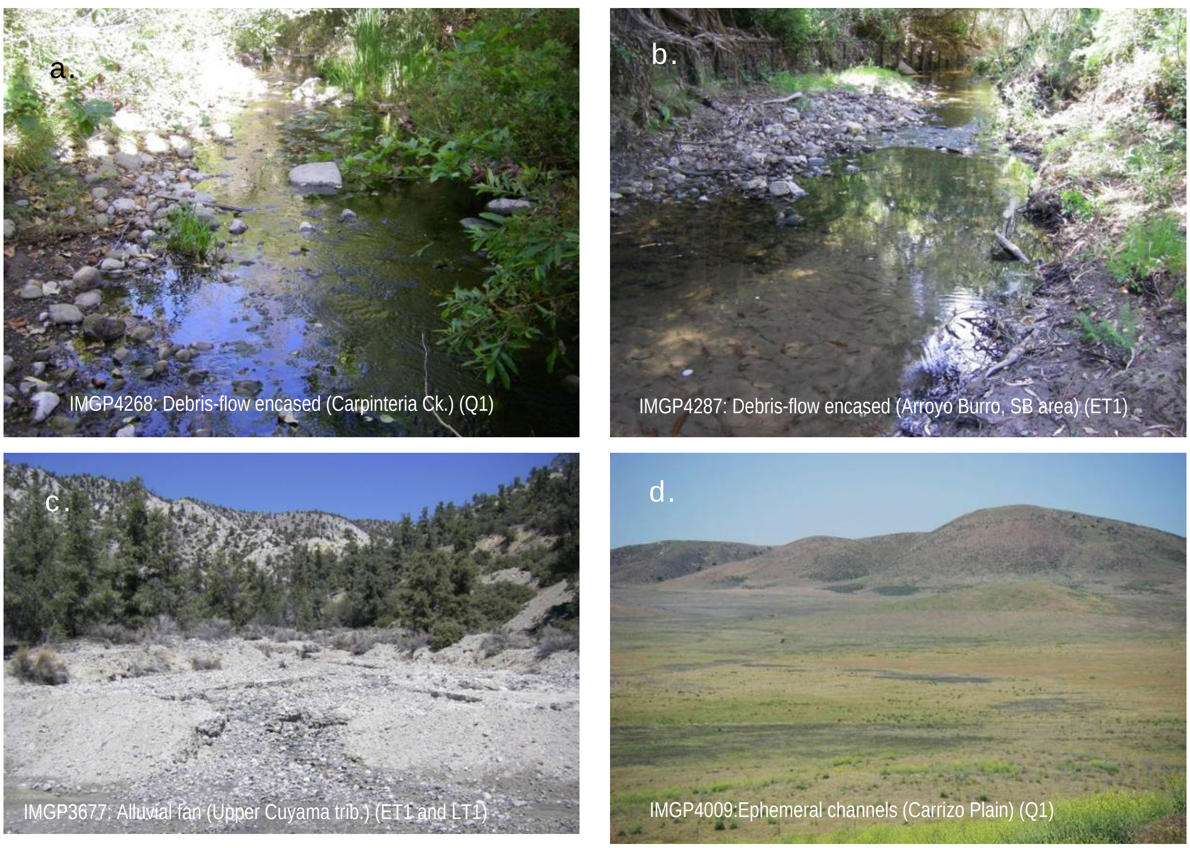


Figure 3-6. Channel types predominately in the transition zone between mountains and lowland valleys. Because this physiographic region also includes a range of intermediate-gradient topography, channel types present in both the mountainous (Figure 3-4) and valley (Figure 3-8) terrains are also common here.

3.2.1.3 Down in the valley

Nearly one-quarter of the Region is flatter than 10%, with the vast majority underlain by Quaternary sediments. It includes much of the dry eastern parts of the Region (Figure 3-7); it also encompasses the terrain where the majority of the population lives and works. Thus, it has disproportionate importance in our consideration of watershed processes, receiving waters, and (ultimately) strategies to achieve hydromodification control.

Figure 3-7. Looking east across one of the largest Quaternary valleys of the Central Coast Region: the Salinas River valley, downstream (north) of King City.

These areas form the large, interior valleys of the Region and a narrow coastal strip along which most of the major population centers are located. Although the rivers and streams that traverse this landscape are simply the downstream extension of their steeper headwaters, their geomorphic forms are characteristic to this low-gradient topography Table 3-4 and Figure 3-8).

Table 3-4. Channel types characteristic of the major valleys of the Central Coast Region, with their common attributes and typical Physical Landscape Zones in which they are found.

Channel type	Process domain	Key attributes	Typical settings	Typical Physical Landscape Zone(s)
Semi-confined, plane bed to pool-riffle (Fig. 3-8a)	Alluvial (primarily)	Alluvial channel forms, moderately incised, gravelly bed with sand; channel slope <4%	Transitional from debris-flow or fan-encased semi-alluvial channel to fully alluvial form	0–10% (all, predominately Q)
Unconfined[1], pool-riffle (Fig. 3-8b)	Alluvial	Sand and gravel channel with self-constructed floodplain; channel slope <2%	Lowland valleys without direct connection to hillslope sediment supply	
Unconfined[1], multi-thread (braided) (Fig. 3-8c)	Alluvial	Low-gradient (<1%) multi-thread channel, sand to fine gravel bed, unconfined, high sediment load	Most common river type of the Quaternary-filled valleys; abundant upstream sediment load; intermittent flow	
Unconfined[1], single-thread, meandering, dune-ripple(Fig. 3-8d)	Alluvial	Low-gradient (<1%) single-thread channel, self-constructed floodplain, stable banks	Channel stability dependent on riparian vegetation; correlates with near-perennial flow (large river and/or dam-release-mediated)	

[1] Note that most of the large lowland rivers are now partly or entirely confined by levees or revetments, which may interact with the flow (and thus partly influence channel morphology).

Figure 3-8. The characteristic channel types of the lowland valleys in the Central Coast Region.

3.2.1.4 Unique settings

Although this simple three-part physiographic division of the landscape (mountains–foothills–valleys) broadly captures the vast majority of the terrain of the Region and the river and stream channels within them, two additional geomorphic channel forms merit inclusion (Table 3-5 and Figure 3-9). They are found in specific physiographic settings that mark the downstream termination of surface (fresh) water flow.

Table 3-5. Channel types of the Central Coast Region in unique settings, with their common attributes and typical Physical Landscape Zones in which they are found.

Channel type	Process domain	Key attributes	Typical settings	Typical Physical Landscape Zone(s)
No channel (Fig. 3-9a)	Non-alluvial	Upstream water source with no downstream surface conveyance	Small drainage area, intermittent flow, infiltrative downslope soils	0–10% Q; PLZ varies in upstream watershed
Estuary (Fig. 3-9b)	Non-alluvial	Slackwater reach with inherited morphology at coastal margin; low pass-through of sediment	Submerged channel mouths across stable/sinking coastal terraces	0–10% Q

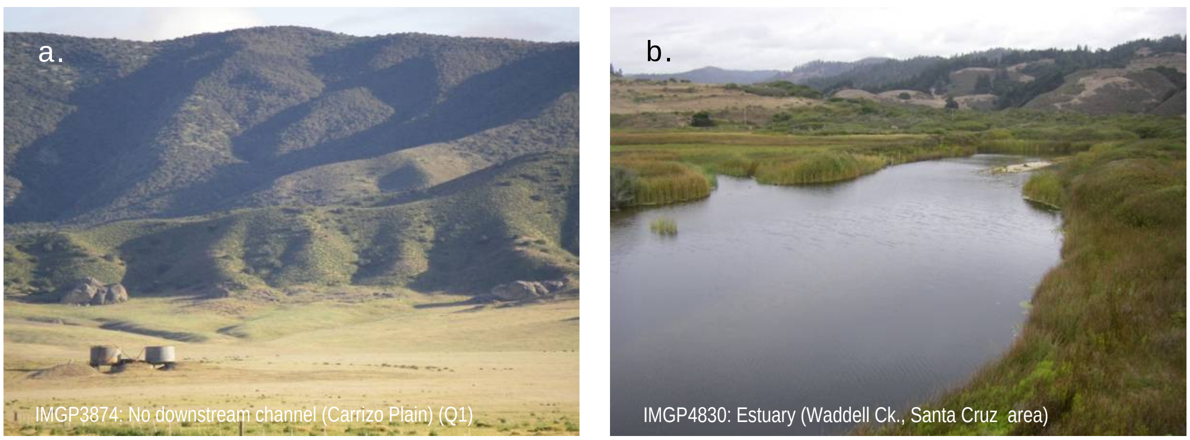


Figure 3-9. Geomorphic channel forms reflecting unique physiographic and/or geomorphic settings in the Central Coast Region.

3.2.1.5 The effects of watershed disturbance on geomorphic form

This catalog of channel types, their typical settings, and the watershed processes that create and support them allows us to anticipate (and to observe) how disturbed watershed processes can alter the "natural" association of Physical Landscape Zones (and thus of watershed processes) with geomorphic channel form (Figure 3-10 and Table 3-6). Because our focus is on hydromodification associated with urbanization, an activity predominately occurring in the lowland valleys and coastal terraces of the Region, we consider only channel types in this physiographic zone in the figure and table below.

CONCEPTUAL FRAMEWORK FOR STREAM-CHANNEL GEOMORPHOLOGY IN DISTURBED WATERSHEDS

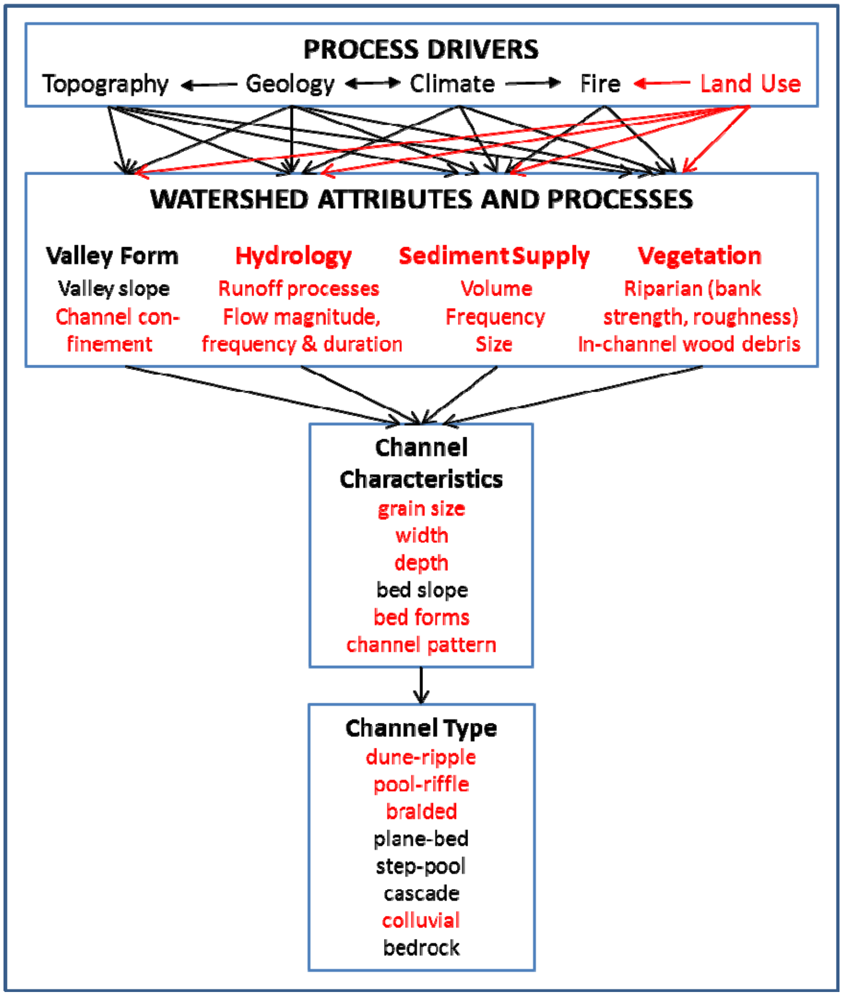


Figure 3-10. Conceptual framework for stream-channel geomorphology as affected by changes in land use (red text, as modified from Figure 3-2). The effects of land-use change are pervasive but not universal; gross attributes of valley and channel slope commonly do not respond strongly, and certain channel types are intrinsically less prone to respond to watershed disturbance.

Table 3-6. Typical morphological expressions of disturbed channels in urban and urbanizing valleys of the Central Coast Region, with their common attributes and typical responses to changes in watershed processes.

Undisturbed channel type, low-slope PLZ's	Key attributes	Infiltration → Surface Runoff	Increase in upstream sediment load	Decrease in upstream sediment load
Semi-confined, plane bed to pool-riffle	Alluvial channel forms, moderately incised, gravelly bed with sand; channel slope <4%	Greater sediment-transport capacity, increased channel incision	Increased downstream sediment delivery; little morphologic change with some potential for bed fining, aggradation, and pool filling.	Bed coarsening; increased channel incision and bank erosion
Unconfined, pool-riffle	Sand and gravel channel with self-constructed floodplain; channel slope <2%	Greater sediment-transport capacity; increased channel incision, downstream sediment delivery, and bank erosion; loss of instream habitat diversity	Bed fining; aggradation; increased downstream sediment delivery and channel migration; pool filling and loss of instream habitat diversity	Bed coarsening; increased channel incision and bank erosion
Unconfined, multi-thread (braided)	Low-gradient (<1%) multi-thread channel, sand to fine gravel bed, unconfined, high sediment load	Greater sediment-transport capacity; increased downstream sediment delivery and bank erosion	Bed fining; aggradation; increased downstream sediment delivery and channel migration	Bed coarsening; increased channel incision and bank erosion
Unconfined, single-thread, meandering, dune-ripple	Low-gradient (<1%) single-thread channel, self-constructed floodplain, stable banks	Greater sediment-transport capacity; increased downstream sediment delivery	Aggradation; increased downstream sediment delivery and channel migration	Bed coarsening; increased channel incision and bank erosion

Higher (and steeper) in the watershed (i.e., those PLZ's on terrain steeper than 10%), the flow-related consequences of unmitigated urbanization are less common, by virtue of where urbanization in the Central Coast Region largely occurs. By observation, however, channel responses in this steeper terrain are already well-described by the Classical Model (Section 2.2.2): channels will tend to expand and incise, at rates and to a degree that is determined jointly by the susceptibility of the channel boundaries to erosion and the magnitude of flow alteration (see also Bledsoe et al. 2010). In areas dominated by subsurface flow, new surface-water discharges can rapidly create new channels where none previously existed, whether by redirected discharge or simply from a loss of vegetation and concentration of surface runoff (Figure 3-11a).

To the extent that urbanization on sloping ground also blocks the introduction of sediment into stream channels (or the free passage of sediment already in stream channels from higher in the watershed), the effects of increased flow on stream-channel morphology will be exacerbated. Increasing the discharge of both water and sediment into a channel, however, does not result in a new "balance" of factors with no untoward effects—observations demonstrate that channels with an increased flux of both water and sediment undergo a variety of morphologic changes, particularly channel expansion and habitat simplification (Figure 3-11b), with undesired consequences for both in-stream and near-stream biota (e.g., Booth 1991, Walsh et al. 2005). The consequences of dramatically increased fluxes of water and sediment into downstream infrastructure can also cause great civic distress.

Figure 3-11. Two types of disturbed channels: (a) gully formed from the surface concentration of runoff; (b) channel impacted by increases in both water and sediment discharge, showing a distinctive homogenized bedform and incision below the surrounding floodplain sediments.

3.2.2 Watershed processes and receiving waters: the hydrologic regime of streams

The natural flow regime for most streams of the Region is intermittent and moderately-to-highly variable (i.e., "flashy"). Over 20 years of scientific study on the variability of hydrologic regime in streams, beginning with Poff and Ward (1989), has provided a common terminology that fits well with the streams of the Region. In Poff and Ward's original study, 78 gage records for rivers and streams in the coterminous United States were analyzed for statistical groupings based on 11 variables that characterized the watershed, flow variability, patterns of the flood regime, and the degree of intermittency. Two streams of the Central Coast (Salsipuedes Creek and Arroyo Seco, USGS gages 11132500 and 11152000) were included in their 1989 study. Both were classified as "intermittent flashy," defined as streams with common periods of no flow and a high frequency of floods that are seasonal in their distribution. Relative to the population of streams across the United States as a whole, this group is notable in the number of days per year with zero flow (about an month's worth, on average), the relatively early calendar date in the year that represents the median day among all days on which floods greater than the 2-year discharge ($Q_{2\text{-yr}}$) occurred over the entire period of record (early March), and the number of calendar dates that *never* experience $Q_{2\text{-yr}}$ (about half the year for this group, on average; and more than 200 days for these two streams). This group of channels are thus moderately intermittent, but with flooding that is strongly seasonal and also relatively common, year-to-year.

Although this analysis of hydrologic stream type has not been carried out for every gaged stream on the Central Coast, we have reviewed a range of them across the Region for conformity to this classification. For example, the gaging station for the Sisquoc River near Sisquoc (USGS 11138500) measures flow from one of the larger unregulated watersheds in the region (281 mi^2 drainage area) and lies upstream of any recognized groundwater basins or even extensive Quaternary deposits likely to promote infiltration and thus to limit surface flow. Nevertheless, it is quite intermittent with an average of 71 days per year with zero or near-zero (<1 cfs) flow. Similarly, the San Lorenzo River, emerging from the mountains above Santa Cruz with a drainage area of 115 mi^2, shows an average of 7 days/year with near-zero flow, still strongly "intermittent" by Poff and Ward's (1989) definition, and so likely resulting in a variety of biological consequences (see below).

Konrad et al. (2008) evaluated a wide range of streamflow attributes, with specific attention to their influence on in-stream biota (see next section). They compiled hydrologic and biological data from 111 sites throughout the western United States, analyzing the hydrologic data for metrics that were anticipated to display the greatest potential influence on macroinvertebrate assemblages. They identified 13 such metrics, associated with flow magnitude, duration, frequency, timing, and variability, that showed statistically significant associations with BMI metrics. Of these 13 attributes, we have identified five that should display a particularly strong response to watershed urbanization (C.P. Konrad, pers. comm. 2011). They are presented in Table 3-7, listed in rank (declining) order of their anticipated magnitude of change in an urban watershed and showing the direction of urban-induced change ("+" = increase in the metric; "–" = decrease in the metric).

Table 3-7. Five hydrologic metrics from Konrad et al. (2008), arranged in declining rank order of their anticipated response to watershed urbanization (and direction of change, either + (increasing metric value) or – (decreasing metric value).

Category of hydrologic metric	Hydrologic metric	Direction of urban-induced anticipated change	Reason for urban-induced change
Flow Variability	Absolute value of the percent daily change in streamflow (analogous to R-B Index)	(+)	Urban flows are flashier, a result of a greater fraction of overland flow and shorter flow paths.
Flow Variability	Baseflow recession, calculated as the 10th percentile of all differences in day-to-day flow differences, taken as logarithms of daily streamflow: $\log(Q_{day1})–\log(Q_{day0})$	(–)	Urban hydrographs show a much more rapid decline from peak flows to baseflows, leaving a greater fraction of days with only small day-to-day changes (but very large changes when averaged over all flows).
Peak-Flow Duration	Median annual duration of the longest high flow event	(–)	Urban flows are flashier—the largest peaks do not last long.
Peak-Flow Frequency	Median annual number of continuous periods (high-flow events) when daily streamflow exceeds Q_{10}, the flow exceeded 10% of the time	(+)	Peak events are more numerous in urban streams, because even small rainstorms can contribute overland flow to stream channels.
Flow Variability	Median annual streamflow exceeded 10% of the year as a fraction of median streamflow (Q_{10}/Q_{50})	(–)	More extreme, flashy flows increase the *magnitude* but decrease the *duration* of stormflows (e.g., Q_{10}); when compared to a relatively stable metric (e.g., Q_{50}) the ratio will therefore decline.

As part of our analysis, we looked more closely at one of the metrics commonly used to assess flow variability, the "Richards-Baker Index" (or *R-B Index*; Baker et al. 2004), using daily flow data compiled from 34 USGS gages during Task 3 of the Joint Effort. The Richards-Baker Index was developed as a means to assess the "flashiness" of stream flow (i.e., how quickly the discharge rises and falls) at a given location using daily average flow data, the most commonly available data set in the water resources field and accessed for this project through the US Geological Survey's web portal for California surface-water gages (http://waterdata.usgs.gov/ca/nwis/sw).

The R-B Index is defined as the ratio of the "path length" of a seasonal or annual hydrograph (calculated as the absolute value of the difference in adjacent discharge records, summed over the period of interest) divided by the total of all discharges over the same period. Thus, a rapidly oscillating flow record will have large daily differences and result in a large final R-B Index value. Conversely, a stable discharge record with very small day-to-day changes will produce a small sum-of-differences relative to the sum of those (near-constant) discharges, with a quotient approaching zero as the limiting value for truly constant flow.

Baker et al. (2004) evaluated the R-B Index with respect to a range of measurement and watershed variables. The index shows a strong dependency on watershed area, a consequence of more homogenized mixing of floods across larger stream networks. A related, amplifying effect is the averaging effect of using daily flow data, insofar as smaller watersheds (those below a few tens of square miles in area; see Baker et al. 2004, their Table 3) have a stronger tendency to rise and fall over progressively shorter time periods. They also found particularly high variability in the index values for streams with very low or intermittent flow (below about 0.01 m^3/sec per km^2, or about 1 cfs/mi^2; their Figure 6). If these intrinsic drivers of flashiness can be recognized and canceled out, however, the R-B Index is a potential tool for evaluating the influence of human modifications of the contributing drainage area (e.g., land cover, imperviousness, irrigation management) or of climate (e.g., rainfall intensity or volume). In one such application, for example, strong correlation was found between the R-B Index and watershed imperviousness across 16 sites in western Washington (DeGasperi et al. 2009), although the authors of this study also noted the strong watershed size-dependency of the index.

To explore the relationship of watershed conditions and processes with the hydrologic regime of receiving waters, we analyzed the daily flow records from long-term USGS gages in the Central Coast Region (see Appendix C for full analysis). To reduce the influence of basin size on hydrologic response, the index calculations presented below are restricted to watershed areas of less than 50 mi^2, which leaves 11 relatively high-quality records (Table 3-8). Even within this limited range of watershed areas, a trend of decreasing flashiness with increasing area is evident, together with a lack of systematic differences amongst these sites between the two decadal periods analyzed (Figure 3-12).

Table 3-8. USGS gages used in the assessment of R-B Index, including every such location in the Region with a complete flow record 1980-1990 and 2000-2010 that captures a watershed area of less than 50 mi^2 (see Appendix C). Sites are listed in order of increasing R-B Index value (i.e., increasing flashiness) for the years 2000-2010.

USGS Station ID	Stream	Location	Drainage Area (mi^2)	R-B Index (average of annual values)	
				1980–1990	2000–2010
11143000	Big Sur River	Near Big Sur	46.8	0.23	0.22
11141280	Lopez Creek	Near Arroyo Grande	21.6	0.27	0.30
11160000	Soquel Creek	at Soquel	41.2	0.52	0.49
11159200	Corralitos Creek	at Freedom	28.1	0.68	0.60
11132500	Salsipuedes Creek	Near Lompoc	48.6	0.58	0.71
11152600	Gabilan Creek	Near Salinas	36.5	0.95	0.76
11120500	San Jose Creek	Near Goleta	5.5	0.68	0.83
11119500	Carpinteria Creek	Near Carpinteria	13.0	1.02	1.05
11119750	Mission Creek	Near Mission St nr Santa Barbara	8.7	1.12	1.14
11119940	Maria Ygnacio Ck.	at University Dr nr Goleta	6.4	1.07	1.17
11120000	Atascadero Creek	Near Goleta	19.7	1.19	1.21

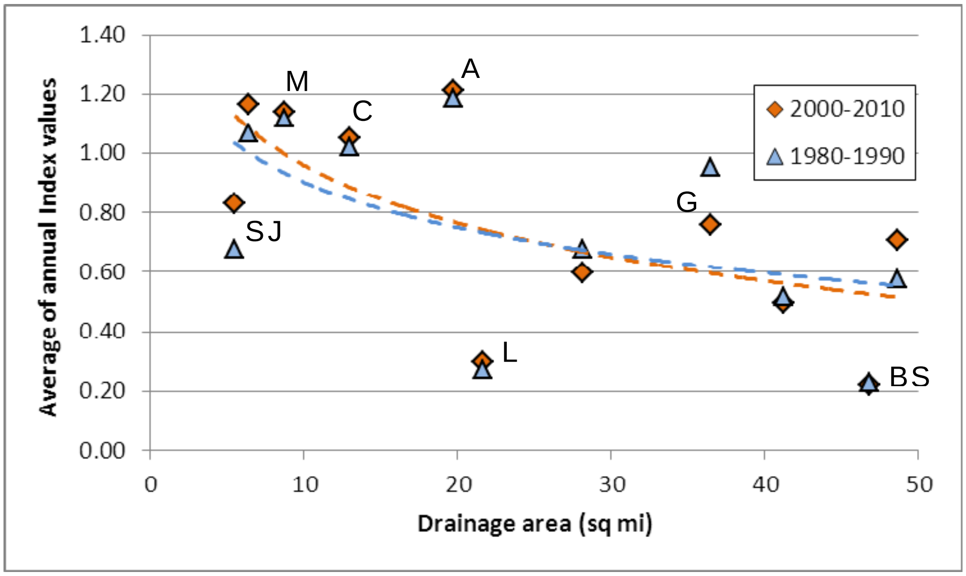


Figure 3-12. Plot of data from Table 3-8. Logarithmic best-fit lines (dashed) show the systematic decline of R-B Index with increasing drainage area, and their similarity reflects a lack of significant systematic differences between the two decadal periods. Notable low-index values (all plotting well below the trend lines): SJ = San Jose Creek, L = Lopez Creek, BS = Big Sur River; high-index values: M = Mission Creek, C = Carpinteria Creek, A = Atascadero Creek. Note low-urban Gabilan Creek (G), plotting well above the trend lines but with the lowest unit-area discharge of the set (0.06 cfs/mi^2), suggesting erratic Index values (Baker et al. 2004).

From these results, we recognize the following patterns in the data, in decreasing order of strength:

1. The R-B Index is watershed-size-dependent (as noted by the original authors).
2. The periods 1980–1990 versus 2000–2010 show statistically insignificant differences. This finding does not preclude the reality of underlying change in either land use or in rainfall patterns between the two decades, simply that any changes were insufficient to show systematic trends. Between these two periods, the R-B Index increased at 5 gages and decreased at the other 6; 4 of the 5 "increasing" gages had an increase in watershed urbanization, but so did 3 of the 6 "decreasing" gages.
3. With the removal of the watershed-size trend, either time period (or their combination) does display an overall land-cover signal (consistent with the findings of DeGasperi et al. 2009): the most urban areas *are* flashier, and the completely nonurban ones less flashy. For example, the largest Index value was attained in Atascadero Creek, below the town of Goleta; Mission and Carpinteria creeks, also both within urban areas of the southern Central Coast, also have high Index values. In contrast, the smallest values are fully undeveloped Lopez Creek and Big Sur River (both <0.30).
4. There is no systematic variability imposed by differences in the Physical Landscape Zones of the contributing watersheds, at least relative to those imposed by watershed size and land cover. This suggests that runoff processes are not dramatically different in different PLZ's (again, in the absence of land-use influences), consistent with our observations of the widespread dominance of subsurface flow across the Region in Task 3. This conclusion is well-illustrated by the two gages with the lowest R-B Index, Big Sur River and Lopez Creek, whose watersheds are both entirely underlain by steep and nominally "low-infiltrative" bedrock. Since their land surface is undisturbed, however, runoff processes remain dominated by subsurface flow.

3.2.3 Watershed processes and receiving waters: in-stream biological conditions and responses

Tracing the causal connections between in-stream conditions and biological health has been a long-standing goal of watershed studies for more than a decade. Karr and Yoder (2004) diagrammed the "linkages" (their term) between five water-resource attributes that are relevant to flowing streams and are affected by human activity (Figure 3-13), emphasizing the multi-faceted nature of these linkages and reminding us of the impossibility of choosing any single disturbance pathway to characterize the biological response to urbanization. In this section, we focus on two of these linkages in greater detail: those relating habitat structure (i.e., stream-channel geomorphology, see Section 3.2.1) and flow regime (see Section 3.2.2) to biological responses.

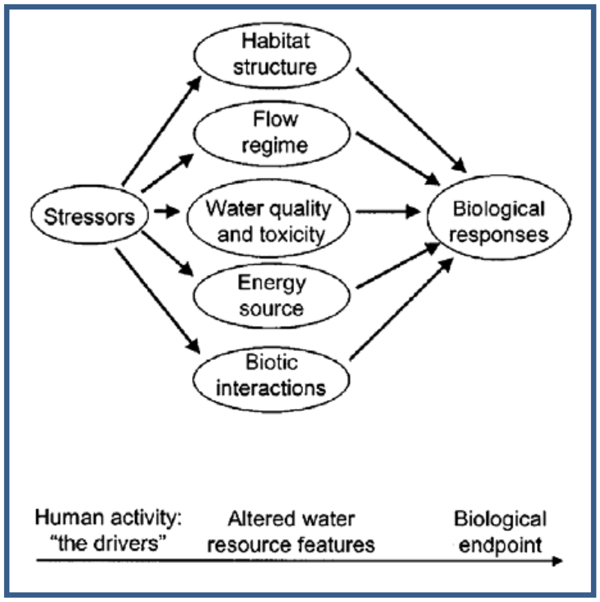


Figure 3-13. Linkages from human activity ("Stressors," in this diagram) through five major water resource features altered by human activity, to biological responses. Model emphasizes the multiple potential causes of resource changes associated with human activities (from Karr and Yoder 2004, their Figure 4).

3.2.3.1 "Geomorphic form" and biological conditions

Channel geomorphology is an expression of watershed processes, particularly those related to flow, the movement of sediment, and the presence of riparian (and in-stream) vegetation (Figure 3-2). Where those processes are altered, channel form is also likely to respond, particularly if the original channel type is characterized as a "response" channel (i.e., dune-ripple, pool-riffle, and braided; Montgomery and Buffington 1997; see Figure 3-8) for its recognized sensitivity to changes in flow regime and/or sediment supply. Thus we here consider the typical morphological elements of these channel types, and the nature of their urban-induced changes as they can impinge on biological conditions.

Relationships between channel form and in-stream biological conditions are widespread. "Fish habitat" is a direct expression of this interaction, whereby particular habitat features (particularly pools and riffles) provide the physical setting in which critical life stages of fish occur (and on which those fish depend). Thus, watershed disturbance that results in a loss (or redistribution of the frequency) of these key habitat features will likely have direct effects on any fish populations that make use of them. One such common consequence of urbanization is homogenization of morphology in pool-riffle channels and (in particular) the loss of pools, a consequence of increased peak discharges and more vigorous and frequent sediment transport (Konrad et al. 2005), and (in forested regions) the loss of in-stream large woody debris as a result of riparian-zone modification or direct removal (Montgomery et al. 1996). Changes in bed sediment, either a coarsening of the bed with increased flows or a burial of gravel beneath eroded upland sediment, can severely limit the availability of spawning gravels of suitable size and permeability.

In the Central Coast Region, there is a paucity of before/after data on how channel geomorphology has changed, and how that change has affected in-stream fish habitat, in response to urbanization. Observations of stream channels within and below urban areas throughout the

Region are consistent with the patterns described from elsewhere throughout the world, but we have found no systematic Region-wide documentation of these phenomena. Local watershed-specific studies, however, do provide useful insight into the geomorphic factors limiting fish populations (particularly steelhead) in their area of study; for example, in both Aptos Creek (Coastal Watershed Council 2003) and Soquel Creek (Santa Cruz County Resource Conservation District 2003), the impacts of fine sediment on spawning gravels and the paucity of pools from a loss of large woody debris were highlighted.

As a more general measure of "biological health," the Joint Effort has embraced the use of benthic macroinvertebrates as a relatively sensitive indicator (Karr and Chu 1999) with abundant preexisting data. The linkages between channel geomorphology and benthic macroinvertebrates has not been explored for as long, or as directly, as for fish—but the basic patterns are no less clear from the existing scientific literature. A dramatically increased frequency of disturbance under an urban flow regime, reflecting more frequent turnover of the channel-bed sediment, was first quantified by Booth (1991) for Pacific Northwest streams; subsequent measuring and modeling (e.g., Konrad et al. 2002) has amply documented this trend, along with its deleterious effects on macroinvertebrate populations.

The specific relationship(s) between changes in channel form and benthic macroinvertebrate populations have never been nearly as well quantified as for fish habitat. The most relevant studies have evaluated the biological effectiveness of direct channel manipulation, in effect creating a controlled experiment whereby geomorphic form is altered but no other instream attribute (nor any watershed process) has been changed. Although we have found no such study with data from Central Coast streams, published results from elsewhere are sufficiently clear to suggest widespread applicability. Larson et al. (2001) used benthic macroinvertebrate data from "stream restoration" projects (collected either pre- and post-project, or upstream/downstream of a project) to conclude that "Biological conditions, as assessed by benthic macroinvertebrates, did not improve as a result of the in-stream rehabilitation projects; instead, they directly relate to the level of development in the upstream watershed." Similarly, Violin et al. (2011) offered the principle that "To be successful at mitigating urban impacts, the habitat structure and biological communities found in restored streams should be more similar to forested reference sites than to their urban degraded counterparts", but using this criterion they found that "reach-scale restoration is not successfully mitigating for the factors causing physical and biological degradation" (p. 1932).

The implications of these findings for the Joint Effort are three-fold:

(1) Geomorphology-based metrics of channel condition are not likely to provide clear guidance for evaluating biological health, even though channel geomorphology is strongly influenced by watershed processes;

(2) Hydromodification control plans based on meeting a particular geomorphic objective (e.g., "stable stream channels") is unlikely to achieve broader biological objectives; and

(3) Alternative hydromodification mitigation that emphasizes in-stream channel manipulation over process-based restoration are unlikely to achieve meaningful management goals.

3.2.3.2 "Hydrology" and biological conditions

Although flow has been often recognized as a "master variable" (e.g., Power et al. 1995; Doyle et al. 2005), researchers have also been quick to warn against simplistic, single-factor "explanations" for biological conditions. Morley and Karr (2002) noted the strong correlation between biological health (as measured by a multi-metric index of benthic macroinvertebrates, conceptually identical to the SCIBI of Ode and others, 2005) and upstream land cover. At the watershed scale, the effects of land cover likely affect instream biota largely through their influence over the flow regime; but Morley and Karr also found a near-equivalent influence of more localized land-cover metrics as well (those relating to vegetation density within a few hundred meters of the measurement site), which presumably influence non-flow attributes as well. Working with the same data set, Booth et al. (2004) found improved correlations between biota and watershed-scale land-cover metrics by including a metric of hydrologic flashiness in their analysis; others have found that including measures of landscape patterns and flow-path connectivity further improve correlations, although discrete causal mechanisms remain inferential rather than directly proven (e.g., McBride and Booth 2005, Alberti et al. 2007).

These findings suggest that the linkage from "flow regime" to "biological response" is strong but by no means overwhelming (Figure 3-13); near-stream influences, likely expressed through changes in habitat structure (which, note, are *also* responsive to flow regime), energy sources (e.g., shade, food supply), and biotic interactions (e.g., invasive species) are also important. In the context of the Joint Effort, these findings remind us that this "Linkage Analysis" will be most robust in consideration of the biological effect of *altered watershed processes*, and less definitively so as we consider the biological effect of individual factors, such as "channel geomorphology" or "flow regime", that are physical expression(s) of those altered processes.

These caveats offer not only a warning for overinterpreting hydrologic data with respect to biological response, but also guidance for conducting a productive analysis. In this vein, Konrad et al. (2008) note that "Streamflow is only one of many environmental and biotic factors that influence the characteristics of invertebrate assemblages" (p. 1983), but they go on to explore the likelihood that well-chosen attributes of the flow regime may *limit* (but not necessarily *correlate with*) various metrics of invertebrate assemblages. The five metrics of Table 3.7 all show strong influence on the distribution of one or more biological metrics, and they are all affected by watershed urbanization. That influence, however, is not in the trend of a "central tendency" (i.e., a simple regression line); instead, it is in putting an upper bound ("ceiling") or lower bound ("floor") on the observed distributions of biological metrics. Their key findings are summarized as follows:

> "…streamflow characteristics appear to be ecologically significant as limiting factors on invertebrate assemblages throughout the western U.S.A…. However, no single streamflow metric provides a comprehensive indicator of the effects of streamflow on the benthic invertebrate assemblages. Instead, each characteristic of benthic invertebrate assemblages responded in a distinct way to streamflow characteristics with the responses often highly specific to a particular pairing of an invertebrate metric and a streamflow metric. Consequently, it is necessary to consider a broad range of streamflow and invertebrate assemblage characteristics employing multiple hydrological and biological metrics when characterizing the influence of streamflow in lotic ecosystems." (p. 1994)

Looking more generally at a range of biological responses (macroinvertebrates, fish, and riparian vegetation), Poff and Zimmerman (2010) similarly concluded that "…analyses do not support the use of the existing global literature to develop general, transferable quantitative relationships between flow alteration and ecological response; however, they do support the inference that flow alteration is associated with ecological change and that the risk of ecological change increases with increasing magnitude of flow alteration" (p. 194). DeGasperi et al. (2009) also found that even their selected hydrologic metrics (including the R-B Index) were little (or no) better predictors of biological health (as measured by a benthic macroinvertebrate index) than gross measures of land cover, such as percent total imperviousness.

These published findings underscore both the importance, and the limitations, of the focus of the Joint Effort: our consideration of the influence of watershed disturbance on the flow regime is entirely justifiable in pursuit of better receiving-water conditions, but we have little chance of identifying a single (or even a suite of) hydrologic metrics to fully represent those influences. This challenge is reflected in the current approaches to "eco-hydrology," where consideration of a (very) broad suite of flow metrics is common (e.g., Olden and Poff's 2003 review of 171 hydrologic metrics; see also http://www.fort.usgs.gov/products/software/nathat/) in order to assess potential biological impacts. Such an analysis is beyond the scope of the Joint Effort, and it is unnecessary as well for our present management objectives.

In summary, the linkages between hydrology, channel geomorphology, and biological health is undisputed, but the path of recovery towards healthy watershed is not through fine-tuning any particular flow attribute or reconstructing a desired geomorphic feature. Instead, it can only occur by restoring the degraded key watershed processes that can create and sustain these valued attributes.

3.2.4 Extending the findings from streams to other receiving waters

As noted earlier, streams are particularly useful for observing and inferring the consequences of landscape alteration and disturbed watershed processes on receiving waters. However, we do not anticipate that the findings of the Linkage Analysis will be uncritically applicable to all receiving-water types (Table 3-9). The following caveats are needed to "translate" the stream-based results to these other water bodies:

- **Large rivers.** Although difficult to objectively discriminate from "streams" as discussed throughout this report, those rivers draining many hundreds or thousands of square miles are generally recognized to have a hydrologic response to watershed disturbance that is greatly muted relative to that of small streams. In part this reflects the proportionately smaller watershed area that any given urban development will affect, and in part it reflects the intrinsic "homogenization" of flows imparted by a large drainage network with widely different travel times. Large rivers of the Region are also commonly subjected to a variety of flow-related manipulations (i.e., dams or other impoundments) that are not directly related to watershed disturbance but can impose an overriding influence on the flow regime.
- **Lakes.** Changes to the flow regime are unlikely to be directly relevant to the condition of lakes, except insofar as the most typical changes (namely, increases in peak flows and erosivity) will increase the delivery of sediment from erodible upstream channels. Sensitivity to accumulated contaminants whose total loadings can determine the health of the waterbody, however, emphasizes the importance of water-quality considerations where a lake lies along the channel network, particularly in landscapes where subsurface flow has been replaced with overland flow and so permitting greater opportunities for the wash-off of pollutants. Changes to processes that promote breakdown or sequestration of nutrients, toxics, and other such contaminants are particularly significant in these settings.
- **Wetlands.** In addition to the water-quality issues noted for lakes, changes to the hydroperiod of wetlands can result in substantial effects to wetland biota. This is

most common as a result of changes to hydrologic processes that result in either flashier discharges from inlet streams, reduction in seasonal groundwater levels, or both.

- **Marine nearshore.** Water-quality concerns in this environment are typically muted relative to those of lakes or wetlands, because of the opportunities for rapid mixing with the ocean. However, localized concentrations of pollutants (and loss of the watershed processes that can attenuate them), particularly relating to human health from direct contact or shellfish consumption, raise significant concerns for bacterial contamination of the nearshore environment from stormwater runoff. Water-*quantity* concerns, in contrast, are typically moot.
- **Groundwater aquifers.** The quantity of recharge to groundwater aquifers is inversely related, but imperfectly so, to the amount of surface runoff delivered to stream channels. The geology of the Central Coast provides clear examples of where surface runoff can re-enter the groundwater system, modestly (if at all) diminished in quantity and merely shifted in space and time. Other settings, however, are likely to result in a permanent loss of recharge with a conversion of subsurface flow to surface runoff. Water-quality concerns are limited to a relatively small number of contaminant types, but their presence is critical because of the potential linkage to drinking water and thus human health. These concerns take on yet greater importance in the context of stormwater management strategies that emphasize infiltration from developed land surfaces over deeply permeable deposits, a particularly common social and geological setting in the Region.

Table 3-9. The major categories of receiving-water conditions (left column) and their applicability to evaluating the level of disturbance (or guiding the protection) of the various types of receiving waters.

CONDITIONS	RECEIVING WATER TYPE				
	Streams	**Large rivers**[1]	**Lake/wetland**	**Marine nearshore**	**Groundwater aquifers**
Hydrology	X		X (wetland hydroperiod)		X
Morphology and habitat structure	X	X			
Chemistry (water quality)	X	X	X (esp. sediment, nutrients, toxics)	X (esp. toxics, bacteria)	X
Biological health	X		X	X	

[1] "Large" is used to mean those rivers whose hydrology is not materially affected by typical watershed extent of urbanization.

These considerations are based on several lines of reasoning:

1. Specific contaminants of only limited concern in streams can be critical determinants of the quality of other receiving waters (e.g., nutrients in lakes; nitrates in drinking-water aquifers).
2. Streams are "pass-through" systems for pollutants; typically, their water quality is measured in terms of the instantaneous concentration of contaminants, not their long-term loadings (unlike lakes and wetlands).
3. Similarly, increases in the sediment flux through a stream may impose few changes or degradation of channel form, but the increased delivery of sediment to downstream receiving-water bodies may nonetheless significantly affect the quality of those waterbodies.
4. Conversely, streams are *more* sensitive than other receiving-water types to changes in a variety of watershed processes, particularly those that affect the quantity and rate of water flow that, in turn, increase channel bed or bank erosion or that directly impact in-stream biota during one or more life stages.

3.3 Application of Key Findings for the Joint Effort

These findings of the "Linkage Analysis" provide an important foundation for subsequent stages of the Joint Effort, whose explicit focus will be on the management of hydromodification in the Central Coast Region. In summary:

1. Infiltration and subsurface flow are the dominant hydrologic processes across all intact watersheds of the Region, regardless of the specific Physical Landscape Zone being considered.
2. Different Physical Landscape Zones respond differently to the changes in watershed processes imposed by urbanization, but the shift from infiltration to surface flow is ubiquitous.
3. Stream-channel conditions can provide a useful diagnostic indicator of watershed disturbance, but managing to achieve a particular stream-channel form will not achieve other management objectives for the protection of receiving waters.
4. The consequences of urbanization on receiving waters other than streams is not well-documented and must be inferred, either by studies from other parts of the country or by extrapolation from the Region's stream-specific data. Much of the historical focus of hydromodification control on flow rates in small streams is (at most) marginally relevant, however, to the condition or health of other types of receiving waters. Conversely, certain water-quality constituents of limited concern in streams are critical to the health of non-flowing receiving waters, such as lakes, that lie at the downstream end of the channel network.

4 NEXT STEPS

The tasks that comprise the Joint Effort have been designed and executed to assemble the foundation for developing scientifically based approaches to hydromodification control that are tailored to the watershed conditions of the Central Coast Region. These have included the identification and compilation of relevant technical studies and watershed-relevant data (Task 1), a GIS-based characterization of the Region's landscape and rainfall patterns (Task 2), a field-based characterization of the Region's watersheds and receiving waters (Task 3), and the integration of these descriptions within a science-based framework as informed by many decades of prior investigation (this report, Task 4).

The next, upcoming task (Task 5) has as its overarching objective to translate the scientific foundation of the Linkage Analysis to support management actions. This is anticipated to include the following set of products:

1. A final, GIS-based map of the Physical Landscape Zones, defined and displayed at a scale commensurate with the underlying GIS data that defines them.
2. Two sets of management "overlays" to the basic, map-based definition of Physical Landscape Zones: the first will discriminate watershed areas of the Region that drain to the variety of different receiving-water types; the second will identify those areas of the Region where preexisting degradation, either to watershed processes or to receiving-water conditions, suggests that alternative management objectives may be appropriate. Although for most of the Region the direct or otherwise proximal receiving water will be a stream, there are significant areas that directly discharge to the marine nearshore, to a lake or wetland, to a large river, or to subsurface aquifers without any intervening surface-water body at all.
3. An annotated compilation of current numeric flow-control requirements for hydromodification control, from other California jurisdictions and around the nation. It is not the purpose of Task 5 of the Joint Effort to identify the "correct" numeric criteria for this Region, but rather to summarize the range of existing approaches and identify which are likely to be most (or least) appropriate to the approach being developed here.
4. A series of written reports that summarize and document the methods used to identify PLZ's and the management strategies best suited to them, a "user's guide" for applying the products of the Joint Effort to determine requirements for hydromodification control in any specific locality in the Region, and a summary of the management and policy implications of the Joint Effort.

5 REFERENCES

Alberti, M., D. Booth, K. Hill, B. Coburn, C. Avolio, S. Coe, and D. Spirandelli. 2007. The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. Landscape and Urban Planning 80: 345–361.

Baker, D. B., R. P. Richards, T. T. Loftus, and J. W. Kramer, 2004. A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association 40: 503–522.

Becker, G. S., and I. J. Reining. 2008. Steelhead/rainbow trout *(Oncorhynchus mykiss)* resources south of the Golden Gate, California. Cartography by D.A. Asbury. Center for Ecosystem Management and Restoration. Oakland, CA. 431 pp. http://www.cemar.org/SSRP/SSRP_pdfonly.html [Accessed 27 September 2011].

Beighley, R. E., T. Dunne, J. M. Melack. 2005. Understanding and modeling basin hydrology: interpreting the hydrogeological signature. Hydrological Processes 19: 1,333–1,353.

Bledsoe, B. P., R. J. Hawley, E. D. Stein, and D. B. Booth. 2010. Hydromodification screening tools: technical basis for development of a field screening tool for assessing channel susceptibility to hydromodification. Southern California Coastal Watersheds Research Technical Report 607, 54 pp. ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/607_HydromodScreening_TechBasis.pdf [Accessed 7 November 2011}.

Booth, D. B. 1990, Stream-channel incision following drainage-basin urbanization. Water Resources Bulletin 26: 407–417.

Booth, D. B. 1991, Urbanization and the natural drainage system—impacts, solutions, and prognoses. Northwest Environmental Journal 7: 93–118.

Booth, D. B., E. A. Gilliam, S. Araya, C. Helmle, and J. Riverson. 2011. Watershed characterization part 2: watershed management zones and receiving-water conditions. Prepared by Stillwater Sciences and TetraTech, Santa Barbara, California, for California State Central Coast Regional Water Quality Control Board.

Buffington, J. M., R. D. Woodsmith, D. B. Booth, and D. R. Montgomery. 2003. Fluvial processes in Puget Sound rivers in the Pacific Northwest. Pages 46–78 *in* D. R. Montgomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound rivers. University of Washington Press.

California Department of Water Resources. 2003. California's groundwater. Bulletin 118—Update 2003. http://www.water.ca.gov/groundwater/bulletin118/bulletin118update2003.cfm [Accessed 21 November 2011].

Center for Watershed Protection. 2003. Impacts of impervious cover on aquatic systems. Center for Watershed Protection, Ellicott City, Maryland.

Central Coast Salmon Enhancement. 2010. Santa Rosa Creek benthic macroinvertebrate (BMI) assessment report. Prepared for Greenspace-The Cambria Land Trust, Cambria, California.

Coastal Watershed Council. 2003. Aptos Creek Watershed Assessment and Enhancement Plan. April 2003. Prepared by Maya T. Conrad, Coastal Watershed Council, Santa Cruz. http://www.rcdsantacruz.org/modules/tabular_download_gallery/dlc.php?file=139 [Accessed 7, November 2011].

DeGasperi, C. L., H. B. Berge, K. R. Whiting, J. J. Burkey, J. L., Cassin, and R. R. Fuerstenberg, 2009. Linking hydrologic alteration to biological impairment in urbanizing streams of the Puget Lowland, Washington, USA. Journal of the American Water Resources Association 45 512–533.

Doyle, M. W., E, H. Stanley, D. L. Strayer, R. B. Jacobson, and J. C. Schmidt. 2005. Effective discharge analysis of ecological processes in streams. Water Resources Research 41 1–16.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman and Company New York.

Ecology Consultants. 2011. Southern COASTAL Santa Barbara Creeks Bioassessment Program, 2010 report. Prepared for City of Santa Barbara, Creeks Division and County of Santa Barbara, Project Clean Water.

Jennings, C. W., R. G. Strand, and T. H. Rogers. 1977. Geologic map of California: California division of mines and geology, scale 1:750,000.

Karr, J. R., and E. W. Chu.1999. Restoring life in running waters. Island Press, Washington, D.C.

Karr, J. R., C. O. Yoder. 2004. Biological assessment and criteria improve total maximum daily load decision making. Journal of Environmental Engineering 130: 594–604.

Kellerhas, R., and M. Church. 1989. The morphology of large rivers: characterization and management. Pages 31–48 *in* D.P. Doge, editor. Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences.

Kellogg, K. S., S. A. Minor, and P. M. Cossette. 2008. Geologic map of the eastern three-quarters of the Cuyama 30' x 60' quadrangle, California: U.S. Geological Survey, Scientific Investigations Map SIM-3002, scale 1:100000.

Konrad, C. P., D. B. Booth, and S. J. Burges, 2005, Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: Consequences for channel form and streambed disturbance. Water Resources Research 41: 1–15.

Konrad, C. P., D. B. Booth, S. J. Burges, and D. R. Montgomery. 2002. Partial entrainment of gravel bars during floods. Water Resource Research 38: 901–916.

Konrad, C.P., A. M. D. Brasher, and J. T. May. 2008. Assessing streamflow characteristics as limiting factors on benthic invertebrate assemblages in streams across the western United States. Freshwater Biology 53: 1,983–1,998.

Larson, M. L., D. B. Booth, and S. M. Morley. 2001. Effectiveness of large woody debris in stream rehabilitation projects in urban basins. Ecological Engineering 18: 211–226.

Leopold, L. B. 1968. Hydrology for urban planning: a guidebook on the hydrologic effects of urban land use. U. S. Geological Survey Circular 554: 18 pp.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman and Company, San Francisco, California.

McBride, M., and D. B. Booth. 2005. Urban impacts on physical stream condition: Effects of spatial scale, connectivity, and longitudinal trends. Journal of the American Water Resources Association 41: 565–580.

Mollard, J. D. 1973. Air photo interpretations of fluvial features. Pages 341–380 *in* Fluvial processes and sedimentation. National Research Council of Canada, Inland Waters Directorate, University of Alberta, Edmonton, Alberta.

Montgomery, D. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35: 397–410.

Montgomery, D. R., T. B. Abbe, J. M. Buffington, N. P. Peterson, K. M. Schmidt, and J. D. Stock. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381: 587–589.

Montgomery, D. R., and J. M. Buffington. 1997. Channel reach morphology in mountain drainage basins. Geological Society of America Bulletin 109: 596–611.

Ode, P. R., A. C. Rehn, and J. T. May. 2005. A quantitative tool for assessing the integrity of southern coastal California streams. Environmental Management 35: 493–504.

Olden, J. D., and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19: 101–121.

Paul, M. J., and J. L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32: 333–365.

Poff, N. L., and J. V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46: 1,805–1,818.

Poff, N. L., and J. K. H. Zimmerman. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshwater Biology 55: 194–205.

Power, M. E., A. Sun, G. Parker, W. E. Dietrich, and J. T. Wootton. 1995. Hydraulic food-chain models. BioScience 456: 159–167.

Reid, L. M. and T. Dunne. 1996. Rapid evaluation of sediment budgets. Catena Verlag GmbH, Germany, 164 pp.

Santa Cruz County Resource Conservation District. 2003. The Soquel Creek Watershed Assessment and Enhancement Project Plan. http://www.rcdsantacruz.org/media/watershed_plans/SCWEP.pdf [Accessed 7 November 2011].

Segura, C., and D. B. Booth. 2010. Effects of geomorphic setting and urbanization on wood, pools, sediment storage, and bank erosion in Puget Sound streams. Journal of the American Water Resources Association 46: 972–986.

Stillwater Sciences. 2010. Santa Rosa Creek Watershed Management Plan: watershed geomorphology assessment. Final Technical Report. Prepared by Stillwater Sciences, Berkeley, California for Greenspace-The Cambria Land Trust, Cambria, California.

Violin, C. R., P. Cada, E. B. Sudduth, B. A. Hassett, D. L. Penrose, E. S. Bernhardt. 2011. Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. Ecological Applications 21: 1,932–1,949.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan II. 2005. The urban stream syndrome: Current knowledge and the search for a cure. Journal of the North American Benthological Society 24: 706–723.

Warrick, J. A. and L. A. K. Mertes. 2009. Sediment yield from the tectonically active semiarid Western Transverse Ranges of California. Geological Society of America Bulletin 121: 1,054–1,070.