Methods and Findings of the Joint Effort for Hydromodification Control in the Central Coast Region of California

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1 INTRODUCTION

The Central Coast Joint Effort for Hydromodification Control (the "Joint Effort") is a collaborative, region-wide approach municipalities are using to implement low impact development and hydromodification control. The goal of the Joint Effort is to protect or restore key watershed processes that otherwise would be, or that already have been, adversely affected by human activity. The approach taken by the Joint Effort to reach this goal is to use a foundation of landscape characterization to identify the hydromodification control strategies for new urban development and redevelopment that will be most effective at achieving the protection and restoration of aquatic resources. The interim products of the 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); the data- and field-supported identification of landscape attributes, watershed processes, receiving-water conditions, and primary disturbances present on that landscape (Task 3); and a GIS-based analysis of a final set of "Physical Landscape Zones" (PLZ's) and a systematic description of the primary landscape attributes and the dominant watershed processes associated with each one (Task 4).

The specific purpose of this report is to document the entire Joint Effort methodology and findings, including the determination of Watershed Management Zones and the identification of associated hydromodification management strategies. This report describes how each of the following steps were undertaken, and the results of each step:

1. Definition and mapping of Physical Landscape Zones;
2. Association of key watershed processes with each PLZ;
3. Definition of the interrelationships between landscape disturbance, PLZ's, watershed processes, and receiving waters;
4. Definition and mapping of Watershed Management Zones;
5. Identification of hydromodification management strategies associated with each WMZ; and
6. Incorporation of local-scale and/or site-specific data to inform final stormwater management controls and their numeric criteria.

2 STEPS IN THE JOINT EFFORT METHODOLOGY

2.1 Defining and mapping Watershed Processes and Physical Landscape Zones

2.1.1 Watershed Processes

"Watershed processes" is the term adopted by the Joint Effort to encompass the storage, movement, and delivery of water, chemical constituents, and/or sediment to receiving waters. Watershed processes across the landscape of the Central Coast region were anticipated to be similar to those found throughout temperate latitudes throughout the world, and so characterizations and discussions in the scientific literature formed the basis for initial definition of those processes, and subsequently for making and interpreting field observations. Most commonly, that literature subdivides the set of watershed processes into those relating to the movement of *water* and to the movement of *sediment*. Although obviously interrelated, that subdivision is maintained here.

The delivery, movement, storage, and loss of water within a watershed is one set of watershed processes, most commonly represented by the hydrologic cycle. Components of the hydrologic cycle constitute the fundamental ***hydrological processes*** that are active in any watershed: precipitation, surface runoff, infiltration, groundwater flow, return flow, surface-water storage, groundwater storage, evaporation and transpiration (e.g., Beighley et al. 2005). Although present virtually everywhere across a watershed, these individual processes vary greatly in their importance to watershed "health" and functions of its physical, chemical, and biological processes. Recognizing their magnitude and spatial distribution has been a long-standing effort of landscape studies, of which the Joint Effort is merely the latest (e.g., England and Holtan 1969).

Hillslope processes are a second set of watershed processes that strongly influence watershed health and function. They broadly refer to the movement or deposition of sediment, driven largely but not exclusively by the movement of water, that affect the land surface. In the Central Coast region, these processes are primarily erosion, landsliding and other mass wasting, and sediment transport and deposition in stream channels and other receiving waters. Their magnitude and distribution across different landscapes has also been the focus of much scientific study, albeit for not nearly as long as for their hydrological counterparts (local examples include Warrick and Mertes 2009, Stillwater Sciences 2010).

Less precisely defined or constrained are a third set of watershed processes, namely those physical, chemical, and biological actions that occur within receiving waters themselves. These have no uniformly used name in the scientific literature; we here refer to them as ***within-waterbody processes*** to distinguish them from the hydrologic and hillslope processes that are active across the landscape as a whole.

Our prior literature review of approaches to hydromodification control, including prior assessments of watershed processes (Task 1, *Literature Review*), includes a number of references that list the "typical" watershed processes for temperate-region parts of the planet. Additional text references (e.g., Reid and Dunne 1996, Ritter et al. 2011) modestly augmented these sources. Field review and common knowledge of the region then guided the condensation of the original list down to those watershed processes that we judge to be important in some or all of the Central Coast Region. Table 1 summarizes the outcome of this (largely literature-based) assessment of potential key watershed processes:

Table 2-1. Summary of literature-derived watershed processes likely to be important in the Central Coast Region. More detailed descriptions of the key processes are provided in Section 2.2.

<table>
<tr><th>Predominantly hydrologic processes
(i.e., "water")</th><th>Predominantly hillslope processes
(i.e., "sediment")</th></tr>
<tr><td>Evapotranspiration</td><td>Creep</td></tr>
<tr><td>Overland flow</td><td>Sheetwash</td></tr>
<tr><td>Surface infiltration</td><td>Rilling and gullying</td></tr>
<tr><td>Shallow, lateral subsurface flow
("interflow")</td><td>Other mass failures ("landsliding")</td></tr>
<tr><td>Deep infiltration to groundwater
("groundwater recharge")</td><td>Tributary bank erosion</td></tr>
<tr><td>Transport of organic matter</td><td>Chemical, biological reactions in soil</td></tr>
<tr><th colspan="2">Within-waterbody processes</th></tr>
<tr><td colspan="2">Fluvial transport and deposition; mainstem bank erosion</td></tr>
<tr><td colspan="2">Biological interactions (nutrient dynamics, trophic interactions)</td></tr>
<tr><td colspan="2">Chemical and biological reactions of sediment- and water-borne constituents</td></tr>
</table>

Note that most of the hydrologic processes (left-hand column) can only be inferred, given the limitations of one-time observation in non-rainy conditions. However, some of these processes are virtually certain to occur to *some* extent in every part of the landscape (e.g., evapotranspiration and surface infiltration); subsequent analyses, however, might be necessary to quantify their relative or absolute magnitude if this proves to be an important parameter.

In contrast, most of the "hillslope" processes (we recognize that runoff also occurs on hillslopes but use this term to identify those processes responsible for sediment movement and delivery) typically have direct field expression even if the process is not active at the time of observation. Gullies are one such example; mass failures are another. Creep is generally inferred by the absence of other expression, but it is known to be ubiquitous across nearly all landscapes and can be the dominant sediment-delivery process where other modes of sediment movement are not active.

2.1.2 Physical Landscape Zones

Although the conditions that affect the delivery of water, chemical constituents, and/or sediment to the receiving water vary greatly over time, different parts of the landscape can be readily identified as to their *relative* production and delivery potential, and the dominant process(es) by which this happens. The primary determinants of watershed processes have been cataloged by many prior studies. Commonly recognized attributes include the material being eroded (i.e,. lithology), a measure of topographic gradient (hillslopes, basin slope), climate (mean annual temperature, mean annual precipitation, climate zone, latitude), land cover (vegetation, constructed cover and imperviousness), and episodic disturbance (e.g., fire, large storms).

Individual studies have tended to focus on a subset of these factors, reflecting both the importance any given set of factors relative to others and their range of variability within a circumscribed region. Montgomery (1999) suggested that four factors— regional climate, geology, vegetation, and topography—determine the geomorphic processes over a given landscape. Reid and Dunne (1996) noted that every study area requires simplification and stratification, with topography and geology as the primary determinants. In their framework, land cover is recognized as a potentially significant influence on watershed processes but is considered a “treatment” variable within each topography–geology class, rather than an intrinsic property of the landscape itself. Note that these scientific studies identify *geology*, rather than *soils*, as a key factor—this reflects the physical attribute that most fundamentally determines the landscape- and watershed-scale response to precipitation. Site-specific soils are also important, but primarily in determining the feasibility of particular stormwater controls to protect those responses.

The purpose of defining landscape groups at this step was to characterize watershed processes in their natural, undisturbed state. Thus, lithology and hillslope gradient (but *not* land cover) were the landscape attributes characterized for this step. Data were compiled in a GIS format for the entire watershed at a resolution determined by the coarsest dataset. Rock types were derived from the geologic map of the State of California, originally produced by Jennings et al. (1997) and available electronically at 1:750,000 scale. Mapped units were grouped into seven categories, largely discriminating based on material competency and degree of consolidation.

The relative proportions of the geology categories are summarized in Table 2.2.

Table 2. Geology categories, generalized from Jennings et al. (1977) and as applied across the Central Coast Region.

Geology category	% of area
Quaternary sedimentary deposits	30%
Tertiary sedimentary rocks	37%
Mesozoic metasedimentary rocks	12%
Tertiary volcanic rocks	11%
Granitic rocks	
Mesozoic and Paleozoic metamorphic rocks	
Franciscan mélange	11%

Hillslope gradients were generated directly from the digital elevation model (DEM), which in turn was based on a USGS 10-m DEM. Based on the distribution of slopes and on observed ranges of relative erosion and slope instability seen in previous studies within and adjacent to the Region (e.g., Stillwater Sciences 2010), the continuous range of hillslope gradients was categorized into three groups: 0–10%, 10–40%, and steeper than 40%. The discrete categories defined for these two factors (geology and slope) can overlap into 21 possible combinations—that is, areas that each has a unique combination of these factors that are judged to be the major determinants of watershed processes. This overlap was done in a Geographic Information System (GIS).

However, the resulting data were much too "grainy" to be directly useful for a regional application. In particular, the original topographic data source (USGS/NED, 1-arc second) required "smoothing" in order to be useful, even after grouping into the three slope classes (0–10%, 10–40%, and >40%).

To create the final set of areas based on the combination of geology+slope, both datasets were first projected into NAD 1983 California Teale Albers. Slope-zone geoprocessing was carried out in ESRI ArcGIS 10 Platform and based on Spatial Analyst and ArcInfo supported toolboxes, supported by custom Python scripts. The following steps were then followed:

1. Class boundary filtering: used for cleaning ragged edges between slope classes, based on 'expand and shrink' method on the slope raster data.
2. Neighboring cell filtering: replacing cells in the slope raster based on the majority of their contiguous neighboring cells. This filtering process was based on eight neighboring cells (a 3-by-3 window) using a 'majority' replacement threshold (three out of four or five out of eight connected cells must have the same value before replacement occurs), and was applied sequentially 50 times.
3. Raster-to-vector conversion: the filtered slope raster was converted into polygons without polygon generalization.
4. Sliver polygon filtering: eliminating "small" polygons by merging them with the neighboring polygons with the largest area or the longest shared border. For our purposes, areas smaller than 12 hectares (0.12 square kilometers, equivalent to a square 345 m on a side) were flagged as 'sliver polygons' and so eliminated. This threshold was chosen on the basis of positional accuracy of the data (±125 m), the likely scale of the final map products (presumed 1:250,000), and judgment about the overall appearance and usability of alternative results using different thresholds.

Once the final set of smoothed slope polygons were defined, they were overlaid with the geology polygons to define twenty-one unique "topographic–lithologic" units (i.e., 3 slope classes and 7 geology units) plus open water.

Following this exclusively GIS-based characterization, Task 3 of the Joint Effort (Booth et al. 2011a) comprised a comprehensive field-based and 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. Watershed processes in different parts of the 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 as well.

As a result of the field observations, the original seven lithologic groups were redefined. Those mapped separately as Tertiary volcanic rocks, granitic rocks, and Mesozoic and Paleozoic metamorphic rocks were combined into a single category, because no systematic differences in watershed processes could be observed in the field; and one group (Tertiary sedimentary rocks) was subdivided into "Late" and "Early-Mid" Tertiary sedimentary rocks, because these two categories were distinguishable on the map of Jennings et al. (1997) and displayed markedly different field attributes. Thus, fifteen final landscape categories (plus "open water") were defined (Table 3 and Figure 1):

1. Franciscan mélange, a heterogeneous collection of resistant rocks within a matrix of weaker material that has filled the spaces between the resistant clasts (exposed over 8% of the land area of the Region).
2. Pre–Quaternary crystalline rocks, a group of geologically old and generally quite resistant rocks (23% of the Region).
3. Early to Mid–Tertiary sedimentary rocks, primarily resistant sandstones but also some weaker shales and siltstones (30% of the Region).
4. Late Tertiary sediments, weakly cemented sedimentary rocks of relatively young geologic age (6% of the Region).
5. Quaternary sedimentary deposits, weakly cemented or entirely uncemented silt, sand, and gravel that has been deposited in geologically recent time (i.e., the last 2.5 million years; 33% of the Region).

These five lithologic categories were each subdivided by hillslope gradient, which can be considered "flat" (i.e., <10% gradient), "steep" (>40% gradient), and in between (10–40% gradient). Thus, 15 "Physical Landscape Zones" (PLZ's) can be identified across the Central Coast Region, each with a set of properties that are well-correlated with their key watershed processes in an undisturbed landscape. Other factors of potential relevance, particularly the spatial variability of precipitation and the influence of different vegetation types in undisturbed watersheds (e.g., trees vs. shrubs vs. grasslands) were explored but were found to have at most a secondary influence on the dominance of particular watershed processes across the Region as a whole.

Table 2-3. PLZ areas as a proportion of the Central Coast Region.

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%

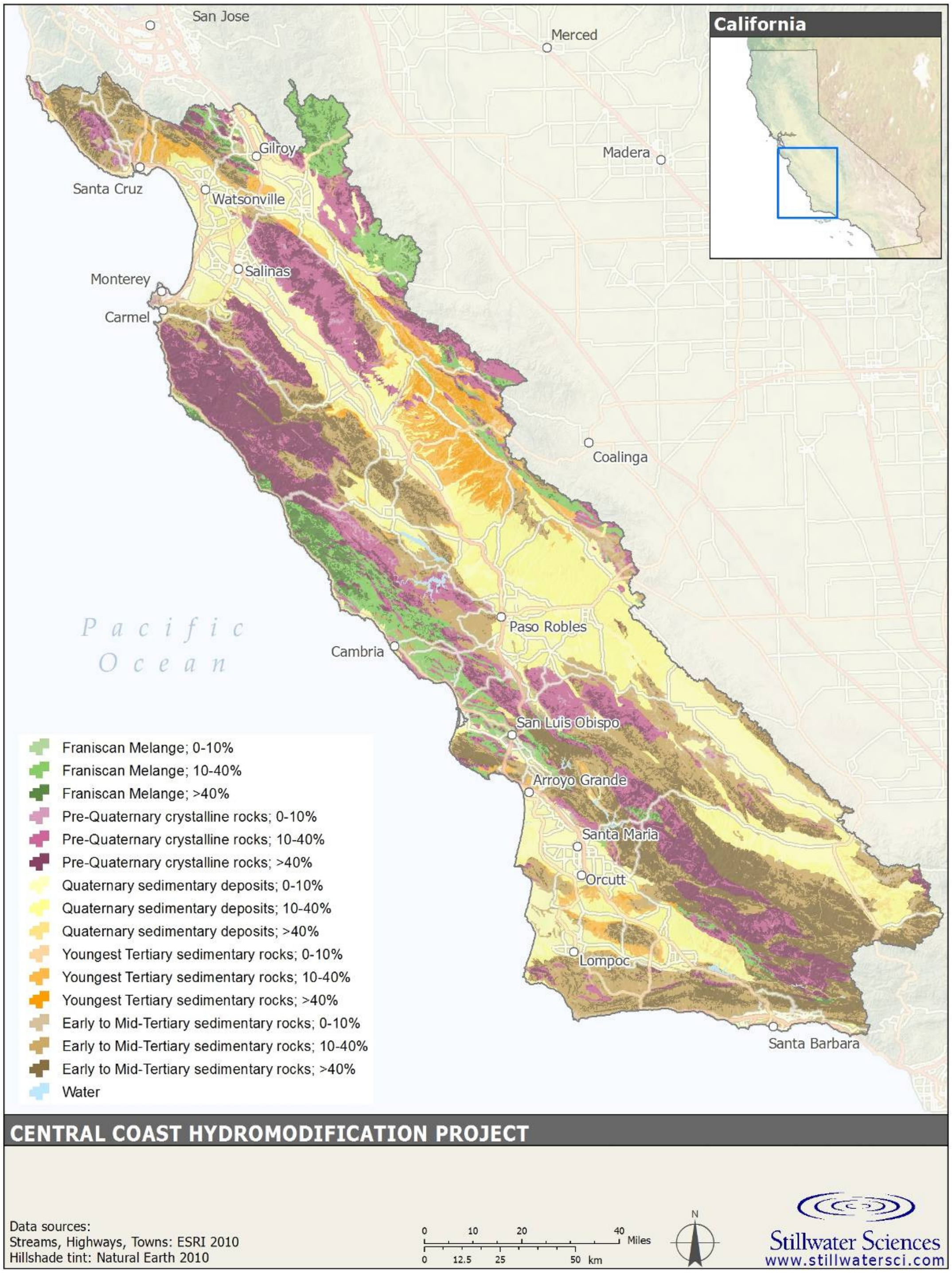

Figure 1. Final map of the Physical Landscape Zones.

2.2 Associating key watershed processes with each PLZ

2.2.1 Non-urbanized landscapes

Observations of hillslope conditions and processes, emphasizing non-urbanized and (relatively) undisturbed landscape settings, were conducted across the entire geographic extent of the Central Coast Region, with two (and sometimes more) professional geomorphologists accessing every part of the Region accessible by automobile (and some more remote but unique areas by foot). Over a thousand georeferenced photographs, accompanied by field notes, confirmed an overall consistency of the conditions and processes expressed by the intact watersheds throughout the Region with prior assessments of watershed processes. Only a few differences, systematic and readily recognized, distinguished different suites of processes in different PLZ's. 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 the hydrologic processes of infiltration and subsurface movement of water after precipitation first falls on the ground surface.

These hydrologic processes, in turn, largely control the movement of sediment and plant detrital material. 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 (Booth et al. 2011a), are summarized in Table 4.

Several of the listed processes are particularly relevant to the watershed changes imposed by urbanization, and they are described in greater detail here:

- **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 (Booth et al. 2011a). 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.

- **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.

- **Interflow:** Interflow takes place following storm events as shallow subsurface flow (usually within 3 to 6 feet of the surface) occurring in a more permeable soil layer above a less permeable substrate. In the storm response of a stream, interflow provides a transition between the rapid response from surface runoff and much slower stream discharge from deeper groundwater. In some geologic settings, the distinction between "interflow" and "deep groundwater" is artificial and largely meaningless; in others, however, there is a strong physical discrimination between "shallow" and "deep" groundwater movement. Development reduces infiltration and thus interflow as discussed previously, as well as reducing the footprint of the area supporting interflow volume.

- **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 2-4. Tabular summary of the observed (and observationally 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 5, 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	L	L	L	L	L	L	L
	Pre-Quaternary crystalline	L	L	L	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	L	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	M	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	M	M	M	M	M	H	H
	Quaternary deposits	M	M	M	M	M	H	H

In addition to these watershed processes, whose activity and influence were observed or inferred from observation, four other processes long-recognized from prior watershed studies were included in the subsequent application of this analysis to the determination of effective stormwater-management strategies:

- **Evapotranspiration:** In undisturbed humid-region watersheds, the process of returning water to the atmosphere by direct evaporation from soil and vegetation surfaces, and by the active transpiration by plants, can account for nearly one-half of the total annual water balance; in more arid regions, this fraction can be even higher. However, there is little reason to anticipate that this fraction will materially change in different PLZ's, and so this process is presumed to have a "M" rating for all areas.

- **Delivery of sediment to receiving waters:** Sediment delivery into the channel network is a critical process for the maintenance of various habitat features in fluvial systems (although *excessive* sediment loading from watershed disturbance can also be a significant source of degradation). Quantifying this rate can be difficult and discriminating the relative contribution from different geologic materials even more so; however, the overriding determinism of hillslope gradient is widely documented. Thus, relative rates of this process are presumed to scale directly (and only) with slope class. Thus, "L" = all PLZ's with slope 0–10%, "M" = 10–40%, and "H" = >40%.

- **Delivery of organics to receiving waters:** Unlike sediment, organic delivery is most critically dependent on the presence, width, and composition of the vegetative riparian zone. This has no systematic relationship with PLZ, and so (as with evapotranspiration) this is presumed to have a "M" rating for all areas.

- **Chemical and biological transformations:** This encompasses the suite of watershed processes that alter the chemical composition of water as it passes through the soil column on its path to (and after entry into) a receiving water. The conversion of subsurface flow to overland flow in a developed landscape eliminates much of the opportunity for such transformations, and this loss is commonly expressed through degraded water quality. The dependency of these processes on watershed conditions is almost unimaginably complex in detail, but in general a greater residence time in the soil should be correlated with greater activity for this group of processes. Since residence time is inversely proportional to the rate of movement, the relative importance of this process is anticipated to be inversely proportional to slope; thus, "H" = all PLZ's with slope 0–10%, "M" = 10–40%, and "L" = >40%.

2.2.2 The effects of urbanization

For the subsequent application of this table to the impacts of urban development and the application of stormwater management strategies, additional refinements were added. Most importantly, the anticipated changes in watershed processes as a result of urbanization were assigned. They were inferred primarily on the basis of more than half a century of study of urban watersheds (e.g., Leopold 1968, Booth 1991, Paul and Meyer 2001, Walsh et al. 2005), which has developed what we have called the "Classical Model" of watersheds and urbanization, and which we embrace 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; disturbed (and, in particular, urbanized watersheds) create large areas of overland flow. 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).
- 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.

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.

For most processes, urbanization decreases the magnitude of the process, but there are two exceptions. For "overland flow," the change imposed by urbanization is an increase, rather than a decrease, in this process. Similarly, impairment to "delivery of sediment" is presumed to result in less sediment input to the receiving water. This is counterintuitive to typical concerns of "construction erosion control," where the goal is to minimize sediment releases. In the post-construction period, however, maintenance of sediment delivery is essential to the health of certain receiving-water types (as is organic delivery), and it is this (long-term) process that is being addressed here.

Other changes to the initial representation of PLZ's and watershed processes (Table 4) include the following:

- The processes of overland flow and rilling & gullying were combined, since the latter is simply the most visible expression of the former and because the latter (erosive) process requires the former (hydrologic) one. The inverse, however, is NOT true—overland flow on a flat slope will not result in rills, and so their combination is not strictly accurate. However, management practices to minimize creation of overland flow are not anticipated to materially differ on flat slopes because of an absence of rilling—and so the simplification here is judged reasonable and non-consequential to management. Note that "rilling and gullying" (a hillslope process) is not the same as "stream-channel erosion" (a reflection of increase release of rapid runoff to a stream). The latter is symptomatic of a change in watershed process(es) but is not considered an altered process itself.
- Infiltration and groundwater recharge were combined into the same category, because the assessment of their relative importance and susceptibility to disturbance differs only for two uncommon PLZ's (pQ0 and pQ10) (and even there only modestly), and they are otherwise so closely linked that management strategies identified for this process set are not anticipated to be affected by their combination in either of the two affected PLZ's.
- Creep and landsliding are not included, because they are generally not directly influenced by stormwater-management strategies.

Applying these considerations leads to the summary representation of PLZ's, watershed processes, and the effects of urban disturbance shown in Table 5.

Table 5. Final table showing the association of watershed processes with PLZ's, based on Booth et al. (2011b) and subsequent review of data. The table 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).

PLZ's	Watershed Processes						
	Overland flow, rilling & gullying (OF)	Infiltration and groundwater recharge (GW)	Interflow (i.e., shallow groundwater mvmt. (IF)	Evapotranspiration (ET)	Delivery of sediment to waterbody (DS)	Delivery of organic matter to waterbody (DO)	Chemical/biological transformations (CBT)
Franciscan mélange 0-10%	L	L	L	M	L	M	H
Pre-Quaternary crystalline 0-10%	L	L	L	M	L	M	H
Early to Mid-Tertiary sed. 0-10%	L	H	M	M	L	M	H
Late Tertiary sediments 0-10%	L	H	M	M	L	M	H
Quaternary deposits 0-10%	L	H	M	M	L	M	H
Franciscan mélange 10-40%	M	L	L	M	M	M	M
Pre-Quaternary crystalline 10-40%	M	L	L	M	M	M	M
Early to Mid-Tertiary sed. 10-40%	L	M	M	M	M	M	M
Late Tertiary sediments 10-40%	L	H	M	M	M	M	M
Quaternary deposits 10-40%	L	H	M	M	M	M	M
Franciscan mélange >40%	M	L	L	M	H	M	L
Pre-Quaternary crystalline >40%	M	L	L	M	H	M	L
Early to Mid-Tertiary sed. >40%	M	M	M	M	H	M	L
Late Tertiary sediments >40%	M	M	M	M	H	M	L
Quaternary deposits >40%	M	M	M	M	H	M	L

2.3 Relating landscape disturbance, PLZ's, watershed processes, and receiving waters

Two broad categories of watersheds, which lie along a continuum of human disturbance, were examined. The first we term "intact," describing landscapes that maintain a predominance of native vegetation with limited grazing or row agriculture, scattered (or absent altogether) rural residences, and minimal intrusion of roads into the stream corridor. Observations in these watersheds provided the basis for the relationships between watershed processes and PLZ's described in the previous section.

The second category of watershed, "disturbed," has one or (more commonly) more land-use impacts occurring over a substantial fraction of its 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 receiving waters (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.

Receiving waters of the Central Coast are diverse, comprising streams, rivers, lakes, wetlands, marine nearshore, and groundwater aquifers. The analyses for the Joint Effort has emphasized 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. We also recognize that the division between certain categories is gradational and somewhat arbitrary. In particular; for purposes of the subsequent analyses a "stream" is presumed to be highly sensitive to changes in hydrologic regime as a consequence of upstream urbanization, whereas a "river" is largely unaffected.

2.3.1 Assessing the condition of receiving waters

The purpose of assessing the condition of receiving waters was not to assess their health *per se*, but rather to confirm that disturbance to key watershed processes is indeed significant, and detrimental, to the condition of those receiving waters. To guide this assessment, we used reports from the scientific literature, regional assessments and empirical observation. In any region, and especially in one as varied as varied as the Central Coast, no single metric can appropriately be used to characterize receiving water conditions. There is not even a single discipline-specific perspective over what should reflect the "quality" or the "health" (or, conversely, the magnitude of degradation) of a waterbody. The Clean Water Act calls out "physical, chemical, and biological integrity," suggesting at minimum that no single metric, and no single discipline, should be used to make such an assessment.

In streams, the scientific literature for more than a decade has shown that biological metrics are typically the most sensitive to the earliest impacts of urbanization (Booth and Jackson 1997, Karr and Yoder 2004, King et al. 2011), with multimetric indices based on benthic macroinvertebrates being the most common quantification of instream biological health. Hydrologic changes in urbanizing streams have been recognized for even longer (e.g., Hollis, 1975), but there is less agreement on the appropriate hydrologic metric(s) to discern the "signal" of urbanization in the contributing watershed. In other types of receiving waters, neither biological metrics nor (particularly) hydrologic metrics are nearly as useful because of the fundamental nature of these waterbodies (e.g., gage data are irrelevant for a lake or the marine nearshore).

Based on inspection of the receiving-water data acquired from local municipalities during Task 1 and the overall goals of the Joint Effort, the framework of "*selected* receiving waters" (and their associated sub-watersheds) was embraced with the intention that they can provide broad representation of conditions across the Region, and that they could demonstrate whether impacts to key watershed processes result in receiving-water degradation. An initial list of sites was identified based on available hydrologic and (or) biological data for the analysis of receiving water trends. The distribution and patterns of sites and receiving waters were evaluated to further refine the selection- The geographic distribution of sites north-to-south and dry-to-wet was reviewed on a map, with any gaps filled in as possible. Finally, we reviewed the data provided by the Regional Board and local jurisdictions to determine if any other receiving water(s) held the promise of being so well characterized by available data that their inclusion in this review would likely provide additional insight to the goals of the Joint Effort.

We compiled available chemical data on selected lakes, marine nearshore areas, and groundwater bodies of the region because these other types of receiving waters are of equal concern to streams under the protective goals of the Joint Effort. To date, however, these data are much more limited than those pertaining to streams, and they do not characterize the conditions of these other receiving waters to the same degree of quantification.

2.3.1.1 Hydrologic metrics

A total of 183 USGS gaging stations in the Central Coast Region were initially evaluated to begin an investigation of hydrologic measures of receiving-water condition, specifically limited to streams. The entire period of record was evaluated at each gage, with the objective of selecting stations with relatively low impairment and long temporal records, because stations of this nature will have a greater chance of capturing hydrologic changes for flow duration trend analysis.

A statistical test was performed to determine whether rainfall over two periods (1981–1990 and 2001–2010) could be considered sufficiently "similar" to exclude climatological variations from any changes that were subsequently recognized. Similarly, the variability and the average of annual runoff values were summarized from the online data for each of the USGS gages selected. Annual runoff means in the two periods (1981–1990 and 2001–2010) were also compared to each other and to rainfall totals from the two periods to determine whether meaningful relationships between watershed conditions (particularly those associated with hydromodification) and streamflow could be drawn to support future analyses under the Joint Effort.

Of the entire population of 183 USGS gage stations, 36 had ample coverage of good-quality data for the period of interest (1951–2010). Average annual rainfall totals in the watershed upstream of each gage (based on the PRISM dataset) were evaluated for the entire period of record and the two decadal periods coinciding with the selected land-use profiles (1981–1990 and 2001–2010). Because the period of time for the decadal comparison is relatively short (10 years, versus 61 years for the entire period of interest), the 95% confidence intervals are relatively wide. A statistical test suggests that no individual station has a significantly different annual average rainfall totals between the two decadal periods, because the confidence intervals overlap at every station.

For streamflow, the data across the two decadal periods also showed too much variability to draw meaningful conclusions. There was not a consistent relationship between streamflow and observed precipitation, for various possible reasons. For example, there may be other unfactored conditions or activities upstream of each gage, such as inter-basin transfers, reservoirs, or other hydraulic modifications. The results of this analysis were therefore inconclusive.

2.3.1.2 Benthic macroinvertebrate data

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 most comprehensive collection of biological data in the Central Coast Region 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 (in total more than 600 unique sites). Because of its geographic extent, we used other criteria (availability of flow data, geographic "holes" in the coverage) to identify sites from this compendium for use in the characterization of receiving-water condition. Detailed, high-quality benthic macroinvertebrate data are also available from the City of Santa Barbara and compiled into annual reports (most recently Ecology Consultants 2010, 2011; available at http://www.sbprojectcleanwater.org/waterquality.aspx?id=66#bioassess; accessed August 7, 2011). We took advantage of several paired sites with multiple years' biological data showing consistent trends, strategic placement up- and downstream of urban development, fully interpreted results, and (in several cases) correspondence with flow data.

Based on data availability and watershed size, a preliminary set of streams were selected, based first on the size of the drainage area contributing to a USGS gage site with high-quality, long term records. Additional sites were added to capture otherwise underrepresented watershed types found in the Region, namely those typified by flat groundwater basins, and the dry eastern side of the coastal and inland mountains. Abundant biological data also led us to include three other channel systems (Aptos, Chorro, and Santa Rosa) in the final list. In total, the receiving waters evaluated for this Task of the Joint Effort were as follows (Table 6).

Table 6. Final set of selected receiving-water sites.

Stream name	Drainage area (mi^2)	USGS gaging station*
Maria Ygnacio Ck (Goleta)	6	11119940
San Jose Ck (Goleta)	6	11120500
Mission Creek	8	11119750
Aptos Creek	25	(11159690, 11159700)
Carpinteria Creek	13	11119500
Atascadero Creek	19	11120000
Orcutt Creek	19	(11141050)
Lopez Ck (Arroyo Grande)	21	11141280
San Simeon Creek	26	(11142300)
Corralitos Creek	28	11159200
Alamo Pintado Ck (Solvang)	29	11128250
Zaca Creek (Buellton)	33	11129800
Gabilan Creek (Salinas)	37	11152600
Soquel Creek	40	11160000
Chorro Creek	45	-
Big Sur River	46	11143000
Salsipuedes Creek	47	11132500
Santa Rosa Creek	47	-
Santa Cruz Ck (Santa Ynez)	74	11124500
San Luis Obispo Creek	84	-
Upper Cuyama River	90	(11136500, 11136600)
San Lorenzo River (Santa Cruz)	106	11160500
Nacimiento River	162	11148900
Carmel River	193	11143200
San Antonio River	217	11149900
San Lorenzo Creek (King City)	233	11151300
Arroyo Seco	244	11152000

* USGS gage numbers in parentheses were not part of the hydrologic analysis by virtue of insufficient length and/or quality of record.

The results of this inventory and metric calculation are presented in Figure 2. Overwhelmingly, these data show "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 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); 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.

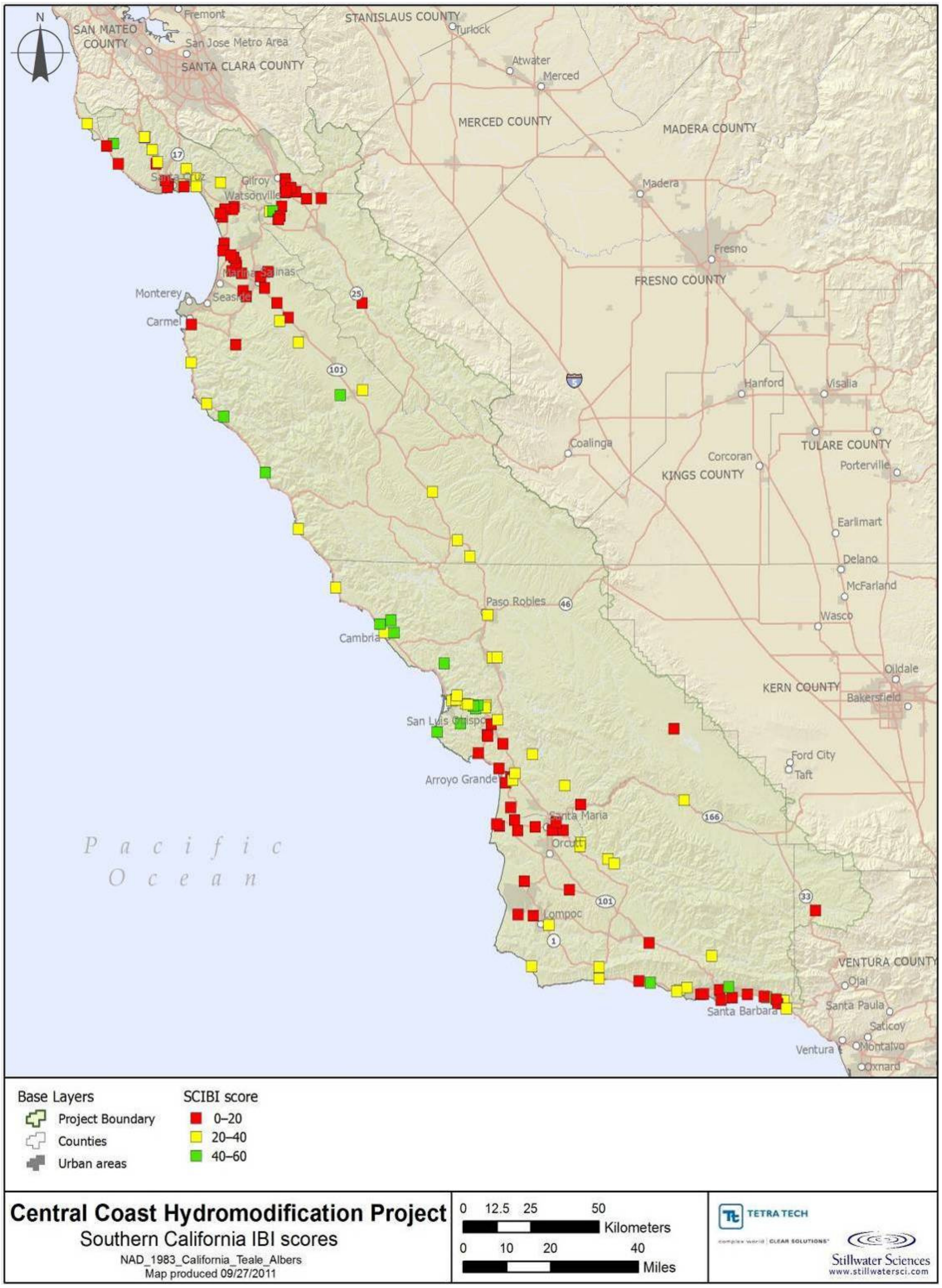

Figure 2-2. Calculated Southern California Index of Biotic Integrity (SCIBI; Ode et al. 2005) scores from BMI data in the Central Coast Region. 149 unique sampling locations are displayed here, of which most represent the average score from two to six annual sampling events. SCIBI scores can range from 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").

We also looked for atypical patterns in biological response. Two types of divergence from the Classical Model were identified in limited areas. The first such type is poor biological conditions in streams draining nonurban watersheds, which in part reflects the impacts of nonurban land disturbance (e.g., grazing or agriculture) and in part demonstrates 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 atypical response, 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 (Aptos Creek and Santa Rosa Creek, discussed in detail in Booth et al. 2011b). 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.

2.3.1.3 Field investigations

During the five weeks' field work for the observation and evaluation of landscape zones, disturbance, and watershed processes, we had ample opportunity to visit the full range of receiving waters present in the Central Coast Region (except groundwater; streams, rivers, wetlands, lakes, and marine nearshore areas were all included). Reflecting the focus of the other data sources, the visited sites were overwhelmingly streams. Observations were made of the general geomorphic character, specifically the substrate size and embeddedness, general channel morphology, and the presence or absence of bank erosion. Significant macrophyte (algae) growth was noted, and in many cases the presence or absence of benthic macroinvertebrates was noted, albeit not under any systematic sampling protocol. The goal was not to specify the "condition" of the stream (a single dry-weather observation at a single location along a channel can never achieve this) but rather to characterize the very general quality of the channel (particularly significant physical degradation, which is generally easy to recognize where present) and to complement any other available data of a more quantitative nature.

In summary, the condition of receiving waters were evaluated through a combination of field observations, data on receiving-water conditions previously collected and compiled by others, and reference to an extensive scientific literature that we 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 were found to be largely supported by data from the Central Coast Region (and throughout the world), to wit:

- Flows are flashier, and with bigger peaks, in urbanized watersheds.
- Aquifer recharge from precipitation sources is decrease due in response to decreased infiltration.
- Physical stream habitat loses 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 declines 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 lose detrital material due to loss of upland and riparian vegetation.
- Instream biota diverge from reference conditions, in response to changes in biotic and abiotic processes in both the contributing watershed and the near-stream riparian zone.

This phase of the Joint Effort relied heavily on the predictions and expectations of the Classical Model, because the scope and timeline of the work did not admit to a systematic evaluation of this framework in the Region. Such an evaluation was also judged unnecessary, since the various elements of the Classical Model have already been explored and almost universally validated in literally hundreds of scientific studies over the past decades. These findings were no less supported by the observations and data analysis performed here as well.

2.3.2 The Linkage Analysis

In the terminology of the Joint Effort, the "Linkage Analysis" was the characterization of the relationships between disturbance, dominant watershed processes, and receiving-water conditions, following the conceptual framework of Figure 2..

IN AN UNDISTURBED ("INTACT") LANDSCAPE:

WMZ →
Watershed Processes →
Receiving Water Conditions

IN A DISTURBED (SPECIFICALLY, URBANIZED) LANDSCAPE:

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

Figure 2.3: Conceptual framework of the Linkage Analysis, tracing the physical attributes of a Watershed Management Zone (WMZ) 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 WMZ'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 for receiving-water conditions.

The dominant patterns, and the rare exceptions, of linkages were explored between PLZ's and key watershed processes, and between watershed processes and the resulting conditions in downstream (or downgradient) receiving waters. As described above, the first such association (between PLZ's and their key watershed processes) were evaluated observationally, using the presence or absence of surface-water channels and other signs of overland flow and surface erosion in a wide range of locales throughout the region. The second such association (between watershed processes and receiving-water condition) was evaluated largely by calculating IBI scores (using the protocol of the Southern California Index of Biotic Integrity; Ode et al. 2005) from the widely distributed benthic macroinvertebrate data set compiled by the Regional Board staff, and evaluating the spatial distribution of high and low values to specific PLZ's in the contributing watershed and to land-use disturbance, particularly urbanization (and, to a lesser extent, to grazing and agriculture).

Patterns expressed by the data from the Central Coast confirmed the key tenets of the Classical Model almost uniformly. Although the focus of this analysis was on finding potentially instructive exceptions to the anticipated replacement of infiltration with overland flow from urbanization, and an associated degradation of biological health, no compelling or instructive examples of such exceptions were identified.

2.4 Defining and mapping of Watershed Management Zones

Although prior steps of the Joint Effort identified Physical Landscape Zones, the key watershed processes associated with each of them, and the likely response of those processes to watershed urbanization, this information alone is insufficient to guide stormwater management strategies. This is because the nature of the receiving water is essential to determining whether any particular watershed process, which may be impaired as a result of urbanization, is actually critical to the health of that receiving water.

Receiving waters of the Central Coast are diverse. The Task 4 report emphasized *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. However, 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.

The consequences of urbanization on receiving waters other than streams typically must be inferred, either by studies from other parts of the country or by extrapolation from stream-specific data. The management of these systems will differ, and as a result the actual *management* of particular locations on the landscape will depend not only on the key watershed processes associated with the PLZ but also on the nature of the receiving water. Thus the Joint Effort recognizes "Watershed Management Zones" (WMZ's), which reflect the combination of PLZ's and the variety of receiving waters that they drain to, as the key indicators of appropriate stormwater management strategies.

Six types of surface-water features (streams, rivers, lakes, wetlands, marine nearshore, and groundwater aquifers) were identified across the urban and urbanizing areas of the Region. Primary data sources were the "NHD High" data layer from the US Geological Survey (which shows all streams represented on a 1:24,000 topographic map) and the US Fish and Wildlife Service's national wetland inventory—those areas not draining to streams, rivers, lakes or wetlands identified by these two data layers were adjacent to the coastline and presumed to directly flow to the ocean. "Large" rivers were defined as those features on the NHD High coverage with a cumulative drainage area of at least 200 square miles; lakes had a minimum surface area of 2 acres. Areas with potential recharge to groundwater were presumed to overly the mapped groundwater basins of the Central Coast Region, using a GIS coverage of groundwater basins supplied by the Regional Board; these areas therefore have two such "receiving waters," namely the groundwater aquifer and the surface-water feature previously identified. Catchment boundaries were taken from the NHD High coverage for simplicity, although they do not always correspond precisely to the drainage divide as expressed by the highest resolution Digital Elevation Model (10-m) available for the region (and typically do not reflect any surface-water diversions resulting from constructed drainage infrastructure at all). The watershed areas associated with each particular type of receiving water thus represent a set of polygons that are shown in Figures 4 and 5: the former cover the five "surface" receiving waters, whereas the latter shows the boundaries of the subsurface groundwater aquifer basins, as mapped by the Central Coast Regional Board.

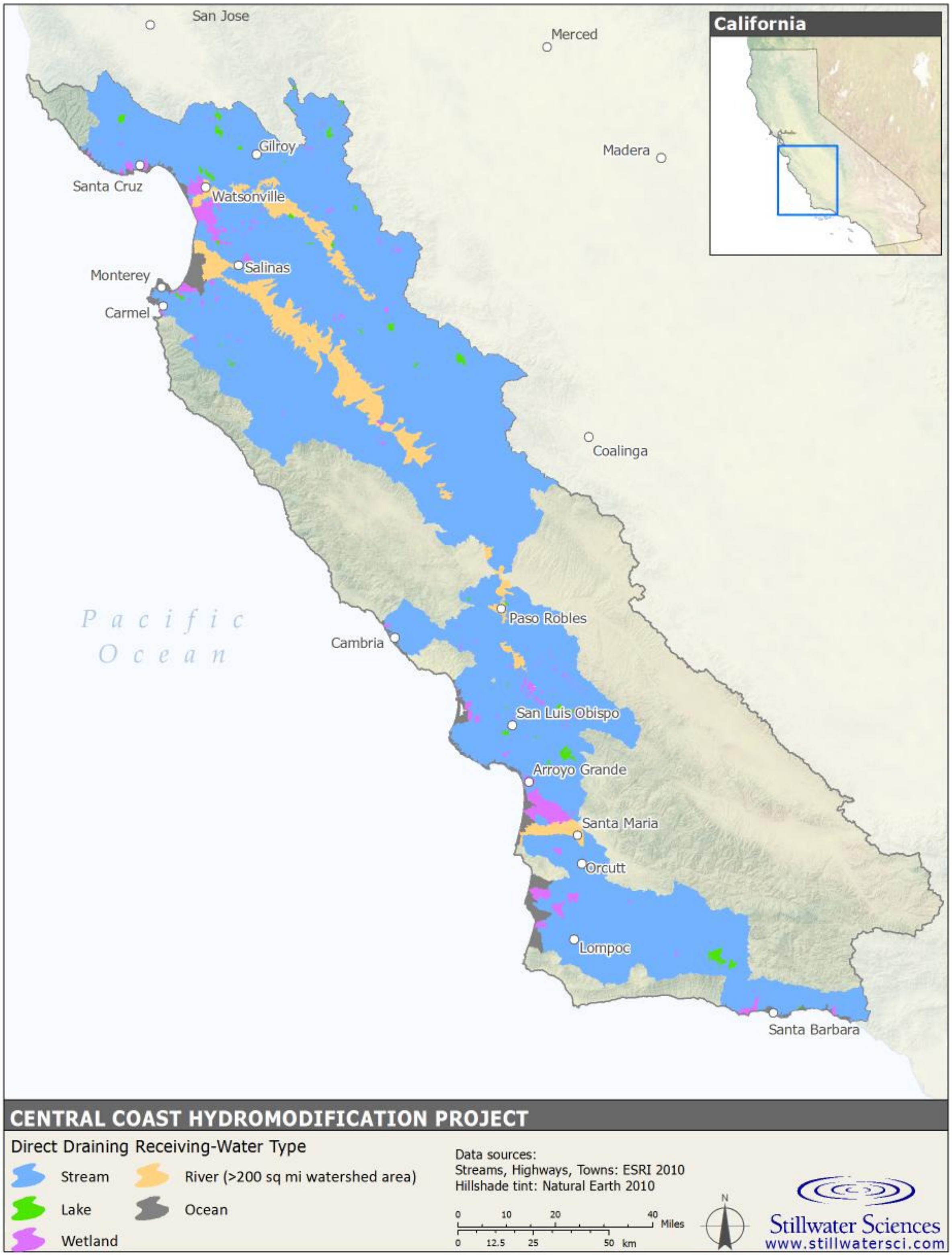

Figure 4. Map of the contributing watershed areas for the five "surface" receiving-water types across all urban areas in the Central Coast Region.

Figure 5. Mapped groundwater basins of the Central Coast Region, showing the urban areas (outlined).

These two maps of contributing areas to receiving waters can be intersected with that of the PLZ's (Figure 1), resulting in the first-order definition of "Watershed Management Zones": namely, the amalgam of landscape areas having specific combinations of lithology and hillslope gradient (the PLZ's) with the type of receiving water to which they drain. Although the number of WMZ's is theoretically large (i.e., 15 PLZ's times 6 receiving-water types = 90 combinations), many of the unique WMZ's were found to have the same suite of stormwater management strategies associated with them, resulting in a much simpler set of final "management zones." Their definition constitutes the next step of the methodology.

2.5 WMZ's, key watershed processes, and management strategies

Identifying the management strategies that will be most protective of the watershed processes in any given Watershed Management Zone required two steps— (1) filtering the key watershed processes within the underlying PLZ to the (potentially) shorter list whose disturbance can impair the actual downstream receiving water, and (2) the association of effective management strategies with each of the uniquely defined WMZ's.

2.5.1 Watershed processes and receiving waters

Not every watershed process within a given PLZ influences the condition of every downstream receiving-water type equally. A simplified, binary division into those that are "significant" and "not significant" was based on the assessment of watershed processes and their influence of the variety of receiving waters, using either the observational results from Task 3 or the scientific foundation from the published literature (Table 2.7).

Table 2.7. Significance of key watershed processes on the different types of receiving waters (marked with an "X"). Note that the interrelated processes of overland flow, interflow, infiltration, and ET, which in combination determine surface-water flow rates and volumes, are collectively of concern only for streams and wetlands.

RECEIVING WATER TYPE	Watershed Processes						
	Overland flow, rilling & gullying (OF)	Infiltration and groundwater recharge (GW)	Interflow (shallow groundwater mvmt.) (IF)	Evapotranspiration (ET)	Delivery of sediment to streams (DS)	Delivery of organic matter to waterbody (DO)	Chemical/biological transformations (CBT)
Streams	X	X	X	X	X	X	X
Wetland	X	X	X	X		X	X
Lake						X	X
Large rivers					X		X
Marine nearshore					X		X
Groundwater basins		X					X

A few patterns are evident:

(1) Streams are commonly affected by alterations to any of the watershed processes—as noted in the Task 4 report, streams 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, but their sensitivity to changes in the delivery of water, sediment, and organics is not fully shared by every other receiving-water type.

(2) Natural rates of sediment delivery are presumed important (and beneficial) for streams, large rivers, and the marine nearshore environment, because they sustain in-stream habitat and maintain beaches. Conversely, sediment delivery is not a beneficial process to maintain for lakes and wetlands (indeed, processes that indirectly increase rates of sediment delivery, particularly overland flow, are detrimental) and is irrelevant for groundwater recharge.

(3) All receiving waters are influenced by changes to CBT (i.e., all are water-quality sensitive).

(4) The interrelated processes of overland flow, interflow, infiltration, and ET, which in combination determine surface-water flow rates and volumes, are only of concern for streams and wetlands—lakes and large rivers are defined on the basis of their anticipated insensitivity to typical urban-induced changes in these discharge parameters (and thus management strategies do not target these processes for these receiving waters).

(5) Groundwater aquifers obviously depend on infiltration, but its management will have very different criteria (and perhaps different strategies as well) than for managing discharge to streams.

The commonality of watershed processes amongst the various PLZ's, and the similarity of "process sensitivity" for large rivers and the marine nearshore (i.e., both are insensitive to flow rates and volumes, but are dependent on a natural rate of sediment delivery and chemical/biological transformations), permits condensation of the original 15 PLZ's and 6 receiving-water types into a final list of 9 PLZ's (for all three slope classes, Franciscan mélange was combined with pre-Quaternary crystalline rocks, and Late Tertiary sediments was combined with Quaternary deposits) and four surface receiving-water types. Consideration of groundwater recharge above recognized aquifers is added for those surface receiving-water types (lakes, large rivers, and the marine nearshore) that might otherwise be insensitive to changes in infiltration.

2.5.2 Defining the Watershed Management Zones

With these associations, a final tabulation of 54 unique combinations of PLZ's and receiving-water types was made. The associated watershed processes that require protection in the face of urbanization, however, form an even fewer number of unique combinations, since more than one receiving water–PLZ combination can share the same group of potentially impaired processes. The processes identified for each Watershed Management Zones (WMZ) are taken directly from the evaluation of importance and magnitude of urban-induced change summarized in Table 5 for their associated PLZ; its relevance to the receiving water is summarized in Table 7.Table 2.8 displays the final compilation of these factors, which results in the definition of 10 unique Watershed Management Zones. These are mapped in Figure 2.6.

Table 8. Watershed Management Zones associated with each unique PLZ–receiving water combination. Same-colored cells are anticipated to require the same set of stormwater management strategies, and so they are placed in the same WMZ. Asterisks indicate those WMZ's for which management strategies will differ given the presence (*) or absence of an underlying groundwater basin. For the others, strategies will be the same regardless.

	DIRECT RECEIVING WATER					
PHYSICAL LANDSCAPE ZONE	**Stream**	**Wetland**	**Lake**	**Lake, w/GW basin**	**Large rivers & marine nearshore**	**Rivers & marine, w/GW basin**
Franciscan mélange 0-10%	3	3	4	4	4	4
Franciscan mélange 10-40%	9	9	10	10	10	10
Franciscan mélange >40%	6	9	10	10	7	7
Pre-Quaternary crystalline 0-10%	3	3	4	4	4	4
Pre-Quaternary crystalline 10-40%	9	9	10	10	10	10
Pre-Quaternary crystalline >40%	6	9	10	10	7	7
Quaternary deposits 0-10%	1	1	4	4*	4	4*
Quaternary deposits 10-40%	1	1	4	4*	4	4*
Quaternary deposits >40%	5	8	10	10*	7	7*
Late Tertiary sediments 0-10%	1	1	4	4*	4	4*
Late Tertiary sediments 10-40%	1	1	4	4*	4	4*
Late Tertiary sediments >40%	5	8	10	10*	7	7*
Early to Mid-Tertiary sed. 0-10%	1	1	4	4*	4	4*
Early to Mid-Tertiary sed. 10-40%	2	2	10	10*	10	10*
Early to Mid-Tertiary sed. >40%	5	8	10	10*	7	7*

KEY:

1. OF, GW /IF, ET	**1**
2. OF / GW, IF, ET	**2**
3. CBT / OF, ET	**3**
4. CBT (*)/	**4**
5. DS / GW, IF, ET	**5**
6. DS / OF, ET	**6**
7. DS / (*)	**7**
8. / GW, IF, ET	**8**
9. / OF, ET	**9**
10. / (*)	**10**

Abbreviations:

OF = apply strategies to protect OVERLAND FLOW (avoidance)
GW = apply strategies to protect GROUNDWATER RECHARGE
IF = apply strategies to protect INTERFLOW
ET = apply strategies to protect EVAPOTRANSPIRATION
CBT = apply strategies to protect CHEMICAL AND BIOLOGICAL TRANSFORMATIONS
DS = apply strategies to protect DELIVERY OF SEDIMENT
DO = apply strategies to protect DELIVERY OF ORGANICS
(*) = apply strategies to protect GROUNDWATER RECHARGE, but only where underlain by mapped groundwater basin

- Processes listed before the "/" = key watershed processes; of primary concern for protection; should be subject to most stringent numerical criteria (red cells of Table 5).
- Processes listed after the "/" = watershed processes of less critical importance; could be subject to less stringent numerical criteria (yellow cells of Table 5).

Three of the WMZ's (4, 7, and 10) are further subdivided by the presence/absence of a mapped groundwater basin, because these WMZ's do not require protection of the process of groundwater recharge *unless* a groundwater basin is explicitly recognized to underlie them.

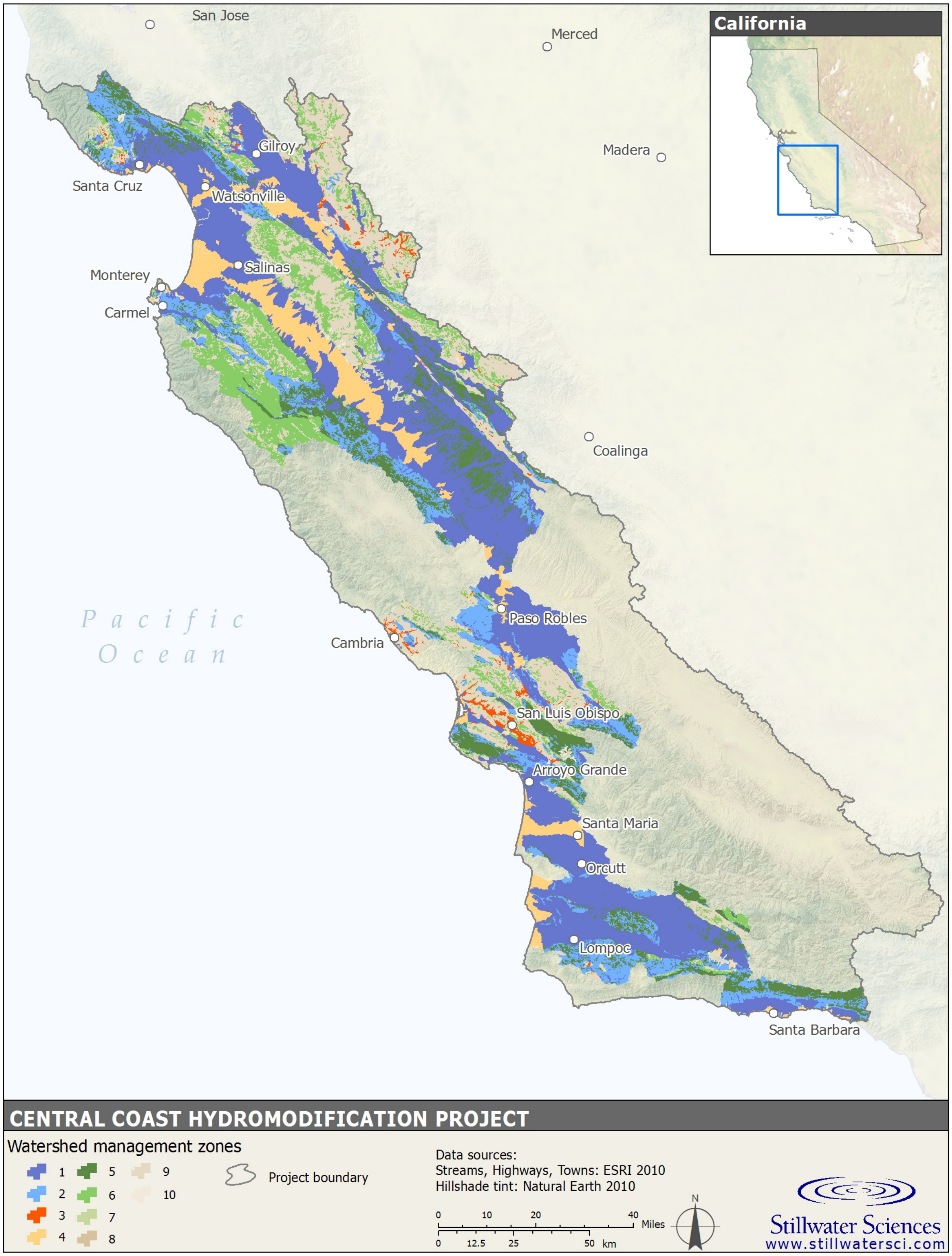

Figure 2.6. The Watershed Management Zones, as mapped across the Central Coast Region to cover all identified urban areas. More detailed maps are available for each individual urban area as pdf's HERE. GIS coverages are available from the links provided HERE.

Summary Characteristics of the Watershed Management Zones

1. **<u>Characteristics</u>: drains to stream or to wetland; underlain by Quaternary and Late Tertiary deposits 0-40%, and Early to Mid-Tertiary sed. 0-10%**
   <u>Attributes and Management Approach</u>: This single WMZ includes almost two-thirds of the urban area of the Region; it is defined by low-gradient deposits (Quaternary and Tertiary in age) together with the moderately sloped areas of these younger deposits that drain to a stream or wetland. The dominant watershed processes in this setting are infiltration into shallow and deeper soil layers; conversely, overland flow is localized and rare. Management strategies should minimize overland flow and promote infiltration, particularly into deeper aquifers if overlying a groundwater basin in its recharge area.

2. **<u>Characteristics</u>: drains to stream or to wetland; underlain by Early to Mid-Tertiary sed. 10-40%**
   <u>Attributes and Management Approach</u>: This WMZ is similar to #1 in both materials and watershed processes, but groundwater recharge is anticipated to be a less critical watershed process in most areas (only 1% of the urban areas of the Region in this WMZ overlie a groundwater basin); thus, whereas management strategies need to minimize overland flow as with WMZ#1, they need not emphasize groundwater recharge as the chosen approach to the same degree.

3. **<u>Characteristics</u>: drains to stream or to wetland; underlain by Franciscan mélange and Pre-Quaternary crystalline 0-10%**
   <u>Attributes and Management Approach</u>: This WMZ includes those few flat areas of the Region underlain by old, generally impervious rocks with minimal deep infiltration (and intersecting with no mapped groundwater basins). Overland flow is still uncommon over the surface soil; chemical and biological remediation of runoff, reflecting the slow movement of infiltrated water within the flat soil layer, are the dominant watershed processes. Management strategies should promote treatment of runoff through infiltration, filtration, and by minimizing overland flow.

4. **<u>Characteristics</u>: drains to lake, large river, or marine nearshore; underlain by all types 0–10%, and Quaternary and Late Tertiary deposits 10-40%**
   <u>Attributes and Management Approach</u>: This WMZ covers those areas geologically equivalent to WMZ's 1 and 3 but draining to one of the receiving-water types that are not sensitive to changes in flow rates. The dominant watershed processes in this low-gradient terrain are those providing chemical and biological remediation of runoff, but a specific focus on infiltrative management strategies is only necessary for those parts of this WMZ that overlie a groundwater basin (which, for this WMZ, constitute in total about 10% of the Region's urban areas).

5. **<u>Characteristics</u>: drains to stream; underlain by Quaternary deposits, Late Tertiary deposits, and Early to Mid-Tertiary sed. >40%**
   <u>Attributes and Management Approach</u>: These steep, geologically young, and generally infiltrative deposits are critical to the natural delivery of sediment into the drainage system; management strategies should also maintain the relatively high degree of shallow (and locally deeper) infiltration that reflects the relatively permeable nature of these deposits. Because this WMZ only covers steeply sloping areas, however, it is relatively uncommon in urban areas

(<3%).

6. <u>Characteristics</u>: **drains to stream; underlain by Franciscan mélange and Pre-Quaternary crystalline rocks >40%**
   <u>Attributes and Management Approach</u>: The steeply sloping geologic deposits not in WMZ 5 are included here; they are similarly important to the natural delivery of sediment into the drainage system but have little opportunity for deep infiltration, owing to the physical properties of the underlying rock. Management strategies should maintain natural rates of sediment delivery into natural watercourses but avoid any increase in overland flow beyond natural rates, which are low where undisturbed even in this steep terrain.

7. <u>Characteristics</u>: **drains to large river or marine nearshore; underlain by all types >40%**
   <u>Attributes and Management Approach</u>: This WMZ is very rare in the urban parts of the region (0.1% total) because such terrain provides little space or opportunity for urban development. The receiving waters that characterize this WMZ are insensitive to changes in runoff rates but still depend on natural sediment-delivery processes for their continued health; thus, management strategies need to focus on maintaining this process in the few areas that the WMZ is found.

8. <u>Characteristics</u>: **drains to wetland; underlain by Quaternary deposits, Late Tertiary deposits, and Early to Mid-Tertiary sed. >40%**
   <u>Attributes and Management Approach</u>: Equivalent to WMZ 5 but with a different receiving-water type, these steep and generally infiltrative deposits should be managed to maintain the relatively high degree of shallow (and locally deeper) infiltration that reflects the relatively permeable nature of these deposits. Delivery of sediment, however, is unlikely to be important to downstream receiving-water (i.e., wetland) health. Even more so than with the other steep WMZs, this type is extremely uncommon in the Region's urban areas (<0.1%).

9. <u>Characteristics</u>: **drains to wetland; underlain by Franciscan mélange and Pre-Quaternary crystalline rocks >10%; *or* drains to stream or wetland; underlain by Franciscan mélange and Pre-Quaternary crystalline rocks 10–40%**
   <u>Attributes and Management Approach</u>: These moderately sloping, older rocks that drain to either a stream or wetland are neither extremely sensitive to changes in infiltrative processes (because the underlying rock types are typically impervious) nor key sources of sediment delivery (because slopes are only moderate in gradient). Overland flow is still uncommon over the surface soil, and so management strategies should apply reasonable care to avoid gross changes in the distribution of runoff between surface and subsurface flow paths. About 6% of the urban parts of the region are found on this WMZ; none include an underlying groundwater basin, emphasizing the relative unimportance of maintaining deep infiltration.

10. <u>Characteristics</u>: **drains to lake and underlain by all types >40%**; **drains to lake, large river, or marine nearshore and underlain by Early to Mid-Tertiary sed., Franciscan mélange, or Pre-Quaternary crystalline rocks 10-40%**
    <u>Attributes and Management Approach</u>: Underlying less than 1% of the urban areas of the Region, this WMZ drains into those receiving waters insensitive to changes in runoff rates. It includes the moderately sloped areas that are anticipated not to be key sediment-delivery sources (by virtue of hillslope gradient) or that drain into lakes (which generally do not require natural rates of sediment delivery for their continued health). Across the entire urbanized part

of the Region, less than 1 square kilometer of this WMZ also overlies a mapped groundwater basin, suggesting that a broad management focus on deep infiltration is unwarranted.

2.5.3 Associating key watershed processes and stormwater management strategies

In focusing on the protection of key watershed processes, the Joint Effort abandoned the historic, symptomatic approach to stormwater management and hydromodification control. Instead of identifying a problematic outcome of urban development (e.g., "eroding stream channels") and requiring a targeted 'fix' to the 'problem' (e.g., "armor the bank"), it identified the root causes of changes to receiving waters—namely, disruption of the watershed processes that sustain the health and function of these waterbodies. Management strategies, therefore, must similarly focus on these processes.

This approach embodies a key assumption: protecting watershed processes will protect receiving waters. Most current hydromodification control plans are antithetical to this approach, typically with an exclusive focus on metering out surface runoff at a rate designed to minimize in-stream erosion but with no recognition of whether overland flow ever existed in that location, or whether the myriad of other watershed conditions and functions are also being protected by such a narrow focus.

To support this chosen mitigation framework, it proved instructive to identify broad sets of "management strategies" that are appropriate to the protection of watershed processes in various settings, and for which numeric performance criteria can be assigned. Although there is no formally accepted "list" of such strategies, the following set was found to be a useful organizational framework:

- FC: Flow control (either "volume" or "rate")
- PSO: Preserve delivery of sediment and organics (typically, via riparian or other waterbody buffers)
- MSV: Maintain soil and vegetation regime (fostering the movement of water through native vegetation and soil layers)
- PR: Land preservation (both riparian and upland; is an effective subset of MSV but also embraces PSO when implemented adjacent to receiving waters)
- WQ: Water-quality treatment

Flow Control encompasses a broad range of stormwater criteria for addressing hydraulic and hydrologic goals. This includes regulations that typically mandate that (1) post-development peak flows are less than or equal to pre-development peak flows for a series of intermediate and/or large design storm events (i.e., "storm event peak flow" control); (2) runoff from flows with the highest risk potential for channel erosion, and by extension damage to aquatic habitat, are not increased in duration ("flow-duration control"); and (3) runoff is infiltrated or retained onsite, without specific reference to the range of stream-channel flows that are affected, to maintain groundwater flow or reduce overall runoff volume ("retain volume").

Preserve Delivery of Sediment and Organics into the channel network is critical for the maintenance of various habitat features and aquatic ecosystems in the fluvial setting. While preservation of these functions is not a goal found in most stormwater regulations, it is often discussed qualitatively as a goal in establishing or justifying riparian buffer requirements.

Maintain Soil and Vegetation Regime is a valuable and highly effective alternative to water-quality treatment, because much impairment is due to the isolation of soil and vegetation from the path of urban stormwater runoff, which in turn eliminates the processes of filtration, adsorbtion, biological uptake, oxidation, and microbial breakdown (collectively termed the watershed process of "chemical and biological transformations" by the Joint Effort). Note that this management strategy overlaps with several others: not only can it accomplish water-quality treatment, but also it can constitute stormwater volume-based flow control; if adjacent to water bodies, it preserves the delivery of sediment and organics to waterbodies; and it is a (typically intentional) byproduct of any application of land-preservation strategies as well.

Land Preservation includes open space requirements and the minimizing of effective impervious area. Both have the goal of avoiding or directing runoff from impervious surfaces to pervious areas, rather than routing it directly to the storm drainage system.

Water Quality Treatment includes a suite of stormwater control measures (SCM's) that address the major link between urbanization and water quality impairment, which is caused by the increased runoff from impervious surfaces and soil compaction of pervious areas, and the delivery of urban sources of pollutants such as nutrients from fertilizer, metals from brake pads, and sediment from exposed soil surfaces.

Within each broad category of management strategies, multiple "stormwater control measures" (SCM's) are available for direct application to meet performance criteria. Similarly, a single SCM may reflect multiple management strategies and address more than one watershed process, which provides the reminder that well-chosen stormwater control measures can accomplish multiple objectives within a relatively simple mitigation approach. This great variety of available measures means that any proscriptive approach to the implementation of stormwater management on a site is ill-advised and likely infeasible, and so there was no attempt within the Joint Effort to mandate specific SCM's, only to provide relevant examples.

Table 9 lists a broad range of SCM's that are commonly implemented in stormwater management and hydromodification control plans, and that directly address one or more watershed processes. They are grouped by watershed process, and so many SCM's appear more than once. Within each process they are grouped by their type and note (in parentheses) the management strategy(s) for which they can be applied effectively.

Table 9. Typical associations of watershed processes, stormwater control measures, and management strategies.

KEY to type of SCM's:
Key watershed process
Parcel-Scale Site Design
Parcel-Scale Post-Construction SCM's
Other Strategies

1. Overland flow, rilling & gullying (avoidance)
Vegetation + soil preservation (PSO, MSV, PR, WQ)
Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
Impervious surface disconnection (FC)
Bioretention, biofiltration, native vegetation restoration (FC, PSO, MSV, WQ)
Permeable pavement (FC, WQ)
Vegetated roofs (FC, MSV, WQ)
Cisterns, rainwater harvesting (exits watershed) (FC, WQ)
Cisterns, rainwater harvesting (remains in watershed) (FC, WQ)

Retention ponds, infiltration basins (FC, WQ)
Detention ponds/vaults (FC, WQ)
Riparian restoration
Regional by-pass
2. Infiltration and groundwater recharge
Vegetation + soil preservation (PSO, MSV, PR, WQ)
Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
Permeable pavement; other impervious surface disconnection (FC, WQ)
Bioretention (FC, MSV, WQ)
Native vegetation restoration (PSV, MSV)
Soil amendments (FC, MSV, WQ)
Cisterns, rainwater harvesting (remains in watershed) (FC, WQ)
Retention ponds, infiltration basins (FC, WQ)
3. Interflow (shallow groundwater movement)
Vegetation + soil preservation (PSO, MSV, PR, WQ)
Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
Permeable pavement; other impervious surface disconnection (FC, WQ)
Bioretention (FC, MSV, WQ)
Native vegetation restoration (PSV, MSV)
Soil Amendments (FC, MSV, WQ)
Retention ponds, infiltration basins (FC, WQ)
4. Evapotranspiration
Vegetation + soil preservation (PSO, MSV, PR, WQ)
Receiving water preservation and setbacks (PSO, MSV, PR, WQ)
Impervious surface reduction (FC, PR)
Impervious surface disconnection (FC)
Bioretention, biofiltration, native vegetation restoration (FC, PSO, MSV, WQ)
Vegetated roofs (FC, MSV, WQ)
Cisterns, rainwater harvesting (remains in watershed) (FC, WQ)
Retention ponds, infiltration basins (FC, WQ)
Riparian restoration
5. Delivery of sediment to streams
Soil preservation (type and structure) (PSO, MSV, PR)
Receiving water preservation and setbacks (PSO, MSV, PR, WQ)
Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
6. Delivery of organic matter to waterbody
Vegetation preservation (PSO, MSV, PR, WQ)

Receiving water preservation and setbacks (PSO, MSV, PR, WQ)
Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
Bioretention, biofiltration, native vegetation restoration (FC, PSO, MSV, WQ)
Riparian restoration
7. Chemical/biological transformations
Vegetation + soil preservation (PSO, MSV, PR, WQ)
Receiving water preservation and setbacks (PSO, MSV, PR, WQ)
Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
Permeable pavement; other impervious surface disconnection (FC, WQ)
Bioretention, biofiltration, native vegetation restoration (FC, PSO, MSV, WQ)
Bioswales (filter strips), proprietary WQ treatment devices, detention ponds/vaults (WQ)
Source Control
Illicit discharge detection
Riparian restoration

As noted above, hydromodification control plans are assumed to always include a basic level of water-quality treatment and buffers around receiving waters. The SCM's that can address these goals (and their associated management strategies) are as follows, from those at the top of the list that emphasize preservation (and a broad suite of protected processes) to those at the bottom with a more limited, but potentially better targeted, strategic approach:

- Receiving water preservation and setbacks (PSO, MSV, PR, WQ)
- Vegetation + soil preservation (PSO, MSV, PR, WQ)
- Native vegetation restoration (FC, PSO, MSV, WQ)
- Grading limits, building/road placement, impervious surface reduction (FC, PSO,MSV, PR)
- Bioretention and biofiltration (FC, PSO, MSV, WQ)
- Permeable pavement; other impervious surface disconnection (FC, WQ)
- Bioswales (filter strips), proprietary WQ treatment devices, detention ponds/vaults (WQ)

2.5.4 Associating Stormwater Management Strategies with each WMZ

One of the foundational principles of the Joint Effort is that not every location on the landscape requires the same set of stormwater mitigation measures, because of intrinsic differences in the key watershed processes at each locale and the sensitivity to those processes of the downstream receiving water(s). These differences are captured in the map of Watershed Management Zones (Figure 4). Based on the effectiveness of the various stormwater management strategies (and some examples of their associated SCM's) at protecting or replacing the key watershed processes, the following table (Table 10) display those management approaches that are most likely to provide successful mitigation as needed for each WMZ. In the tables that follow, the red-highlighted columns are those requiring the most effective measures, because those are the watershed processes that are most strongly (and, given the downstream receiving water, the most critically) affected by urbanization. Yellow-highlighted columns denote less-strongly or less-critically affected processes, thereby suggesting that a somewhat less stringent criteria may be appropriate. Purple-highlighted columns apply only for those WMZ's (#'s 4, 7, and 10) for which the presence of an underlying groundwater basin will impose additional concerns for the protection of watershed processes.

The entries for Table 10 reflect a qualitative assessment of the degree of effectiveness of each listed SCM for the protection or replacement of the indicated watershed process. Only those that have moderate (3/4 circle) or high (full circle) effectiveness are included for the highlighted watershed processes. In combination, they suggest a possible range of strategies that, in total, can be effective at addressing the suite of key watershed processes. Note, however, that they do not specify any singular approach for a specific site—that lies beyond the ability of any generalized framework to provide.

Table 10. Key watershed processes (highlighted) for each of the 10 watershed management zones, together with the stormwater management strategies and some example criteria that are likely to be effective in their protection.

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #1 (OF, GW; also IF, ET) Management Strategy	Example Criteria	Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
		Watershed Processes							
Flow Control	San Diego County – Hydromodification Plan	○	◕	◕	◑	○	○	◕	◕
	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔
	State of Delaware – Final Draft Stormwater Regulations to Minimize Effective Impervious Area	◕	◕	◕	◕	○	○	◕	◑

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #2 (OF; also GW, IF, ET) **Management Strategy**	**Example Criteria**	Watershed Processes: Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
Flow Control	San Diego County – Hydromodification Plan	○	◕	◕	◑	○	○	◕	◕
	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔
	State of Delaware – Final Draft Stormwater Regulations to Minimize Effective Impervious Area	◕	◕	◕	◕	○	○	◕	◑

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #3 (CBT; also OF, ET) **Management Strategy**	**Example Criteria**	Watershed Processes: Overland flow	Watershed Processes: Infiltration and groundwater recharge	Watershed Processes: Interflow	Watershed Processes: Evapotranspiration	Watershed Processes: Delivery of sediment to waterbodies	Watershed Processes: Delivery of organic matter to waterbodies	Watershed Processes: Chemical/biological transformations	Stream Stability
Flow Control	San Diego County – Hydromodification Plan	○	◕	◕	◑	○	○	◕	◕
	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔
	State of Delaware – Final Draft Stormwater Regulations to Minimize Effective Impervious Area	◕	◕	◕	◕	○	○	◕	◑

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #4 (CBT*/) Management Strategy	Example Criteria	Watershed Processes: Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
Flow Control	San Diego County – Hydromodification Plan	○	◕	◕	◑	○	○	◕	◕
	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔
	State of Delaware – Final Draft Stormwater Regulations to Minimize Effective Impervious Area	◕	◕	◕	◕	○	○	◕	◑

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #5 (DS / GW, IF, ET) **Management Strategy**	**Example Criteria**	**Watershed Processes:** Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	**Stream Stability**
Flow Control	San Diego County – Hydromodification Plan	○	◕	◕	◑	○	○	◕	◕
	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Preserve Delivery of Sediment and Organics	Santa Cruz – City-wide Creeks and Wetlands Management Plan (Variable Width)	◔	◑	◔	◔	◕	◕	◔	◔
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔
	State of Delaware – Final Draft Stormwater Regulations to Minimize Effective Impervious Area	◕	◕	◕	◕	○	○	◕	◑

Preserve/maintain ● ◕ ◑ ◔ ○ No benefit

WMZ #6 (DS / OF, ET) Management Strategy	Example Criteria	Watershed Processes: Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
Flow Control	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Preserve Delivery of Sediment and Organics	Santa Cruz – City-wide Creeks and Wetlands Management Plan (Variable Width)	◔	◑	◔	◔	◕	◕	◔	◔
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔
Land Preservation	State of Delaware – Final Draft Stormwater Regulations to Minimize Effective Impervious Area	◕	◕	◕	◕	○	○	◕	◑

Preserve/maintain ● ◕ ◑ ◔ ○ No benefit

WMZ #7 (DS / *) Management Strategy	Example Criteria	Watershed Processes: Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
Flow Control	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Preserve Delivery of Sediment and Organics	Santa Cruz – City-wide Creeks and Wetlands Management Plan (Variable Width)	◔	◑	◔	◔	◕	◕	◔	◔
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #8 (/ GW, IF, ET) Management Strategy	Example Criteria	Watershed Processes: Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
Flow Control	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #9 (/ OF, ET) Management Strategy	Example Criteria	Watershed Processes: Overland flow	Infiltration and groundwater recharge	Interflow	Evapotranspiration	Delivery of sediment to waterbodies	Delivery of organic matter to waterbodies	Chemical/biological transformations	Stream Stability
Flow Control	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔

Preserve/maintain ● ◕ ◑ ◔ ○ **No benefit**

WMZ #10 (/ *) **Management Strategy**	**Example Criteria**	Watershed Processes: Overland flow	Watershed Processes: Infiltration and groundwater recharge	Watershed Processes: Interflow	Watershed Processes: Evapotranspiration	Watershed Processes: Delivery of sediment to waterbodies	Watershed Processes: Delivery of organic matter to waterbodies	Watershed Processes: Chemical/biological transformations	Stream Stability
Flow Control	San Diego County – Hydromodification Plan	○	◕	◕	◑	○	○	◕	◕
	Section 438 of EISA – Retain 95th Percentile Event	◕	◕	◕	◕	○	○	◕	◑
	State of New Jersey – Groundwater Recharge	◑	●	●	◑	○	○	◑	◔
Water Quality Treatment	City of Santa Monica – Urban Runoff Mitigation Plan	◑	◕	◕	◕	○	○	◕	◑
Land Preservation	King County, Washington – Requirements for Sensitive Watersheds	◕	◕	◕	◕	◕	◕	◑	◔

2.6 Implementing process-based stormwater management strategies

The preceding analysis accomplished several key objectives of the Joint Effort:

- Identifying and mapping distinctive landscape types requiring tailored stormwater-management approaches (the Watershed Management Zones);
- Associating the key watershed processes needing protection or mitigation in each WMZ;
- Identifying particular stormwater management strategies that have proven effective in other jurisdictions for protecting those watershed processes.

The task that remains is to define specific, measureable standards that will allow developer, designer, and regulator alike to determine the performance of any given stormwater control strategy, as implemented on-site through one or more specific stormwater control measures (SCM's). Numeric performance criteria for each of the identified stormwater management strategies were identified by review of existing hydromodification control plans (and other types of stormwater-management programs) in California and nationwide, and evaluating the effectiveness of the standards adopted by those plans with respect to the protection of watershed processes.

The basis for the numeric performance criteria is a combination of science-based findings and practical considerations borne of long experience. For example, there is excellent scientific basis to focus on the creation of impervious area to address damaging changes to watershed processes. There is no scientific basis to "ignore" or "exempt" projects below a certain minimum size, because it is their additive effect over the watershed as a whole that results in impacts. From the perspective of implementation feasibility, however, providing a simplified list of actions for small projects (and exempting very small projects altogether) is justified. The choice of project-size thresholds is beyond the scope of this document, because they were determined on the basis of general assumptions of "feasibility" and "practicality"; the basis for the chosen numerical performance criteria, however, are discussed below.

- **Performance Requirement No. 1: Site Design and Runoff Reduction.** Minimizing the amount of "connected" or "effective" impervious area (EIA) is a key element of stormwater mitigation (Walsh et al. 2009), reflecting the widely documented correlation of imperviousness with waterbody degradation (e.g., CWP 2003). The listed SCM's are broadly recognized for their simplicity and suitability in a wide range of sites (e.g., PSAT 2005); the benefits they provide, although not quantifiable given the standards of performance under this requirement, are likely significant.

- **Performance Requirement No. 2: Water Quality Treatment.** The key element of this requirement is the need to retain stormwater runoff equal to the volume of runoff generated by the 85th percentile 24-hour storm event, based on local rainfall data. The use of the 85^{th} percentile storm is deeply embedded in the practice of stormwater management over the past decade; many jurisdictions cite ASCE (1998) as the source of this guidance, and the same approach is used here.

- **Performance Requirement No. 3: Runoff Retention.** For projects >15,000 ft^2 of impervious area, this requirement triggers the greatest diversity of WMZ-specific measures. It combines two, related elements: the quantity of runoff that must be retained and the hydrologic processes that must be used to achieve that magnitude of retention. Those WMZ's for which urbanization is recognized to have the greatest effect on the processes of overland flow and infiltration are required to retain the full volume from the 95th percentile storm—in other words, eliminating surface-water release of any runoff from all but the largest storm events. This is consistent with the observations of undisturbed Central Coast landscapes in most of the WMZ's across the Region (#'s 1 and 2, and those portions of WMZ's 4, 7, and 10 that overlie designated Groundwater Basins). The choice of the 95th percentile storm is based on the requirements of federal stormwater control standards promulgated by the Energy Independence and Security Act of 2007 (EISA) and applied throughout the United States (USEPA 2009). The EISA standard includes a 95th percentile retention requirement for federal facilities creating or replacing > 5,000 square feet.

For those WMZ's where a lesser degree of impact to these watershed processes was identified in Booth et al. (2011b; #'s 5, 6, 8, and 9), a less restrictive requirement, that of retaining the 85^{th} percentile storm, has been applied. The choice of this standard is based on the historic rationale akin to that for Performance Requirement No. 2—it reflects a long-established standard-of-practice that has been shown to achieve significant benefits. Its application to runoff volumes for purposes of flow control, however, has a less well-defined history.

- **Performance Requirement No. 4: Peak Management.** This requirement is applied only to projects that create and/or replace >22,500 square feet of impervious surface. The criterion itself (i.e., post-development peak flows shall not exceed pre-project peak flows for the through 100-yr storm events) has precedent in the Central Coast Region as the Santa Barbara County flood control requirement. It is required only where streams are potentially impacted by hydromodification effects resulting from alterations to runoff duration, rate, and volume (WMZ's 1, 2, 3, 6, and 9).

  Water Board staff recognizes that peak management alone is not sufficient to protect downstream receiving waters due to the extended flow durations that can still cause adverse impacts. However, Water Board staff anticipates that the Peak Management criterion, when used in combination with the Runoff Retention requirement, will achieve a broad spectrum of watershed process protection while also protecting stream channels from hydromodification impacts. Water Board staff's judgment is based on the fact that the retention requirement is expected to avoid gross changes in the distribution of runoff between surface and subsurface flow paths for smaller events, and that peak management is expected to provide critical stream protection from the larger events, starting conservatively at the year storm event.

2.7 Identifying local, site-specific data to inform final stormwater management controls and their numeric criteria

Throughout the implementation of the Joint Effort, the limitations imposed by the scale of Region-wide data (primarily GIS-based) and the constraints imposed by the project's schedule and resources have been emphasized. Thus, the types of actions anticipated as necessary to protect key watershed processes are evaluated and displayed by the products of the Joint Effort throughout the urban and urbanizing areas of the Region, but they cannot incorporate every local constraint that may influence the final design of a development project and its stormwater mitigation. Two such categories of "local information" were recognized in the course of developing the Joint Effort methodology, with the caveat that their application to the design and permitting process is still not fully determined, and so the "methodology" of how they should be incorporated into site-specific implementation of feasible and effective stormwater management is acknowledged to be incomplete at present.

2.7.1 Local information that imposes physical constraints on the choice of SMC's

Different parts of the landscape have different properties—this is the underlying principle behind the Joint Effort, and those differences should result in different watershed responses to urbanization and thus differing approaches to stormwater mitigation. However, not all of those landscape differences can be resolved with the data incorporated into the products of the Joint Effort. We recognized three primary limitations of this type:

1. **Near-surface variability in geologic materials.** Geologic materials are a primary determinant of PLZ's and thus of WMZ's, but on a Region-wide basis they have been discriminated only at a coarse scale (1:750,000). Lateral variability beyond that resolved at this scale is likely (indeed, one such example was provided in the Task 3 report). In addition, *vertical* variability is also common—the soil overlying any given geologic deposit commonly, but not uniformly, shares a predictable relationship to the underlying material. Thus, a geologic deposit (and thus the identified PLZ) is likely to give rise to a corresponding soil type sharing similar physical properties, but this is not uniformly true. Soils maps can help resolve such uncertainty and identify potential conflicts between "assumed" and "actual" site conditions, but even these maps are scale-limited. Thus, many jurisdictions already require site-specific field investigations where soil properties are critical to mitigation or structural design.

   Although soil limitations are commonly invoked as a basis for eschewing infiltrative and other LID stormwater-management techniques, Horner and Gretz (2011) found that projects on hydrologic soil groups (HSG) B and C soils were projected to meet the 95th percentile retention standard in all but 12 of 125 of the evaluations they considered using LID methods (type "A" soils, being even more infiltrative, were not assessed in detail). On HSG D soils, all hypothetical projects were able to retain greater than 50 percent of the runoff volume associated with the 85th percentile, 24-hour precipitation event and the authors noted that opportunities to use practices or site design principles not modeled in their analysis could potentially further increase the runoff retention volume. Based on the mapped distribution of soils in the urban areas of the Region (Table 11), this constraint is likely to be significant in only a modest subset of cases.

   Table 11. Hydrologic Soil Groups within the urban areas of the Central Coast

Hydrologic Soil Group	Percentage in Urban Areas
A	13%
B	37%
C	19%
D	27%

2. **Uncertainties in receiving-water type.** The NHD High data layer, from which the downslope receiving water for every point on the landscape has been identified, was compiled from 1:24,000-scale topographic maps and has inescapable inaccuracies related to its scale, particularly in very flat areas. Field knowledge of drainage directions

and drainage pathways is essential in such areas; the existing mapping provides good but not infallible guidance. Modifications to the direction of water flow, and thus to the receiving water, may alter the identification of WMZ in some cases and can only be resolved with certainty by detailed topographic mapping or on-the-ground assessment.

3. **Groundwater conditions.** Although the identification of groundwater basins and generally infiltrative geologic deposits are strong indicators of the importance of subsurface flow, they cannot unequivocally discriminate those areas where groundwater is deep and flow directions are generally "down" (i.e., recharge areas, for which infiltration is both feasible and typically advisable) from those areas where groundwater is shallow and the flow is "up" (i.e., areas of groundwater discharge or where groundwater levels are shallow, rendering infiltration at least seasonally difficult). The Joint Effort identified no Region-wide data set that could reliably discriminate these two conditions, commonly occurring in different parts of the same WMZ, and so the task of evaluating the site-specific feasibility of those SCM's that emphasize infiltration requires local-scale assessment.

2.7.2 Local information that informs policy judgments on mitigation

The Joint Effort provides an approach to watershed process-based mitigation of stormwater impacts from urbanization, using a broad-scale characterization of the physical landscape attributes to guide such efforts. Its focus is therefore evaluating the *physical* importance, effectiveness, and feasibility of potential stormwater management strategies and their associated control measures. However, not every such measure is likely to be judged "appropriate" in every physical setting in which it could be applied. Some of the considerations that might lead a policy-setting body to reduce performance or design standards, waive selected requirements altogether, or require mitigation that differs from guidance based on a physical landscape analysis alone include the following:

- Previously constructed constraints (e.g., concrete or otherwise hardened drainage channels, preexisting buffer-encroaching buildings or other structures)
- Documented receiving-water degradation (e.g., known chemical contamination, measured biological condition, filled and/or paved-over wetland)
- Inferred receiving-water degradation (e.g., highly urbanized contributing watershed, intensive upstream agricultural practices)
- Existing infrastructure for water supply, or other critical uses
- Physical constraints (Section 2.7.1) whose limitations would result in very high cost for alternatives to achieve intended levels of mitigation.

These conditions are discussed in greater detail under "Performance Requirement No. 5: Special Circumstances" in the draft *Post-Construction Stormwater Management Requirements for Development Projects in the Central Coast Region*.

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