APPENDIX C - DRAFT TECHNICAL MEMORANDUM

TO: CKB ENVIRONMENTAL CONSULTING

FROM: GEOSYNTEC CONSULTANTS

SUBJECT: **EVALUATION OF POTENTIAL EFFECTS FROM FUTURE DEVELOPMENT, RESULTS OF THE HYDRO-GEOMORPHIC MODEL**

TASK 3.2.5; TECHNICAL MEMORANDUM #5

DATE: APRIL 16, 2007

This appendix presents the analysis of potential future changes by applying the hydro-geomorphic model of the Upper Laguna Creek watershed developed by Geosyntec. This appendix describes the methodology, addresses important hydraulic and geomorphic channel conditions, and evaluates the predicted changes in work done and sediment transport for multiple points throughout the study area.

The hydrologic model results (discussed in Appendix B) are applied at selected field locations where cross section, bed and bank material data and vegetation information are combined to measure the magnitude of work done[1] and/or transport of sediments. There is a minimum flow where erosion and transport are just on the verge of occurring. This threshold is the critical flow for bed mobility or erosion of the toes of stream banks. For every hour of flow greater than the critical flow; the amount of work done contributing to erosion/deposition and transport processes is summed.

The distribution and total amount of work done and sediment transported is compared between three land use scenarios: pre-urban, existing, and future development conditions. These scenarios are compared without any management strategies in place so that we can look at the magnitude of urban changes and the possibility of integrating the various control measures; quality, hydromodification and flood control into a more holistic and multi-objective management strategy.

Our project team is aware of two large regional detention basins at Triangle Rock quarry (Vulcan Mine detention basin, 200 acres) and Southgate detention basin (12 acres)

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[1] Work is defined as the amount of force applied to move an object a known distance (force*distance). In hydraulics, work is defined as the force applied by flowing water times its velocity integrated over the length of time this force persist (force*velocity*time). Work done in a stream channel is a measure of the amount of force applied to the channel boundary causing erosion of particles from the banks and transporting sediment downstream.

planned by the County Department of Water Resources. The objectives of these basins are to mitigate for increased peak flows from future development an eliminating the current interbasin transfer of water from Laguna Creek to nearby Gerber Creek. These regional basins and other flood control facilities may be added to the analysis and evaluated as part of Phase III as we begin to evaluate alternative management strategies.

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1 Background

1.1 Modification of Hydrologic and Sediment Transport Processes

Hydrology plays a critical role in influencing the physical characteristics and ecological health of stream corridors. Stream flow magnitude, frequency, duration, and timing are major driving forces that control the physical and ecological conditions of a riparian corridor. As water flows downstream, it imposes forces on the boundary material due to its weight and velocity that scours, erodes and otherwise shapes the channel boundary. When there is a major change in runoff discharged to streams, or substantial changes in sediment supply, channels adjust until the planform, slope, and cross sectional dimensions have readjusted to the new hydrologic and sediment supply regime. When areas are converted from natural vegetated areas to impervious areas, the area over which infiltration occurs is reduced, surface storage and interception may be reduced, and overland flow increases due to impervious surfaces (Hollis, 1975). Urbanization changes the natural relative proportions of overland flow, interflow, and groundwater flow to stream channels (Booth et al. 1997). As a result, the natural storage of water in the watershed is reduced and more erosive energy is available to perform work on the streambed and banks. Hollis (1975) concluded that the effect of urbanization is most pronounced for flows with a frequency of 1 to 2-years and smaller, where flows increased as much as 20 times.

1.2 Modeling Approach

Recent research has shown that modeling approaches based on design storms are not adequate to address long-term stream channel stability issues. A series of discrete events (2 through 100 year) is often used to evaluate the effects of development. However, this approach neglects changes in flows less than the 2-year event and the cumulative influence of such flows, which can be significant in many stream systems. Andrews (1994) reported that 55% of the total bed load in Sagehen Creek, Tahoe, was carried by flows less than bankfull. Analysis conducted by Geosyntec (2003) indicated that for streams in the San Francisco Bay Area 50% of the sediment load was transported by flows less than the 2-year peak flow.

Geomorphology, stream erosion, sediment transport, and work are all functions of the cumulative effects of all erosive flows. The key to the applied methodology is the use of continuous hydrology and the analysis of all erosive flows as opposed to selecting discrete events. Continuous hydrology and analysis incorporates the full probability distribution of rainfall events and uses the resulting flow time series as a basis for long-term work and sediment load computations. This approach captures all the important geomorphically significant flows regardless of their magnitude and allows one to examine the distribution of work done or sediment load transported and evaluate the most effective discharges.

A distribution of rainfall is transformed into a distribution of runoff using a standard hydrologic model (e.g., HEC-HMS). The distribution of runoff is then analyzed in terms of flow duration, work and sediment load transported. All sediment transporting and erosive flows are accounted for and used to evaluate possible impacts and the effectiveness of management strategies. The project team modeled in-stream flows under pre-urban, existing and proposed future conditions. Flow duration characteristics are compared between pre-urban, existing and proposed land use scenarios, and the magnitude of change is used to assess the likelihood of impacts and evaluate the effectiveness of proposed management strategies. The hydrologic model incorporates information about the watershed characteristics (climate, topography, soils, vegetation, land use, imperviousness, etc.) to estimate how much rainfall is held in the watershed (including infiltration to the soil, interception on vegetation or shallow depressions, Vernal pools, etc.), and how much precipitation results in surface runoff and interflow[2], eventually reaching stream channels.

The project team chose the U.S. Army Corps of Engineers' Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) rainfall-runoff model. The U.S. Army Corps of Engineers developed HEC-HMS to supersede the HEC-1 Flood Hydrograph Package. Unlike HEC-1, HEC-HMS allows continuous hydrograph simulation over long periods of time in addition to event-based analysis.

1.3 Geomorphic Processes and Stability Assessment

Stream channel size and form are established through a balance between the imposed flow energy, sediment type and supply, and the ability of the channel boundary to resist erosion, including the stabilizing effects of riparian vegetation. A stable channel is loosely defined as one that neither aggrades nor degrades, but instead maintains its average cross-section, planform, and profile features over time and within a range of variance. When a stream channel migrates laterally, while maintaining its general shape, channel stability is said to be maintained. Channel instability occurs when excessive erosion leads to degradation or when excessive deposition leads to aggradation. Both aggradation and degradation are often accompanied by bank failures and change in channel dimensions (meander pattern and slope). Excess degradation may even cause the floodplain to be abandoned.

A stable channel can tolerate short-term disturbances without significant change; e.g., El Nino and drought. However, a disturbance of sufficient magnitude and duration that exceeds the stream's ability to self-regulate and causes the channel to begin changing is defined as a disturbance that exceeds the threshold of adjustment. The threshold of adjustment is used to identify the limit of persistent change that can take place within a watershed before significant channel adjustment occurs. Geosyntec has learned that this threshold of

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[2] Interflow is defined as shallow sub-surface flow; where rainfall enters the soil surface and migrates laterally and down gradient to the nearest stream channel. Lateral flows tend to occur when a restricting sub-layer is present (such as hardpan) that slows or prevents water from percolating downwards to deep groundwater aquifers.

adjustment is significantly smaller than the long-term change imposed by development. This is discussed in more detail later in this report.

The erodibility of stream banks is still one of the most difficult elements in assessing stream channel destabilization. Channel erosion can occur through a combination of several mechanisms, although one mechanism may be more or less prevalent than others depending on the stream system and local characteristics.

Generally, the following processes are observed in unstable stream systems in urbanizing watersheds:

- Channel incision and under-cutting of the bank toe due to shear erosion leading to gradual deepening and expansion of the channel bottom.
- Slumping from over-steepened banks or rapid drawdown during the falling limb of a flashy hydrograph.
- Head cut migration within the main stem and/or tributaries.
- Loss of bank vegetation, reducing roughness and apparent bank strength.
- Water forced into the banks from obstructions such as boulders or large woody debris.

Channel incision and bank toe erosion often initiates channel adjustment, although other mechanisms such as bank slumping may be observed as ultimate failure. Channel incision and erosion at the toe increases the height of banks and oversteepens them, priming them for failure by slumping during larger flows. High flow events can saturate the banks, then, as water levels fall during the recession limb of the hydrograph, there can be a rapid reduction in pore water pressure that can contribute to bank collapse.

The ability of a stream bank to resist erosion is dependent on soil properties; such as stratigraphy, vegetation density, root strength and apparent cohesion, the amount of clay or cementing of the matrix particles, bank height and slope. Stream channels bounded by clays, or compacted loams are often more resistant to erosion and respond more slowly to hydrologic changes than channels bound by loosely consolidated sands and gravels. One of the objectives of the field work is to identify and classify these properties and apply this information in the stability analysis.

1.4 Changes in Sediment Supply

In addition to increased flows, urbanization also reduces sediment supply and delivery to the stream system. Surface sediments are dislodged and mobilized by the impact forces of rainfall and overland flow. Not only do impervious surfaces reduce sediment supply, but sediment supply is can be reduced by the grading and landscaping in parks, lawns and golf courses. Debris basins downstream of open space areas can capture and reduce important sediment supplies to riparian habitats.

Reduced sediment supplies can cause similar impacts to receiving channels as increased flows, but in this case degradation is a result of less material being delivered to the stream as opposed to increasing the rate at which material is taken away from the stream. Reductions in supply have more or less effect on channel morphology depending on whether the channel is supply limited or transport limited. In a supply limited channel, the loose sands and gravels that make up the bed are continually transported downstream leaving behind a scoured bed with little substrate for habitat. Impacts on channel morphology involve erosion of the underling parent materials – often consisting of older consolidated deposits. In a supply rich system, reduced sediment supplies will have more immediate effects on channel morphology, causing an evolution from a wider shallow channel, possibly braided at times, toward a deeper single threaded channel. In both cases, longitudinal slope will be reduced.

The Laguna Creek watershed sediment supply appears to be very low naturally and the system appears to be supply limited. The landscape is fairly flat and hummocky, and consists mostly of rural residential and pasture with moderate to high density of grass cover. Vernal Pools and drainage swales are present over much of the landscape capturing and slowing the rate runoff. There is very little loose unconsolidated bed material or bar deposits in the channel. Point bars and channel beds are generally grass covered and are not mobilized very frequently. Loose bed material that is available for transport is thin and believed to have originated from bank erosion and failures. Where bank failures were observed, a deposit was not far from the failure location. Because of this condition, reduction in sediment supply does not appear to be a condition of concern for the Laguna Creek watershed. The morphology and potential for change is primarily a function of the surrounding channel materials controlling bank and bed conditions. Appendix A provides a more detailed discussion of the geomorphic character of the watershed and creek.

2 Computational Methodology

The basis of the hydromodification analysis is to compare the total cumulative amount of erosive work done between pre- and post-development conditions. Erosive work is defined as that which has the capability of moving bed material and contributing to the erosion and deposition processes. The total cumulative amount of work done as well as the total cumulative sediment load transported is calculated for an extended period of years in order to capture the effects of wet and dry annual cycles.

This approach does not presume the absolute accuracy of the work and transport equations used in the analysis, but rather looks at the *magnitude of change* computed as a ratio of post- versus pre- land development scenarios. Comparing changes in terms of ratios is preferred because it reduces the effects of uncertainty or bias in the methods and calculations.

The methodology is based on the concept that a balance among flow energy, sediment supply, and channel resilience must be maintained in order for the stream network to remain stable (MacRae, 1996). The hypothesis is that, over time, the stream channel slope and geometry co-evolved with vegetation, local physiography and climate to establish its pre-development dynamic equilibrium. In watersheds where the natural hydrologic processes are modified, management strategies attempt to re-balance these elements.

When applying this method on a stream system that is currently stable and needs protection the intent is to maintain the natural sediment transport and erosion processes, not to eliminate them. When applying this method on a stream system already unstable or degraded, the intent is to ideally re-establish a balance between flows, sediment supply and channel materials, or at a minimum, to not make the system any worse. In either case, a baseline condition is defined that represents the target condition to be achieved under the post-development conditions. In a restoration project this target is typically taken as a reference reach or stream system.

2.1 Work Index and Erosion Potential

The direction of current research is to use indices to distinguish between eroding and non-eroding, or stable and unstable channel conditions (Booth, 1990; Bledsoe, 2001; MacRae, 1996; and SCVURPPP, 2005). Indices are attractive because they are simple to use and less expensive to apply compared to sediment transport modeling. Sediment transport equations are only approximate and should be verified with field measurements. An un-calibrated sediment transport model is essentially an index method.

The forms of indices are:

Index	Description	No.
Work Done for Consolidated Materials		
$W = \sum_{i=1}^{n} k \cdot (\tau_i - \tau_c)^a \cdot \Delta t_i$	Total Work Done (arbitrary units) Andrew Simon's bank stability model (2002)	(1)
$W = \sum_{i=1}^{n} (\tau_i - \tau_c) \cdot V \cdot \Delta t_i$	Total Work Done (ft-lbs/sq-ft) Effective stream power integrated over time.	(2)
Sediment Transport Functions		
$= a \cdot \sum_{1}^{n} (V_b - V_c)^{1.978}$	Brownlie sediment transport function for sand bedded systems (1981)	(3)
$W = a \cdot \sum_{i=1}^{n} \left(\tau_i / \tau_{ri} \right)^a \cdot \Delta t_i$	Wilcock-Crowe dimensionless sediment transport function. Incorporates grain size distribution and sand fraction (2003).	(4)

Where τ_c = critical shear stress that initiates bed mobility or erodes the weakest bank layer, τ_i = applied hydraulic shear stress, τ_{ri} = reference critical shear stress, V = mid-channel velocity (ft/sec), Δt_i = duration of flows (in hours), k = an erodibility coefficient, a = exponent and n = length of flow record.

The application of these indices requires some discussion. During the initial development of this methodology, Equations 1 and 2 were used to evaluate changes in work done on both the toe channel banks as well as the stream beds (SCVURPPP 2005, MacRae 1996). A recent advancement is the addition of Equation 3 and 4, which apply to the transport of bed material (sands and gravel). Another improvement is the use of Equation 1 as a model to predict the erosion of *consolidated bank materials*. Andrew Simon, USDA Agricultural Research Service (2002), is using this equation with field measurements to determine the erodibility of consolidated bank materials. Therefore, Equations 1 and 2 are applied to represent changes in work done on consolidated bank materials, and Equation 3 and 4 are applied to represent changes in amount of *unconsolidated bed material* transported downstream.

The approach is to compare the Index "W" between pre- and post- development scenarios. The relative change is represented as the *Erosion Potential* (Ep). The Erosion Potential, expressed as a ratio, is defined as:

$$Ep = \frac{W_{post}}{W_{pre}} \qquad (5)$$

Where W_{post} = work index estimated for proposed development, and W_{pre} = work index measured for the baseline condition.

MacRae (1993, 1996) recommended that the Erosion Potential remain the same under both developed and undeveloped conditions over the range of geomorphically significant flows. Management strategies that balance the future sediment transport characteristics (at baseline or below to account for reductions in supplies) are considered effective at achieving stable conditions and is the basis of the recommended hydromodification management approach.

For each drainage area upstream from a cross section of interest, a target Ep value must be defined. For project where reductions in sediment supply are not included, the target Ep would equal 1.0; in other words, the goal would be to match the long-term cumulative sediment load transported in the post-condition to that of the pre-condition. Given the variety of factors that affect stream channel response, it is difficult to achieve an Ep of exactly 1.0 in all cases. Therefore, the target is considered a mean value within an allowable range of tolerance or uncertainty. Although MacRae does not explicitly state a criterion, evaluation of his conclusion suggest MacRae is using a value of 20% as a decision criterion. Soar and Thorne (USACE, 2001) define a sediment transport capacity/sediment supply ratio (CSR) and suggests a value of 10% as a criteria for preserving channel stability. Geosyntec (SCVURPPP, 2005) correlated Ep to observed field conditions (stable and unstable), to empirically relate the likelihood of stream channel instabilities to the erosion potential. Figure 2-1 presents the results of this correlation for 49 cross sections within four separate watersheds in the San Francisco Bay Area. The chart illustrates the likelihood of having stream channel instabilities as a function of increased Work. On the basis of the above information, a 20% range about the target Ep has been selected as an acceptable criterion. Impacts analysis and BMP effectiveness studies are therefore evaluated for their ability to maintain the Ep at 1 ± 20%.

To account for reductions in sediment supply, a lower target must be established in order to prevent stream erosion. For example, if an area experiences a 40% decrease in sediment supply due to development, the baseline Ep of 1.0 must be reduced by 40%, giving a target Ep value of 0.60. In other words, our goal for management is to reduce the post-project sediment transport capacity to 60% of the pre-project condition. Under these conditions, impacts analysis and BMP effectiveness are evaluated for their ability to maintain the Ep at 0.6 ± 20%.

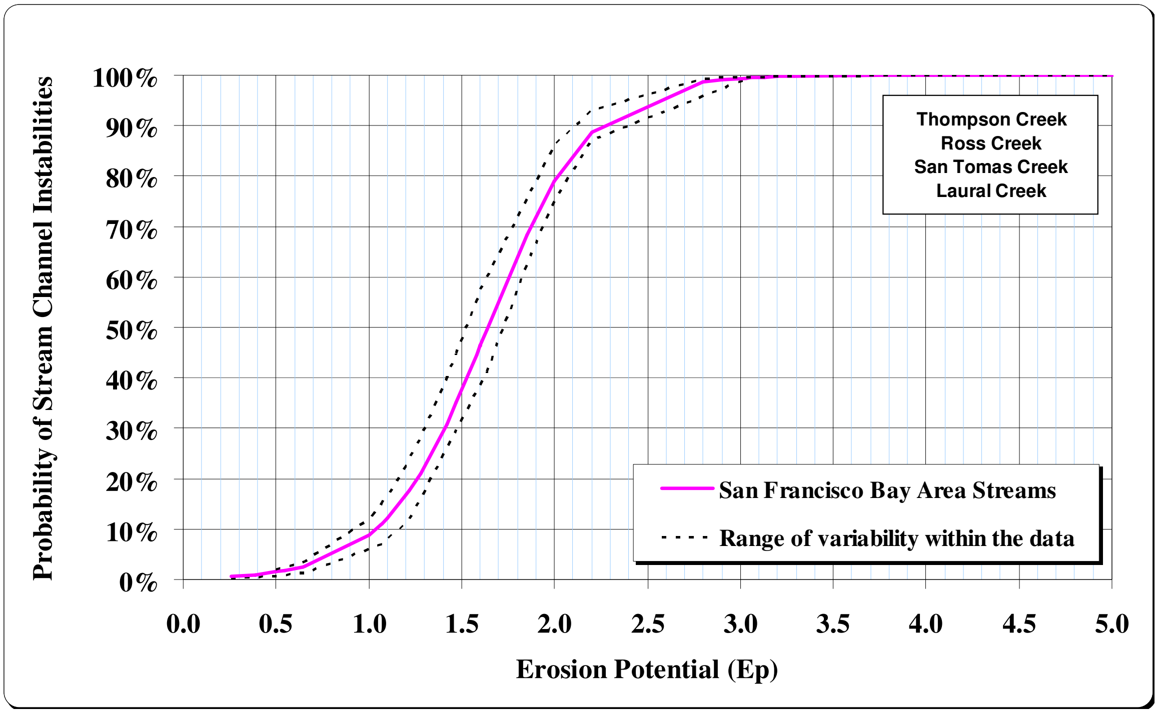

Figure 2-2. Probability of Stream Channel Instabilities (SCVURPPP, 2005)

2.2 Stream Channel Hydraulics

Hydraulic calculations convert flow rates to depth, velocity, and shear stress based on cross-section geometry and longitudinal slope. The depth, velocity, and shear stress used in the stability assessment are taken from the central channel, not including over banks or floodplains (Figure 2-2). Computations follow the method used in HEC-2 software, where channel roughness is specified for each segment between survey points allowing roughness to vary by elevation. Average channel hydraulic conditions are computed based on the composite roughness coefficient. However, shear stress and velocity are computed based on central channel conditions as opposed to the cross sectional average.

Channel hydraulics are computed using normal flow assumptions. Each cross-section is treated independently from the others; thus backwater effects are not considered. The assumption is valid for the range of geomorphic flows considered most important in addressing hydromodification. The computations are completed following the Army Corps of Engineers HEC-2 method, where conveyance (K) is computed and summed between individual survey points. The following equations are used for the hydraulic analysis:

$$Q = 1.49 \cdot K \cdot \sqrt{S} \qquad (6)$$

$$K = \sum \frac{AR^{2/3}}{n} \qquad R = \frac{A}{P}$$

where: K = Conveyance, R = Hydraulic radius, P = Wetted perimeter

Figure 2-2 illustrates the hydraulic computation parameters. Conveyance is computed for each element of the flow area defined between two cross section survey points.

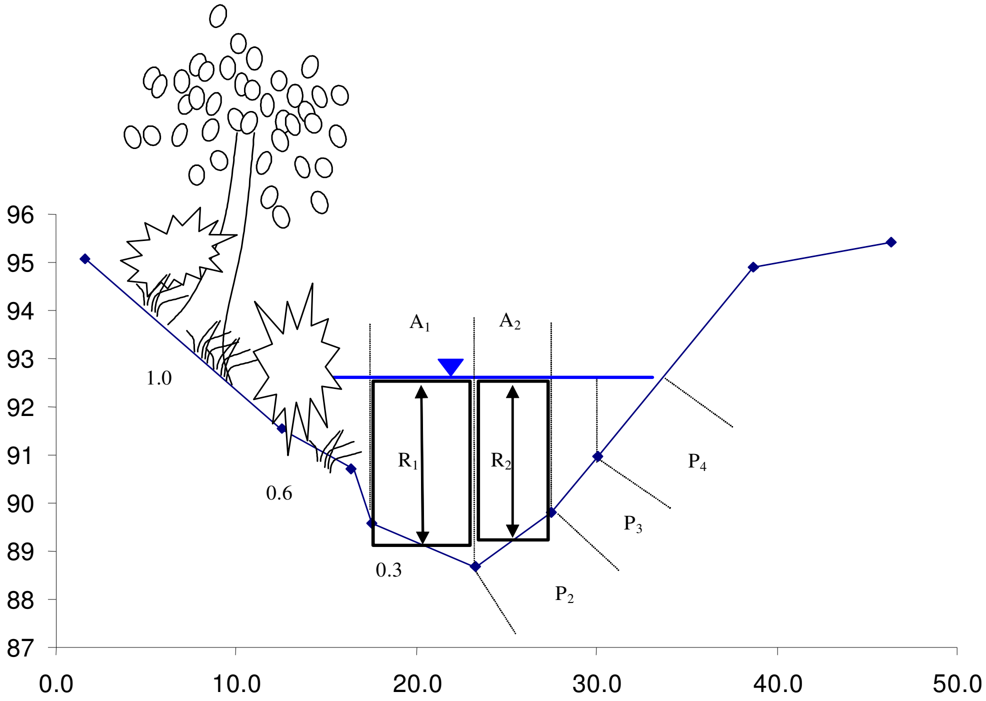

Figure 2-2. Illustration of Hydraulic Computations for a Typical Cross Section

2.3 Critical Shear Stress Values

Critical shear stress values are determined from measured grain size distribution of bed material samples, classification of bank material soils with published values in the ASCE Manual of Engineering Practice No 77.

a) For unconsolidated bed material, Work Index 1 and 2 uses Shields equation applied with a dimensionless critical shear stress of 0.047. The value of 0.047 can be adjusted on the basis of bed material size distribution. Given the bed materials sampled by WLA (2005) and the sand content, a value of 0.03 would make a more realistic and protective value.

b) For consolidated bank and bed material, Work Index 1 and 2 uses critical shear stress values estimated from the ASCE Manual based on bank soil conditions. Geosyntec is evaluating a *Jet Test* instrument to measure the critical shear stress on consolidated materials in-situ.

c) For unconsolidated bed material, the Wilcock-Crowe equation (3), a measured grain size distribution is used and a reference dimensionless critical shear stress is computed using a hiding function and the fraction of sand contained in the sample (Wilcock and Crowe, 2003).

The ASCE Manual No. 77 provides an estimate of critical shear stress for bank materials. Table 2-1 lists values for a range of bank materials types, with and without vegetation. Bank material properties are qualitatively described by the field crews, which is then assigned a material type associated with the types listed in the ASCE Manual.

Table 2-1. Critical Shear Stress Values for Different Bank Materials

Bank Material Type	**Critical Shear Stress** (τ_c lbs/ft^2)
ASCE Manual No. 77	
Hardpans, Duripans	0.67
Compacted Clays	0.50
Graded Loams with Cobble	0.38
Stiff Clays	0.32
Alluvial Silts, compact	0.26
Firm Loam, compact	0.23
Silty Loam, fairly compact	0.17
Sandy Loam, fairly compact	0.12
Fine Gravel	0.075
Alluvial Silts, Silt Loam	0.048
Biotechnical Engineering Data USAE[1]	
Banks with: Woody vegetation	0.41 to 2.5
Short native grass	0.7 to 0.95
Long native grass	1.2 to 1.7
Biotechnical Engineering	0.4 to 8

1. Biotechnical engineering data obtained from "Stability Thresholds for Stream Material", by Craig Fischenich, USAE Research and Development Center, Environmental Laboratory, Vicksburg, MS

2.4 The Effects of Vegetation Density

The effects of vegetation are accounted for through the roughness coefficient and by partitioning the applied shear stress between form roughness and bed roughness. Coefficients are estimated using Cowan's method as described in Chow (1959). Cowan's method sums individual roughness elements of the stream boundary, such as bed material and form, irregularities in the banks, variations in cross-section, obstructions, and vegetation density.

Some flow energy is dissipated in turbulence generated as the flow moves around and amongst vegetation (branches, leaves, etc.) and channel irregularities (rocks, ledges, etc.). Bed roughness is the shear stress actually seen by the streambed and toe of banks. The computed channel shear stress (τ_i) is partitioned according to Equation 6, to estimate the shear stress exerted on the streambed and that which applies to sediment transport.

$$\tau_b = \tau_i \cdot \left(\frac{n_b}{n_c} \right)^{\frac{2}{3}} \qquad \tau_i = \rho g h S \qquad (7)$$

Where n_b equals the bed roughness and n_c equals the composite roughness.

3 Application to the Upper Laguna Creek Watershed

A hydro-geomorphic model was developed for Upper Laguna Creek from the intersection of Waterman Road and Bond Road, upstream to the headwaters of Laguna Creek. The total watershed area is approximately 32 square-miles. This chapter describes the application of the hydromodification methodology to the Upper Laguna Creek watershed.

3.1 Study Layout

The study area and assessment uses 33 sub-catchments and 11 computational flow junctions from the hydrologic model spread out from the headwater sub-catchments to just below Waterman Road. Twenty-nine cross sections were located throughout the upper watershed to measure the changes in creek flows and its effect on the existing erosion and transport conditions. Figure 3-1 presents a map showing the watershed, stream channels and cross section locations.

Although we address the full length of the channels potentially at risk, cross sections are locations where detailed computations are carried out and are used as indicators of potential change and BMP effectiveness. Cross sections are located in reaches with potential changes in flows, downstream from future development and outfalls, in areas of different catchment sizes, soil type and channel slopes. Cross sections are also located in stable channel reaches as well as unstable reaches to assess how much change in flows Laguna Creek can tolerate before significant impacts and/or channel adjustments occur.

3.2 Longitudinal Profile & Slopes

The longitudinal slope is an important parameter in the stability assessment. The applied hydraulic force (shear stress) driving sediment transport is computed as a function of the longitudinal slope, channel geometry and predicted flow. The magnitude of the applied shear stress is a function of slope. Of all the channel variables, the longitudinal slope is the most influential in having erosion and transport. Figure 3-2 presents the longitudinal profile of the main stem of Laguna Creek.

The magnitude of hydromodification impacts is also a function of slope steepness. The greater the longitudinal slope the larger the erosion potential (Ep) will be and the greater the impact is from development and hydromodification. In contrast, the shallower the longitudinal slope the less sensitive the channel will be from the effects of hydromodification. As a result, it is plausible that receiving channels with a shallow slope may not be sensitive to the effects from hydromodification. This study attempts to identify the longitudinal slope upon which hydromodification would not be a concern.

Table 3-1 summarizes the local longitudinal slopes surveyed at each cross section location. The table and data are organized by *reach* as defined William-Lettis & Associates (2005) and the paragraphs below summarize the average slope computed from the longitudinal profile as well as the slope measured at each cross section location.

- Reach 1 has an average slope of 0.0036 ft/ft and is steeper than the other reaches. Local slopes for each surveyed cross section range from 0.006 to 0.01 ft/ft.
- Reach 2 has an average slope of 0.0010 ft/ft. Cross sections GS-6 & -7, and WLA-1 & -2 have slopes ranging from 0.001 to 0.002 ft/ft. Kite Creek and Fry Creek tributary to Laguna Creek have slopes of 0.004 to 0.005 ft/ft.
- Reach 3 has an average slope of 0.0024 ft/ft, and ranges from 0.0022 to 0.0035 ft/ft.
- Reach 4 has an average slope of 0.0007 ft/ft and is the shallowest reach of the study area. Local slopes for each cross section range from 0.0005 to 0.001 ft/ft.

Table 3-1. Longitudinal Channel Slopes used for Analysis

Reach	Soil Type	Location	Catchment Area (sq-mi)	Channel Longitudinal Slope
Reach 1	Redding Gravelly Loam	G.S. XS-1	0.87	1.0%
		G.S. XS-2	1.29	1.0%
		G.S. XS-3	2.17	0.60%
		G.S. XS-4	2.17	0.60%
Reach 2	Hedge & San Joaquin Loam	G.S. XS-5	1.59	0.50%
		G.S. XS-9	1.74	0.40%
		G.S. XS-6	12.24	0.10%
		G.S. XS-7	12.24	0.15%
		WLA Site 1	15.39	0.10%
		WLA Site 2	16.37	0.20%
Reach 3	Redding Gravelly Loam	WLA Site 4	19.09	0.24%
		WLA Site 6	19.09	0.35%
		WLA Site 7	19.09	0.22%
		WLA Site 8	19.09	0.24%
Reach 4	Hedge & San Joaquin Loam	WLA Site 10	19.09	0.07%
		WLA Site 12	20.41	0.07%
		WLA Site 13	20.41	0.07%
		WLA Site 15	21.70	0.10%
Reach 4	Hicksville Loam	WLA Site 16	22.66	0.07%
		WLA Site 17	22.66	0.10%
		WLA Site 18	23.08	0.06%
		G.S. XS-8	31.65	0.05%
	Trib.1	WLA Site 19	5.00	0.15%
	Trib.1	WLA Site 20	5.00	0.15%

3.3 Critical Shear Stress of Bed and Bank Materials

Table 3-2 summarizes the relevant data for bank and bed material for each cross section used in the analysis. The data is listed by cross section from top to bottom and grouped by soil type.

The critical shear for the bank material in Laguna Creek ranges from 0.18 to 0.38 (lbs/sq-ft) for the Hicksville Loams in the downstream portion of the watershed to Redding Gravelly Loam in the upper watershed and again mid-way. Appendix A describes the classification of bank soils observed while collecting data at individual cross sections. Soil samples were collected in a few locations to supplement field observations. The Hedge and San Joaquin soils have been assigned a value of 0.20 (lbs/sq-ft) similar to Hicksville. These values were selected from the material type and the ASCE Manual data listed in Table 2-1.

Table 3-2. Bank & Bed Material Descriptive Data

	Bank Material			Bed Material					
	Location	SCS Hydro-Group	**Critical Shear Stress (lbs/sq-ft)**	D85 (mm)	D60 (mm)	D50 (mm)	D30 (mm)	D15 (mm)	D10 (mm)
Reach 1 - Redding Gravelly Loam	G.S. XS-1	D	0.38	54.3	29.3	23.5	12.7	6.5	4.4
	G.S. XS-2								
	G.S. XS-3								
	G.S. XS-4								
Reach 2 - Hedge & San Joaquin Loam	G.S. XS-5	C/D	0.20	28.8	13	12.2	6.5	2.8	1.5
	G.S. XS-9								
	G.S. XS-6								
	G.S. XS-7								
	WLA Site 1								
	WLA Site 2								
Reach 3 - Redding Gravelly Loam	WLA Site 4	D	0.38	54.3	29.3	23.5	12.7	6.5	4.4
	WLA Site 6								
	WLA Site 7								
	WLA Site 8								
Reach 4 - Hedge & San Joaquin Loam	WLA Site 10	D	0.20	28.8	13	12.2	6.5	2.8	1.5
	WLA Site 12								
	WLA Site 13								
	WLA Site 15								
Reach 4 - Hicksville Loam	WLA Site 16	C	0.18	24.1	13.1	10.2	7.4	2.6	0.9
	WLA Site 17								
	WLA Site 18								
	G.S. XS-8								
Trib.1	WLA Site 19								
Trib.1	WLA Site 20								

Where loose sand and gravel deposits were present, surface samples were collected by Geosyntec and William-Lettis (2005). The data represent the average of samples within each soil type. The average D50 ranges from 10.2 mm up to 23.5 mm. The estimated critical shear for the bed deposits is 0.16 and 0.37 lbs/sq-ft, respectively (τ^* =0.047). Using a dimensionless Shields parameter of 0.03, the estimated critical shear for the deposits is 0.11 and 0.24 lbs/sq-ft, respectively. Cobbles up to 6-inches can be found in many locations throughout the upper watershed. The geomorphic assessment found that gravels and cobbles originate from bank soils and was originally deposited by the ancestral American River. Because field observations suggests that the frequency of loose bed deposits is low; the bed primarily consists of compacted soils, exposed hardpan and cobble armoring; channel morphology is more a function of the surrounding soils and therefore the critical shear stress for analysis was based on consolidated bank material.

As a means to double check our selected values for critical shear stress, Geosyntec conducted a *Jet Test* of creek bank materials near WLA-Site 8 to measure the critical shear stress and the erodibility for these cohesive soils. The Jet Test was conducted as part of an evaluation of the Jet Test device itself and is not part of the scope of this project. The equipment was on loan from the USDA-ARS National Laboratory (Greg Hanson personnel communication).

The method was developed to compute τc in-situ by applying a known force (applied as a jet of water) and measuring the rate of erosion over time. The method involves the application of a *Jet Test* apparatus developed by researchers at the USDA-ARS National Laboratory (Hanson, G. J., and K. R. Cook. 1999). The device directs a jet of water with known dimensions and force at the bank soils that scours a small hole. The depth of erosion is measured periodically over time to develop a data set of erosion depth versus time. The erosion depth versus time data is then fit to the appropriate functions. As the applied shear stress approaches the critical shear stress the rate of erosion slows and eventually stops (if the test were allowed to run for several more hours).

The Jet Test was applied in two bank material types at this single location. The two soil types are a softer alluvial deposit and lightly cemented soils exposed near the toe of the bank. Figure 3-3 presents the applied critical shear stress values over time for one of the tests as an example. If the test was run for a long period of time, the applied shear stress would asymptotically reach the critical shear stress condition. The measured values for the two bank soil types are 0.17 and 0.34 lbs/sq-ft, respectively. These results show that our selected values are within the range of realistic values.

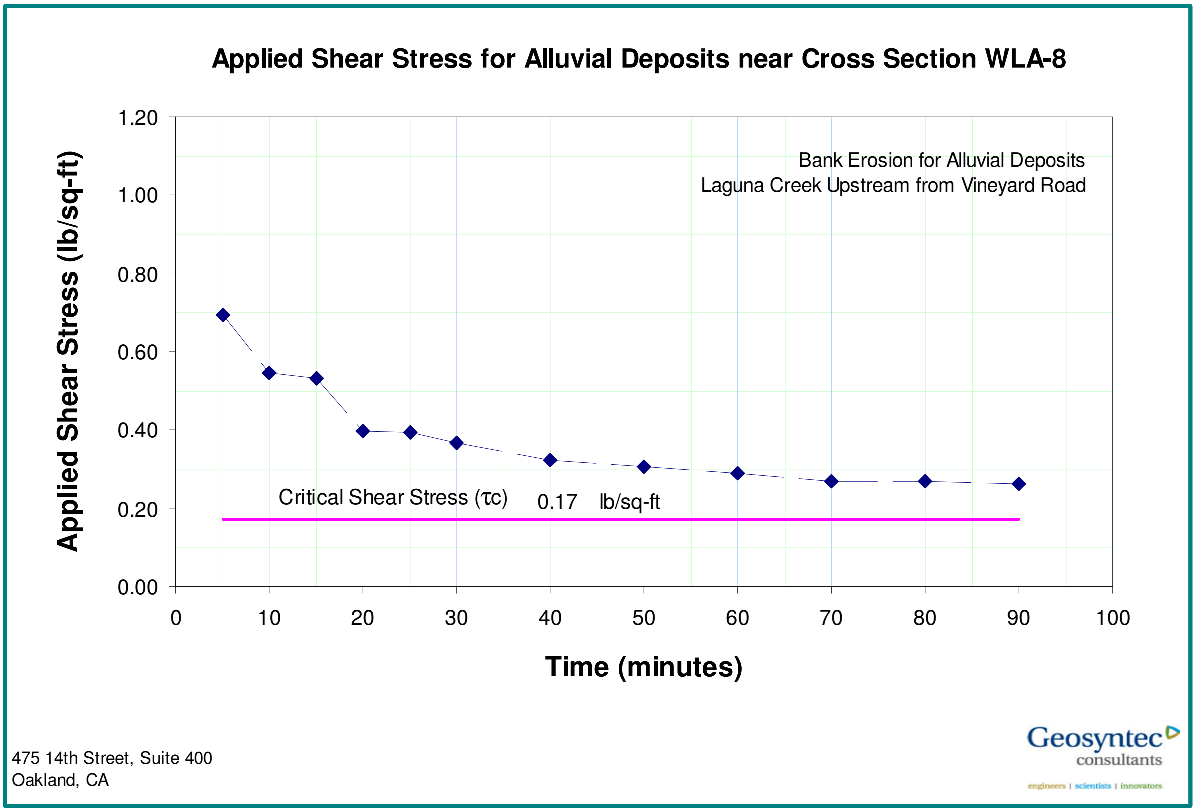

Figure 3-3. Example Results using the Jet Test Device to Measure Critical Shear of Consolidated Bank Materials

3.4 Vegetation Density

Generally, the dominant vegetation type "grasses" do not appear to play a significant role in channel stability. Although the vegetation cover reduces erosion at the soil surface, the depth and density of rooting structure is insufficient to provide resistance to erosion along the banks. Appendix A provides a description of the vegetation characteristics observed in Laguna Creek from a stability point of view.

Vegetation is providing channel stability in Reach 2, cross section GS-6 and GS-7. In this case, emergent vegetation, grasses, shrubs, forbs and trees are present; adding roughness and slowing the flow of water. Vegetation also reduces the apparent shear stress felt by the bank and bed soils by using up some of the energy in turbulent eddies around branches and stalks.

3.5 Cross Section Geometry & Roughness

There are several sources that provide lists of roughness coefficients (Chow, 1959, Barns, 1967 and French, 1985) under a variety of conditions. One method described in Chow (Cowan's method) considers each element that contributes to the total roughness and sums them together to derive the final roughness coefficient. Cowan's method accounts for channel materials, surface irregularities, channel geometry, obstructions, vegetation and sinuosity. Cowan's equation is:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) m_5$$

where:

n_0 = bed roughness
n_1 = degree of irregularity
n_2 = variation in channel cross section
n_3 = degree of obstructions
n_4 = degree of vegetation
m_5 = degree of meandering

Although there is a wide range in conditions that determine roughness coefficients, there are a number of consistently observed factors. The effects of vegetation depend primarily on the height, density, distribution and type of vegetation. With vegetation being one of the most significant factors, than the vegetation association with the geomorphic position, in a channel becomes an important consideration in the design process. Table 3-3 summarizes the relationships between surface roughness and vegetation type and its geomorphic position within the flood control channel. Generally, low terrace woodlands are extremely dense with correspondingly high channel roughness. Low-growing perennials and annuals, vernal pools or grasslands, on the other hand, present little impediment to flood flows, have correspondingly low roughness values.

Table 3-3. Vegetation Association Relative to Channel Roughness

Geomorphic Position	**Vegetation Association**	**Dominant Vegetation**	**Channel Roughness** (Description)	(Range)
Creek bed, sand and gravel	Open water	None	Low	0.02 – 0.03
Summer flow channel	Perennial marsh	Tules	High in low flows, moderate to low in higher flows, seasonal	0.08 – 0.10 0.04 – 0.05
Along banks of summer flow channel	Low terrace woodland	Cottonwood/willow	High	0.08 – 0.16
Bankfull channel bottom Floodplain depressions	Seasonal marsh vernal pools	Low-growing perennials and annuals	Low	0.03 – 0.05
Upper banks of bankfull channel	Low terrace woodland	Valley oaks/willows	High	0.08 - 0.16
Floodplain and flood control channel banks	Grassland	Grasses and tarplant	Low	0.03 – 0.05
Floodplain	High terrace woodland	Valley oaks	Moderate	0.06 – 0.08
Flood control channel banks	Oak woodland	Coast live oak	Moderate	0.06 – 0.08

Research has found that single trunk trees up to 8-inches in diameter do not impede flow as much as woody under story bushy growth. Roughness increases as the water depth increases up to the height of the vegetation. As the water level continues to increase above the height of the vegetation, roughness decreases. Tules in the channel can have a coefficient of 0.1 for flows up to the bankfull flow, but would decrease as the water level increased during flood events. Roughness coefficients for floodplains can vary from 0.03 to 0.15.

Figure 3-4 and 3-5 present Cross Section GS-2 as an example of how each cross section was defined for analysis. Figure 3-4 shows how the roughness coefficients were defined, with a vegetated - cobble bed and dense grass land making up the floodplains.

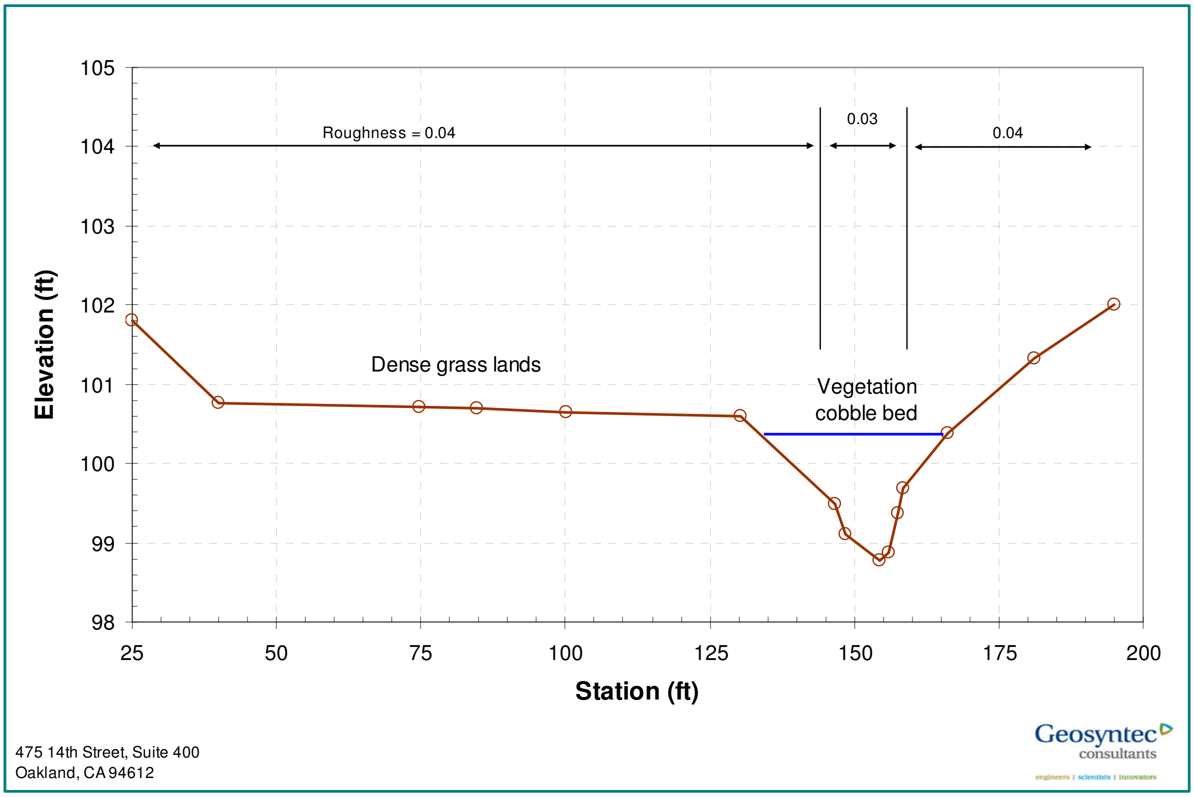

Figure 3-4. Example Cross Section GS-2

Table 3-4 presents a set of example hydraulic calculations for section GS-2, illustrating discharge, stage, flow area, wetted perimeter, hydraulic radius, velocity, stream power, shear stress and the composite roughness coefficient. In this case, the central channel was assigned a roughness coefficient of 0.03 representing grain and form roughness, and channel irregularities; and the floodplains adjacent to the active channel were assigned a coefficient of 0.04 representing shallow flow over dense grasslands. In this example, the range in roughness coefficients is low and doesn't have much effect on the composite roughness coefficients, which ranged from 0.03 to 0.031.

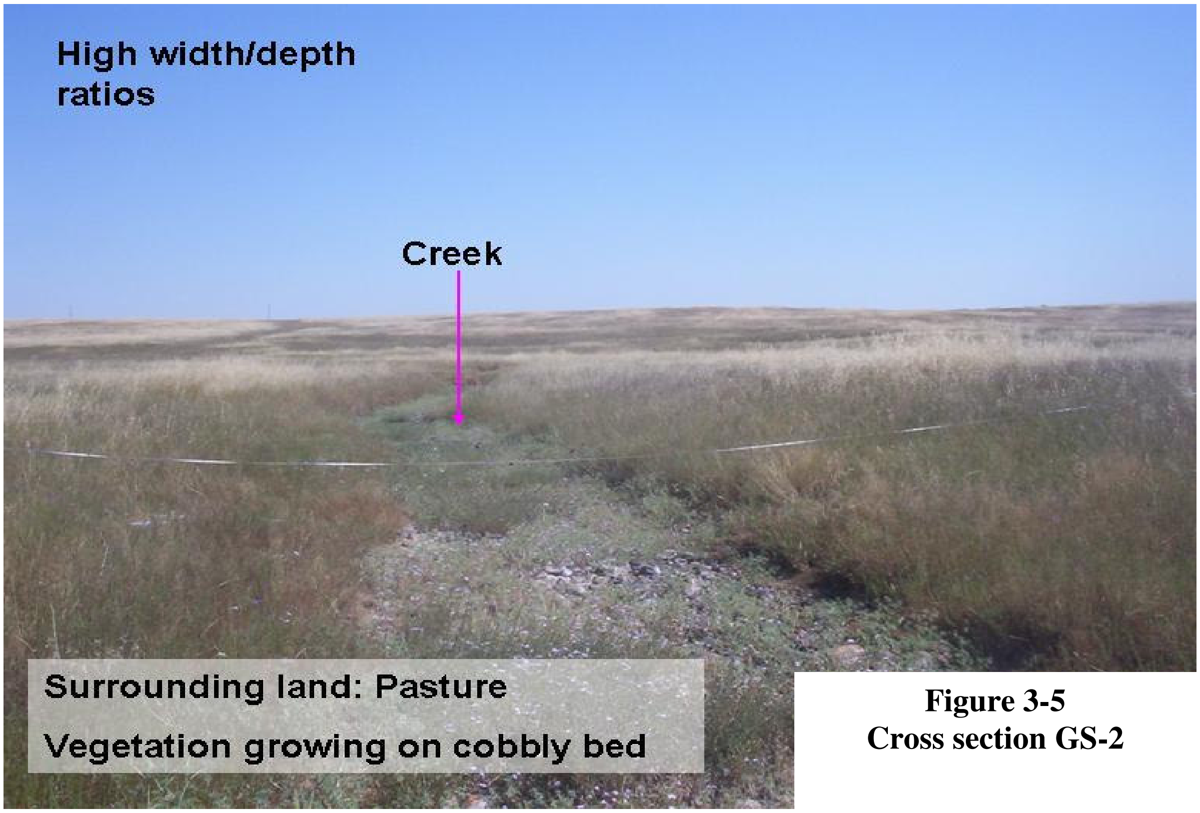

Figure 3-5
Cross section GS-2

Table 3-4. Example Hydraulic Calculations for Cross Sections

Flow (cfs)	Stage (ft)	Flow Area (sq-ft)	Wetted Perimeter (ft)	Hydraulic Radius (ft)	Velocity (ft/s)	Stream Power (watts/sq-ft)	Shear Stress (lbs/sq-ft)	Composite Roughness Coefficient
0.0	98.8	0.0	0.0	0.0	0.0	0.0	0.000	0.000
1.2	99.0	0.9	6.8	0.1	1.3	0.1	0.090	0.030
6.5	99.3	3.1	9.8	0.3	2.2	0.5	0.226	0.030
15.8	99.5	5.7	12.1	0.5	3.0	1.1	0.382	0.030
28.7	99.8	9.3	17.2	0.5	3.5	1.9	0.538	0.030
46.9	100.0	14.4	23.7	0.6	4.0	2.8	0.694	0.030
72.6	100.3	21.0	30.1	0.7	4.4	3.7	0.850	0.030
108.1	100.5	29.4	37.3	0.8	4.7	4.7	0.992	0.031
166.7	100.8	48.0	132.9	0.4	5.0	5.8	1.045	0.035
282.8	101.0	82.0	140.3	0.6	5.2	6.9	1.179	0.035

4 Results and Discussion

This section summarizes the predicted changes in runoff volume and with the seasonality of these flows; range of flow to manage; changes in flow duration characteristics, work done and sediment load transported; and summarizes the final predicted erosion potentials. The analysis considers changes between pre-urban, existing and future conditions.

When correlated to field observations, comparing changes between pre- and existing conditions allows us to evaluate and explain observed conditions. For channel reaches that are currently unstable and that could be correlated to development, predictions can be made on the sensitivity of Laguna Creek to changes in runoff patterns.

4.1 Range of Flows to Manage - Critical Flow

Table 4-1 summarizes the estimated critical flows and 2-Year peak flows for each cross section. Critical flows (Qc) is the magnitude of flow that is just strong enough to erode bank material. Based on the material types; bank material is less resilient than the bed material, which is often cemented in hardpan. As a result, bank material is the most sensitive material and is controlling the ability of the channel to resist the effects of hydromodification, and defines the lower limit on the *range of flows to manage*.

To translate the in-stream critical flow to a project based criteria for stormwater control measures. The 2-year peak flow also makes a convenient basis for translating the critical flow to a project based criteria. Table 4-1 shows that the critical flow for Laguna Creek ranges from 15% to 70% of the 2-year peak flow depending on channel characteristics (such as slope and soils). Because the effects of development and flow changes are a continuum, this is all upstream discharges contribute to the cumulative effects downstream; the most sensitive stream reaches are used to define this criterion and applied throughout the watershed. A single standard is easier to apply for agency personnel and the development community who might be required to apply this criterion.

The criterion applied in this study for the allowable low flow discharge (Qcp) is 25% of Q2. Holding stormwater on-site and discharging under this criterion does not contribute to erosion or the effects of hydromodification; and is allowable. 25% of Q2 is neither the smallest percentage that could be chosen nor the largest. It is slightly smaller than the estimated central tendencies and is considered a reasonable choice considering the uncertainties in model predictions. Only six of 24 cross sections (25 percent) have estimates smaller than 25% of Q2.

The stormwater management strategy used herein is stated as follows: Project discharges shall match the post-development flow duration curve to the pre-development flow duration curve from 25% of Q2 up to the 10-year peak flow.

Table 4-1. Summary of Critical Flow Analysis and Low Flow Discharge Allowance

	Location	Area (sq.mi.)	τc (lbs/sqft)	Qc (cfs)	Q_2 (cfs)	% Q_2	Qc cfs/acre	Q_2 cfs/acre	% Q_2	Qc cfs/acre	Q_2 cfs/acre	% Q_2
Reach 1 - Redding Gravelly Loam	G.S. XS-1	0.87	0.38	20	46	43%				0.036	0.083	43%
	G.S. XS-2	1.29	0.38	16	31	52%				0.019	0.038	52%
	G.S. XS-3	2.17	0.38	23	77	30%				0.017	0.055	30%
	G.S. XS-4	2.17	0.38	27	77	35%				0.019	0.055	35%
Reach 2 - Hedge & San Joaquin Loam	G.S. XS-5	1.59	0.20	14	75	19%	0.014	0.074	19%			
	G.S. XS-6	12.2	0.20	73	438	17%	0.009	0.056	17%			
	G.S. XS-7	12.2	0.20	75	438	17%	0.010	0.056	17%			
	G.S. XS-9	1.74	0.20	11	59	19%	0.010	0.053	19%			
	WLA Site 1	15.4	0.20	139	553	25%	0.014	0.056	25%			
	WLA Site 2	16.4	0.20	275	588	47%	0.026	0.056	47%			
Reach 3 - Redding Gravelly Loam	WLA Site 4	19.1	0.38	309	686	45%				0.025	0.056	45%
	WLA Site 6	19.1	0.38	239	686	35%				0.020	0.056	35%
	WLA Site 7	19.1	0.38	245	686	36%				0.020	0.056	36%
	WLA Site 8	19.1	0.38	481	686	70%				0.039	0.056	70%
Reach 4 - Hedge & San Joaquin Loam	WLA Site 10	19.1	0.20	165	686	24%	0.014	0.056	24%			
	WLA Site 12	20.4	0.20	227	695	33%	0.017	0.053	33%			
	WLA Site 13	20.4	0.20	243	695	35%	0.019	0.053	35%			
	WLA Site 15	21.7	0.20	377	747	50%	0.027	0.054	50%			
Reach 4 - Hicksville Loam	WLA Site 16	22.7	0.18	411	774	53%	0.028	0.053	53%			
	WLA Site 17	22.7	0.18	165	774	21%	0.011	0.053	21%			
	WLA Site 18	23.1	0.18	309	952	32%	0.021	0.064	32%			
	G.S. XS-8	31.7	0.18	505	1091	46%	0.025	0.054	46%			
Trib.1	WLA Site 19	5.00	0.18	61	329	19%	0.019	0.103	19%			
Trib.1	WLA Site 20	5.00	0.18	50	329	15%	0.016	0.103	15%			
				Mean		35%	0.017	0.062	**28%**	0.024	0.057	**43%**
				Median		34%	0.017	0.056	**30%**	0.020	0.056	**35%**
				Std Dev		14%	0.006	0.017	13%	0.009	0.012	13%

4.2 Flow Duration Curves

Flow duration charts present the cumulative frequency distribution showing the total number of hours of flows greater than or equal to the corresponding discharge in cubic feet per second (cfs). For example, Figure 4-1a results show that there are 10 hours of flows greater than or equal to 70 cfs under the existing condition. This figure also shows that the total number of hours of runoff greater than 1cfs is about 42,000 (or about 10% of the time in 49 years). The change in the frequency distribution is illustrated by the difference between the two curves, which also illustrates the change in runoff volume. Since land use is identical, the pre-development curve is hidden by the existing development curve. Flow duration forms the basis of the work and sediment transport analysis, and as such forms the basis of flow management for hydromodification.

Figures 4-1a to 4-1e present *flow duration* results for five locations and for pre, existing and future development conditions. A sub-set of locations is presented for illustrative purposes and show the range of results predicted.

For catchment LCC0 (Figure 4-1a) there is no change between pre and existing development conditions. Future development will increase runoff volume and the total cumulative duration of the full range of flows. The total number of hours reflects the storage and slower discharge of accumulated precipitation in the Laguna Creek watershed – with Laguna's Vernal pool landscape and hardpan layers, the surface soils act like a slow release sponge increasing the length of time runoff occurs.

Figure 4-1b present results for catchment LC30. These results are similar, but this catchment has some of the highest percent impervious surfaces and increased runoff volumes; and as a result shows some of the largest changes in flow duration data. Figure 4-1c shows the curves for a model junction representing stream flows as opposed to catchment runoff. Little change is observed between pre and existing conditions. Farther downstream, at junction LCC10A, the model is showing smaller peak flows between pre and existing conditions; and only small changes between existing and future conditions. Most all of the existing development is within the lower portion of the watershed, which is long and narrow. Runoff from this lower portion is quicker because of the impervious surfaces and drainage infrastructure and pass through Reach 4 before the upper watershed area can respond to the storm event. As a result, smaller peak flow and thus the amount of Work Done are predicted in Reach 4. Figure 4-1e shows similar results at LCC18 (at the end of the model downstream from the intersection of Waterman & Bond), but with slightly less difference.

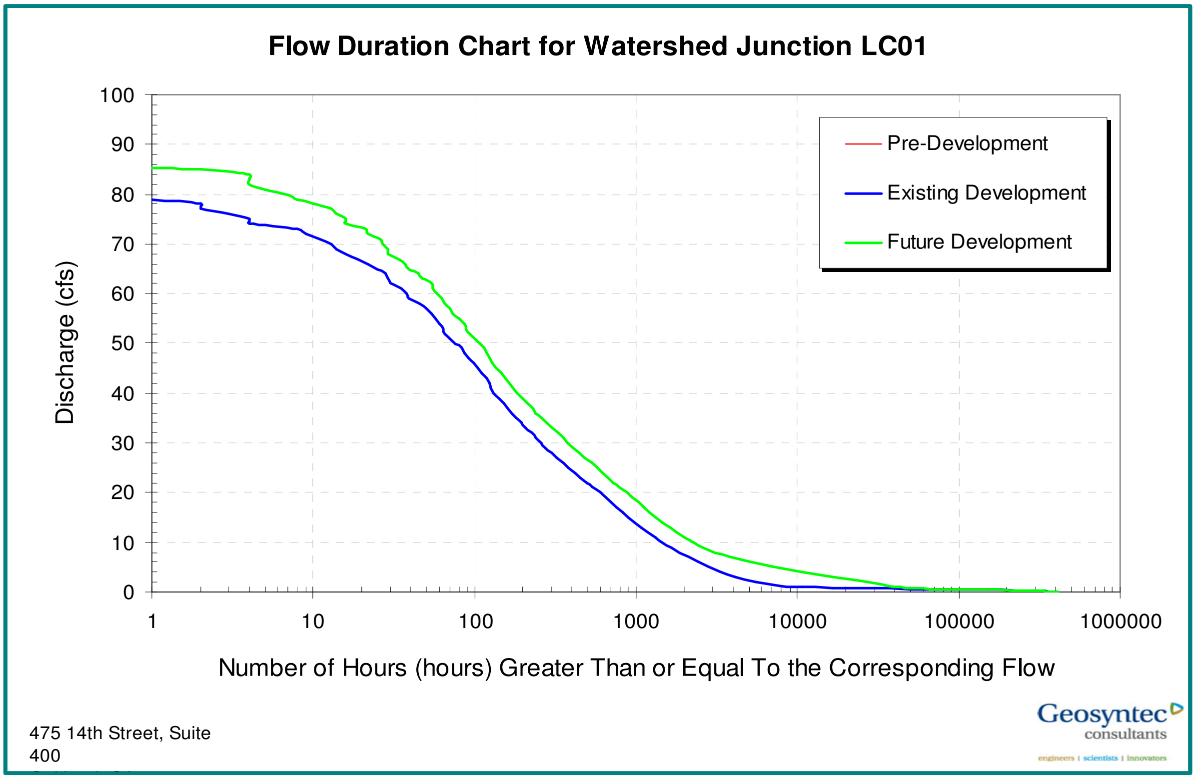

Figure 4-1a

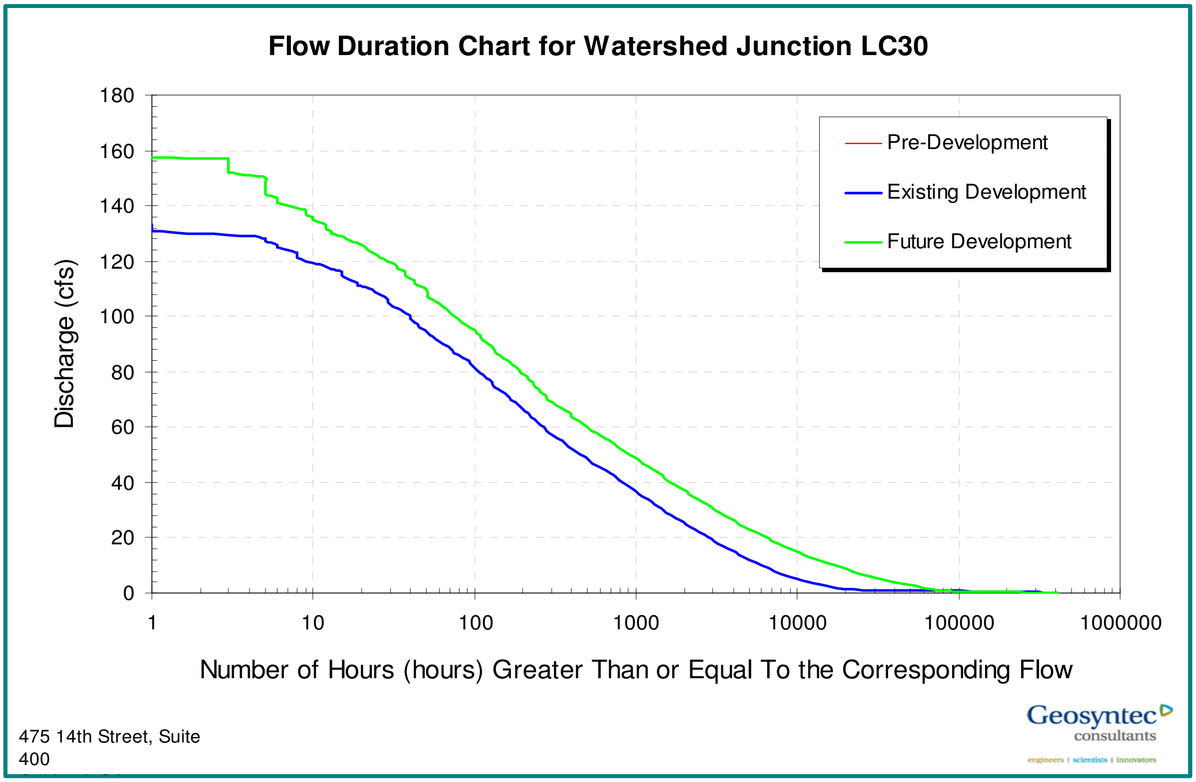

Figure 4-1b

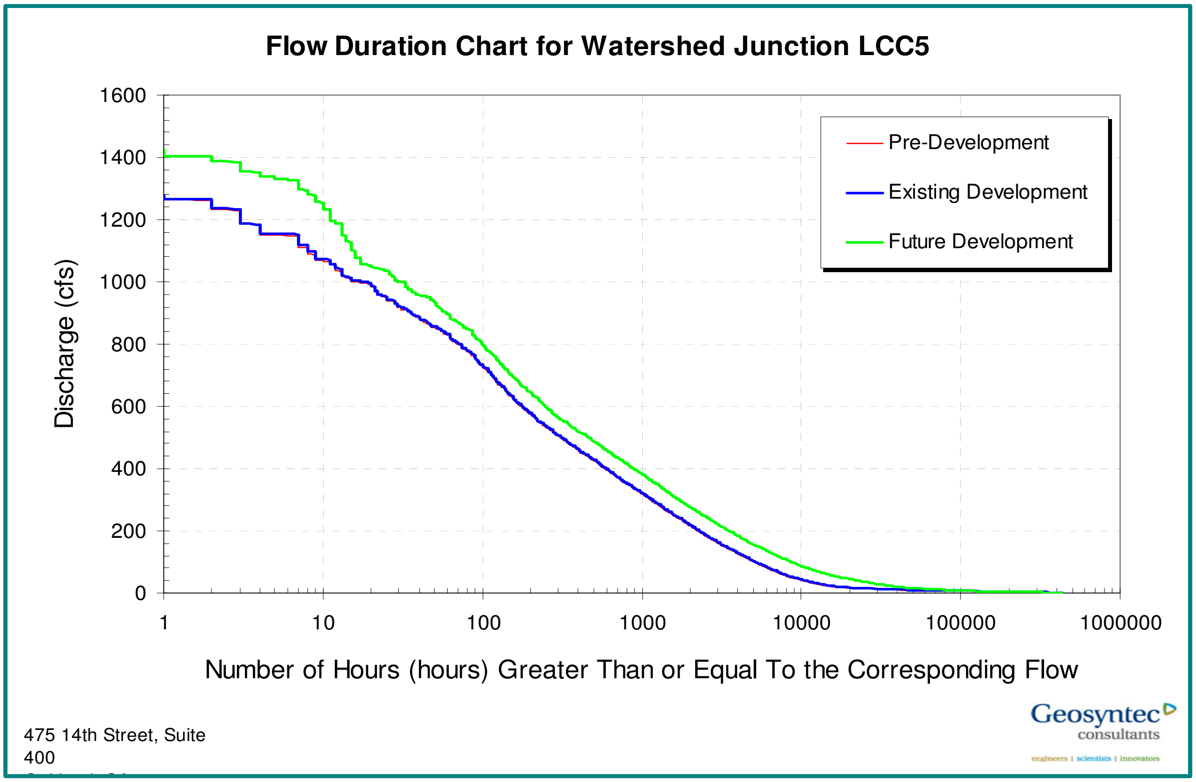

Figure 4-1c

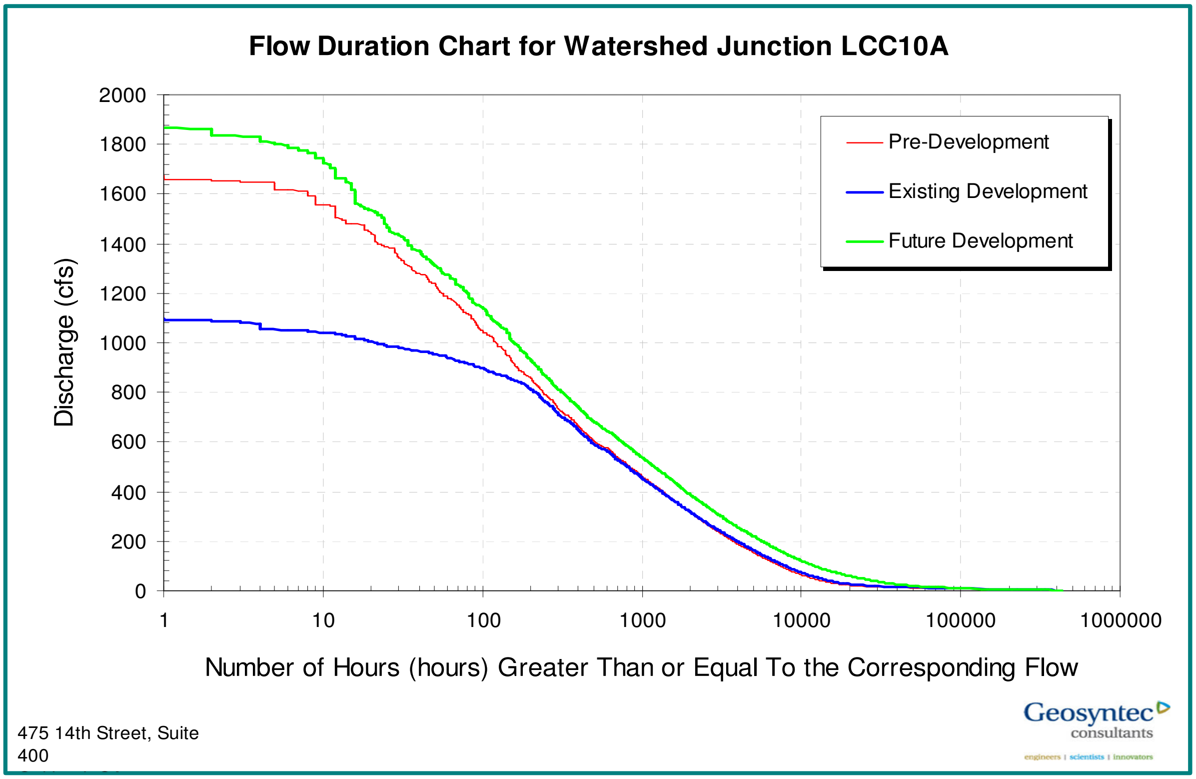

Figure 4-1d

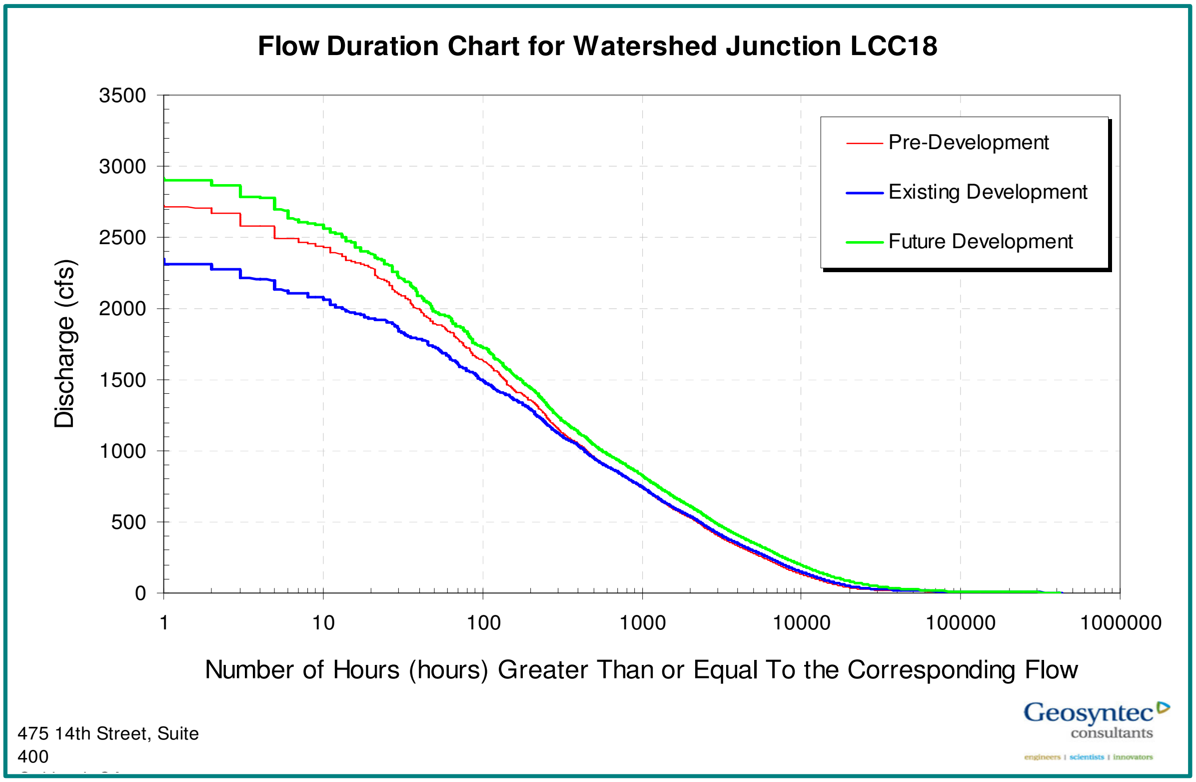

Figure 4-1e

4.3 Work Curves

Work Curves illustrate the distribution of work done by the forces imposed by flowing water on the channel boundary, contributing to the erosion, deposition and transport processes. The work curves presented herein use *Index* 2 for illustrative purposes. The analysis is based on the concept that there is infrequent loose bed material available for transport and the channel form and potential for adjustment is primarily a function of the surrounding soils. As a result, this analysis is based on the application of the two Work Indexes for consolidated boundary materials. Appendix A provides further discussion of the observed channel bed and bank properties.

Work curves illustrate which flows are doing the most work over the long-term. Leopold (1964) used this approach to identify the most effective discharges, which has become synonymous with the term bankfull. For example, Figure 4-2a suggests that the most effective discharges at cross section GS XS-2 is around 28 to 30 cfs. Figure 4-2a also shows that the critical flow for erosion is 16 cfs (point where curves begin to rise). The change in work imposed by Future development is illustrated by the difference between the two curves. In this case, although an increase is predicted over the full range of flows, the greatest increases in work is in the low to moderate flow range (22cfs to 46cfs), which is consistent with the effects from watershed development.

Figures 4-2a to 4-2e present the results for select locations throughout the watershed for illustrative purposes. Figure 4-2a presents the results for Reach 1 near the top of the watershed. Figure 4-2b for cross section GS XS-9 (Fry Creek) shows a typical change in work done by urbanization observed on past projects by Geosyntec. This section (as well as GS XS-5 – Kite Creek, Reach 2) and its associated tributary channel are subject to the most amounts of development and impervious surfaces from the Jackson Corridor. The magnitudes of work is higher here because of the steeper slopes and less resistant boundary materials (soils). These results also suggest a shift in the most effective discharges to smaller flows, which is an affect of increasing the runoff frequency for small storms from paved surfaces. Figure 4-2c presents the results for WLA-1, at the lower end of Reach 2; and shows less overall work being done in this shallow sloped and stable channel geometry. The next figure presented (Figure 4-2d) shows the results for WLA-15, in Reach 4; illustrating the effects of a wide shallow channel geometry. The predicted amount of work being done is further reduced from the upstream sections. Figure 4-2e presents the results for the downstream most point in the modeled study area and shows this shift from higher to lower peak flows predicted in the lower reaches of Laguna Creek (GS XS-8). Slightly more work is being done in the low flow range and less is being done by high flows.

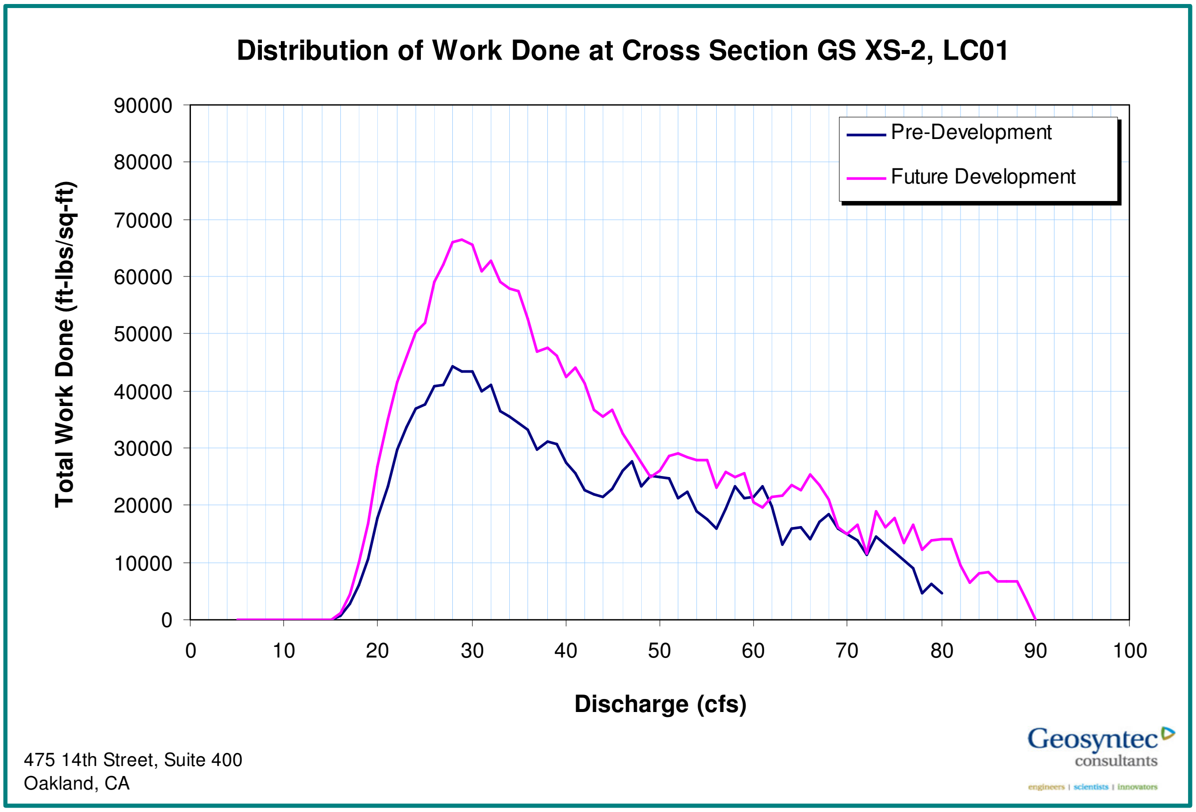

Figure 4-2a

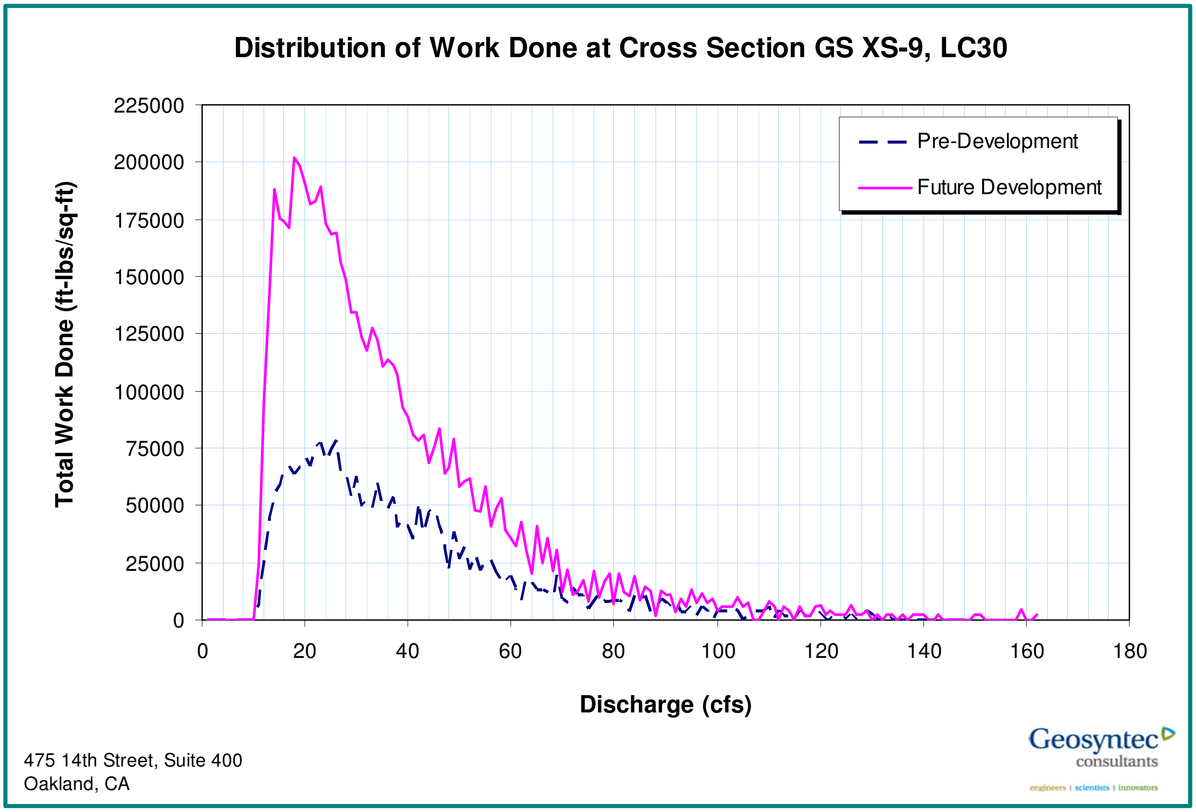

Figure 4-2b

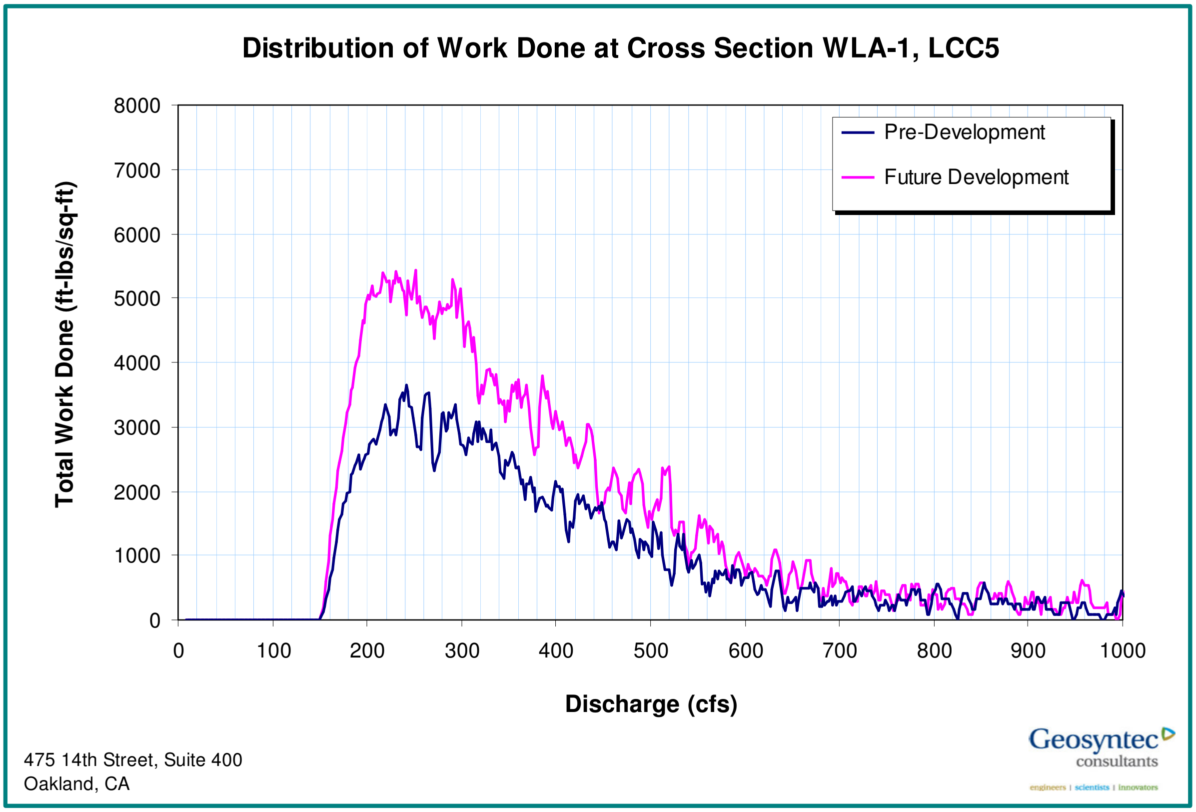

Figure 4-2c

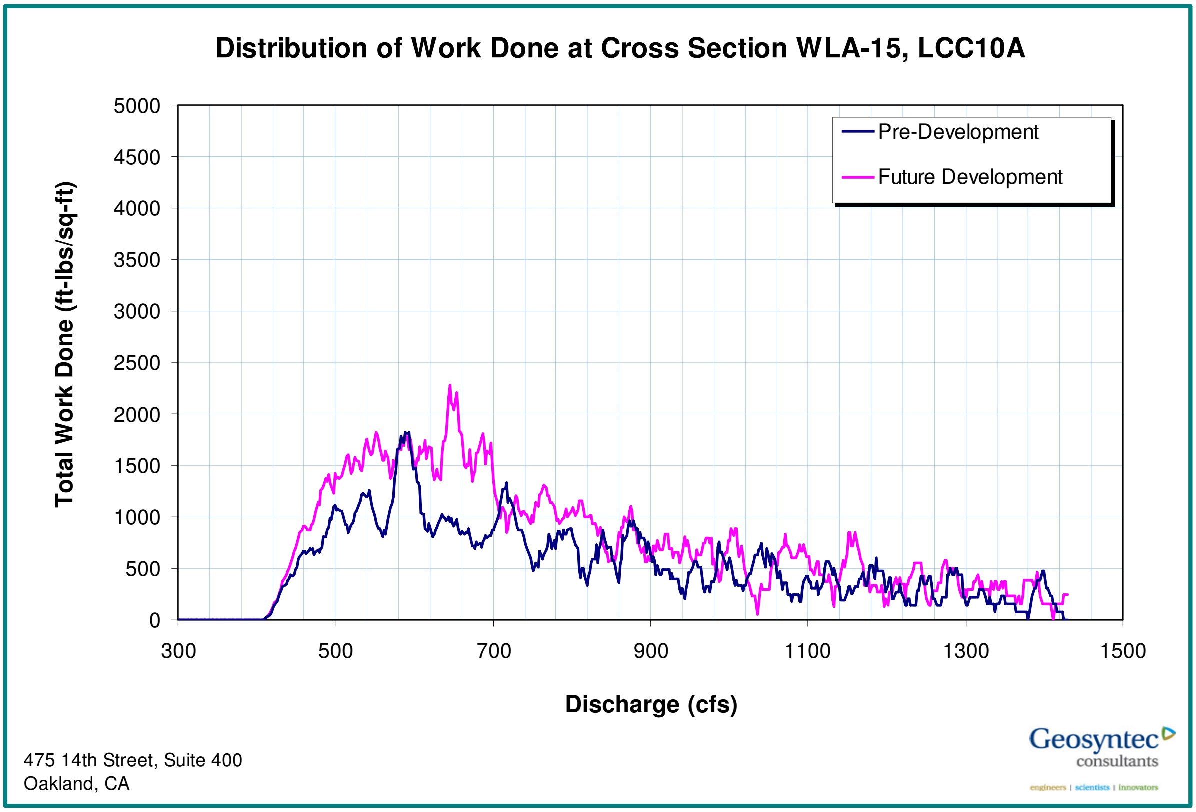

Figure 4-2d

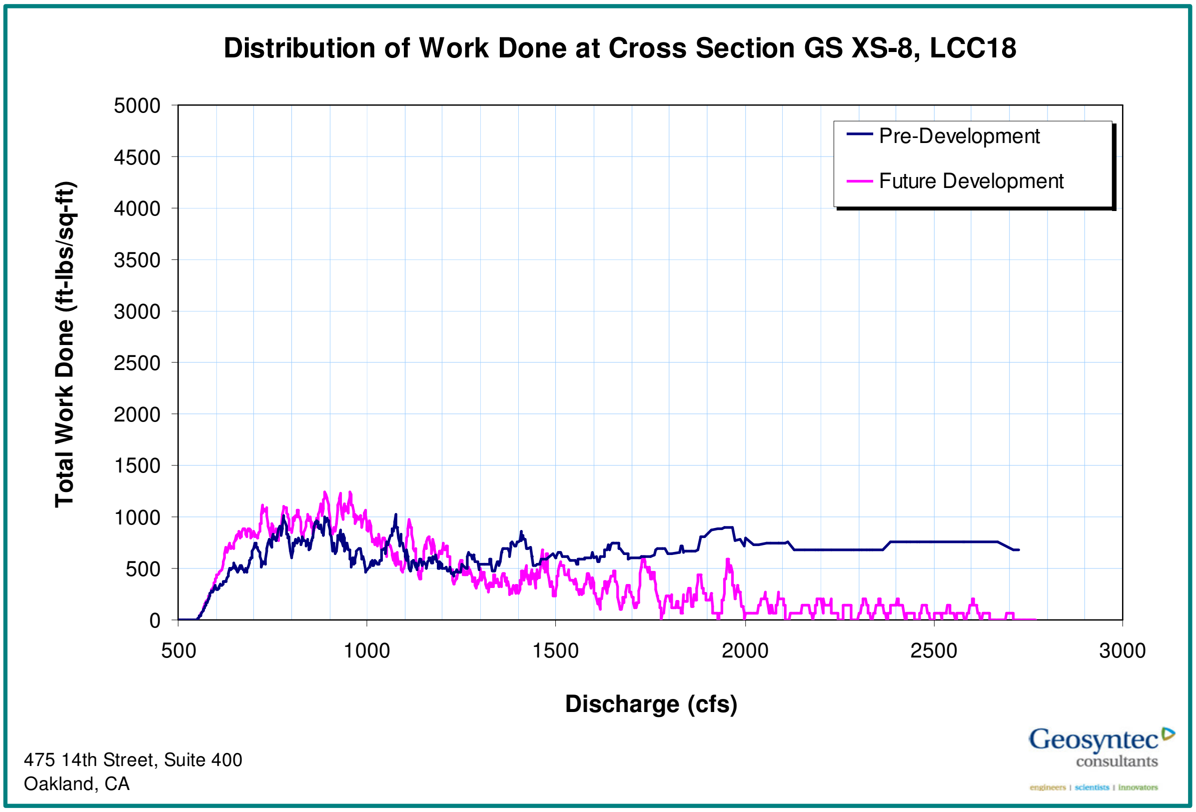

Figure 4-2e

4.4 Estimated Erosion Potential

Existing Conditions Results: Table 4-2 below summarizes the estimated Erosion Potential under *existing* conditions for each location under study. Refer back to Figure 2-1 for an illustration of the project, junctions and cross section locations.

The increase in percent impervious between pre-development and existing development does not begin until part way down Reach 2, at cross section GS XS-6 (4.3% IMP). Given the shallow longitudinal slopes (0.10% to 0.20%) and stable channel geometry; the current level of development (<5% IMP) does not appear capable of causing excessive erosion and channel adjustment. Generally, it would seem that a level of development on the order of 5% imperviousness would not cause a hydrologic condition of concern.

However in the upper portion of Reach 4, the estimated Ep values are high and the channel is currently unstable. The primary cause of instability and high erosion potentials is *channelization*. Channelization (dredging, deepening and straightening) has increased the capacity of the active channel and disconnected it from its floodplains. The full range of flows are now contained within the active channel, increasing the magnitude of *Work Done* by 3 times. Flows that historically spilled out onto floodplains create much less shear force on the channel boundary and cause less erosion of the bed and banks.

Excessive erosion was also observed is the small tributary to Reach 4 (cross sections WLA 19 and 20) with 11.4 percent impervious surfaces. The existing level of development seems to have increased the magnitude of *Work Done* by 2 times. In this creek segment, recent shear erosion was observed along the bed and toes of banks. Recently exposed fine tree roots were present along with vertical cutbanks on the inside meander bend.

An interesting result is the reduction in Ep within Reach 4. The model predicts less intense flows under existing conditions compared to pre-development. There are two possible reasons: 1) the majority of existing development is within the lower watershed. Runoff from this portion is flashier because of impervious surfaces and drainage infrastructure and flows travel through Reach 4 before the upper watershed can respond to the storm event. And 2) the interbasin transfer was not included in the pre-developed condition, which increases flows under the pre-developed condition in this reach. As a result, smaller peak flows and the amount of *Work Done* are predicted in Reach 4.

Figure 4-3 summarizes these results in an Erosion Potential Chart that correlates the field determined channel conditions to the hydro-geomorphic model results. Although the data set is small for unstable conditions, this empirical relationship provides some indication of the magnitude of Ep and the likelihood of having or causing channel instabilities. Certainly, values in excess of 2 will produce unstable channel conditions.

To better define the relationship between stable and unstable conditions, Logistic Regression is used to generate a probability relationship between the two state variables (stable vs. unstable). Figure 4-4 presents the probability curve expressing the likelihood (risk) of having or causing channel instabilities as a function of the Erosion Potential. This relationship expresses the risk of having or causing instabilities for Ep values between 1 and 2. For example, a predicted Ep value of 1.2 has a 20% probability of causing channel impacts. In other words, if 1.2 is used as a management criteria, 1 in 5 channel segments could still end up with unstable conditions.

Future Development Results: Table 4-3 summarizes the predicted erosion potentials under future conditions. Overall, future development in the Laguna Creek watershed is predicted to increase the average erosiveness of creek flows by 45%. A 45% increase in work done is not that high compared to other projects that Geosyntec has worked on over the last few years, where Ep values of 5.0 to 10.0 were common. These results illustrate the unique soil and geology in the Laguna Creek watershed. The change in runoff between pre-urban/existing and future conditions is not as great as it is in other areas where the soils are more permeable.

Results for Reach 1 (not including LC01), located in the Redding/Red Bluff Gravelly Loam soils, suggest that cumulative future development in the headwater areas could increase the amount of work done (by erosive hydraulic forces) from 26% to 47% if left unmanaged (Ep=1.26 and 1.47). The average increase is about 30%.

Results for Reach 2 suggest that future cumulative development could increase the amount of work done by 46% to 56% upstream from Excelsior Road; and by 61% to 66% upstream from Eagles Nest Road if left unmanaged. Soil type in Reach 2 consists of the less resilient Hedge / San Joaquin Soil complexes. The two tributary streams Kite Creek and Fry Creek (XS-5 and XS-9) receiving runoff from the Jackson Corridor are predicted to increase by about 200% (i.e., Ep=1.93 and 2.32).

Results for Reach 3 suggest that future development upstream from Vineyard Road could increase the amount of work done by about 40% if left unmanaged. The longitudinal slope is steeper in this reach, which leads to higher shear forces per unit flow. At the same time the bank material type is slightly more resistant being composed of the Redding/Red Bluff Gravelly loam. The current instabilities observed in the field is believed to be caused by head cut migration and not increases in stream flows from upstream development.

Results for the upper portion of Reach 4 (WLA 10, 12 and 13) suggest that future development will increases the magnitude of work done to 4 times more than the undeveloped watershed. This segment is already unstable and future develop is predicted to intensify the current erosion and channel failures. Results for lower portion of Reach 4 suggest that the amount of work done increases by 28% to 39% if left unmanaged. Soil type in Reach 4 consists of both the least resistant Hedge / San Joaquin Soil complexes and the Hicksville soil complex.

The small tributary discharging to Laguna Creek (WLA 19 and 20) shows increases in work done by about 2 times; just slightly more than currently predicted under existing conditions. This is because the amount of development and imperviousness is not that different.

Table 4-2. Summary of Estimated Erosion Potentials under Existing Conditions

Location		Slope	Existing % IMP	Critical Shear	Erosion Potential (E_p)		Erosion Potential by Reach		
					WORK INDEX		Mean	Median	Std Dev
				(lbs/sqft)	(unitless)	(ft-lbs/sqft)	(ft-lbs/sqft)	(ft-lbs/sqft)	(ft-lbs/sqft)
Reach 1	G.S. XS-1	1.0%	2.0	0.38	1.00	1.00	1.00	1.00	0.00
	G.S. XS-2	1.0%	2.0		1.00	1.00			
	G.S. XS-3	0.60%	2.0		1.00	1.00			
	G.S. XS-4	0.60%	2.0		1.00	1.00			
Reach 2	G.S. XS-5	0.50%	2.0	0.20	1.01	1.01	1.01	1.00	
	G.S. XS-9	0.40%	2.0		1.00	1.00			
	G.S. XS-6	0.10%	4.3		1.04	1.04	1.03	1.03	0.01
	G.S. XS-7	0.15%	4.3		1.04	1.04			
	WLA Site 1	0.10%	3.8		1.02	1.03			
	WLA Site 2	0.20%	3.7		1.02	1.02			
Reach 3	WLA Site 4	0.24%	3.8	0.38	1.03	1.02	1.02	1.02	0.00
	WLA Site 6	0.35%	3.8		1.02	1.03			
	WLA Site 7	0.22%	3.8		1.02	1.03			
	WLA Site 8	0.24%	3.8		1.02	1.02			
Reach 4	WLA Site 10	0.07%	3.8	0.20	2.41	2.36	2.81	2.90	0.41
	WLA Site 12	0.07%	5.0		3.43	3.17			
	WLA Site 13	0.07%	5.0		2.86	2.90			
	WLA Site 15	0.10%	6.1		0.83	0.88			
Reach 4	WLA Site 16	0.07%	6.2	0.18	0.74	0.82	0.91	0.91	0.09
	WLA Site 17	0.10%	6.2		0.76	0.85			
	WLA Site 18	0.06%	6.2		0.95	1.00			
	G.S. XS-8	0.05%	7.8		0.93	0.97			
Trib.1	WLA Site 19	0.15%	11.4		2.22	2.62	2.34	2.34	
Trib.1	WLA Site 20	0.15%	11.4		1.98	2.05			

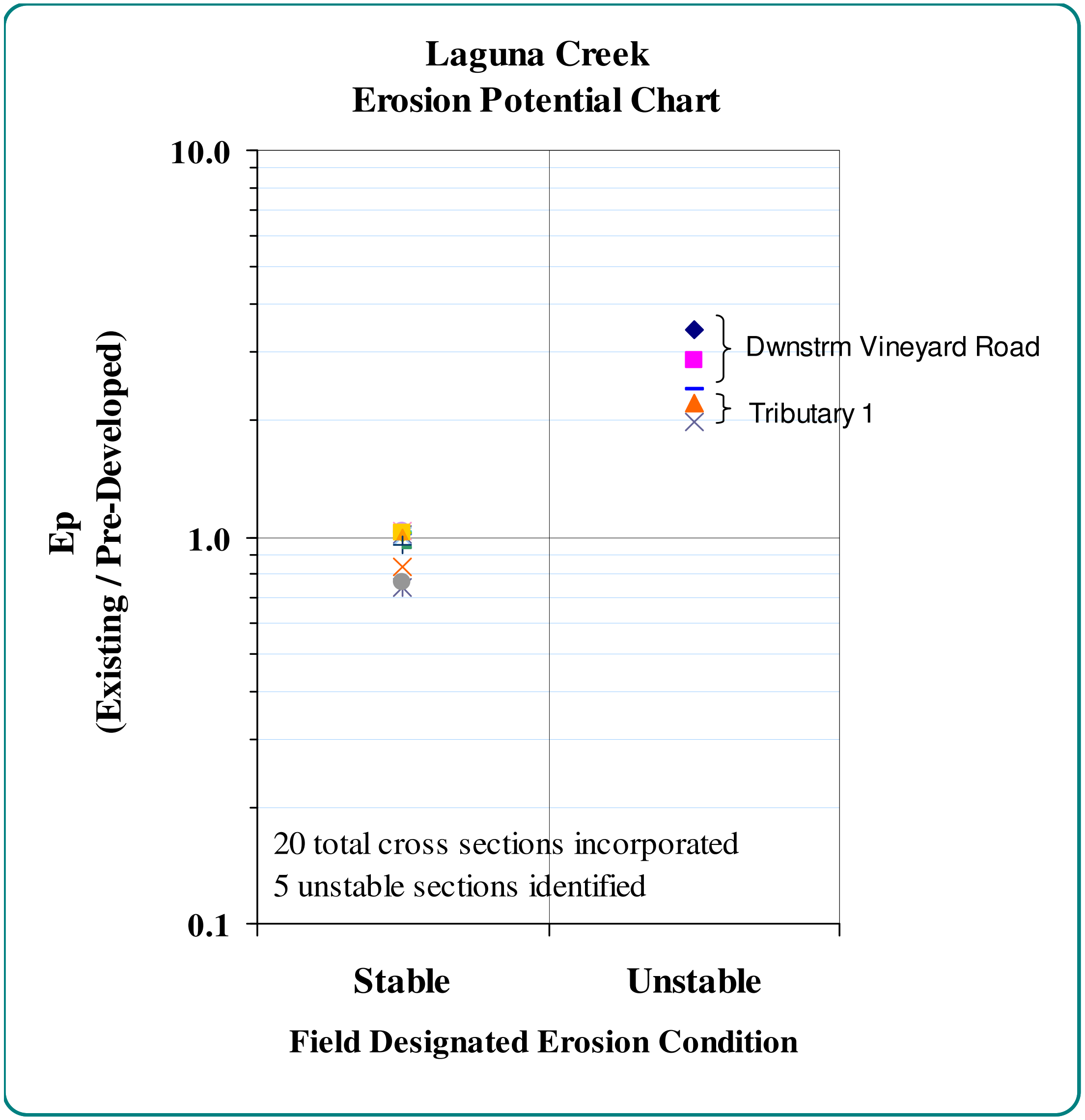

Figure 4-3 – Erosion Potential Chart for Laguna Creek

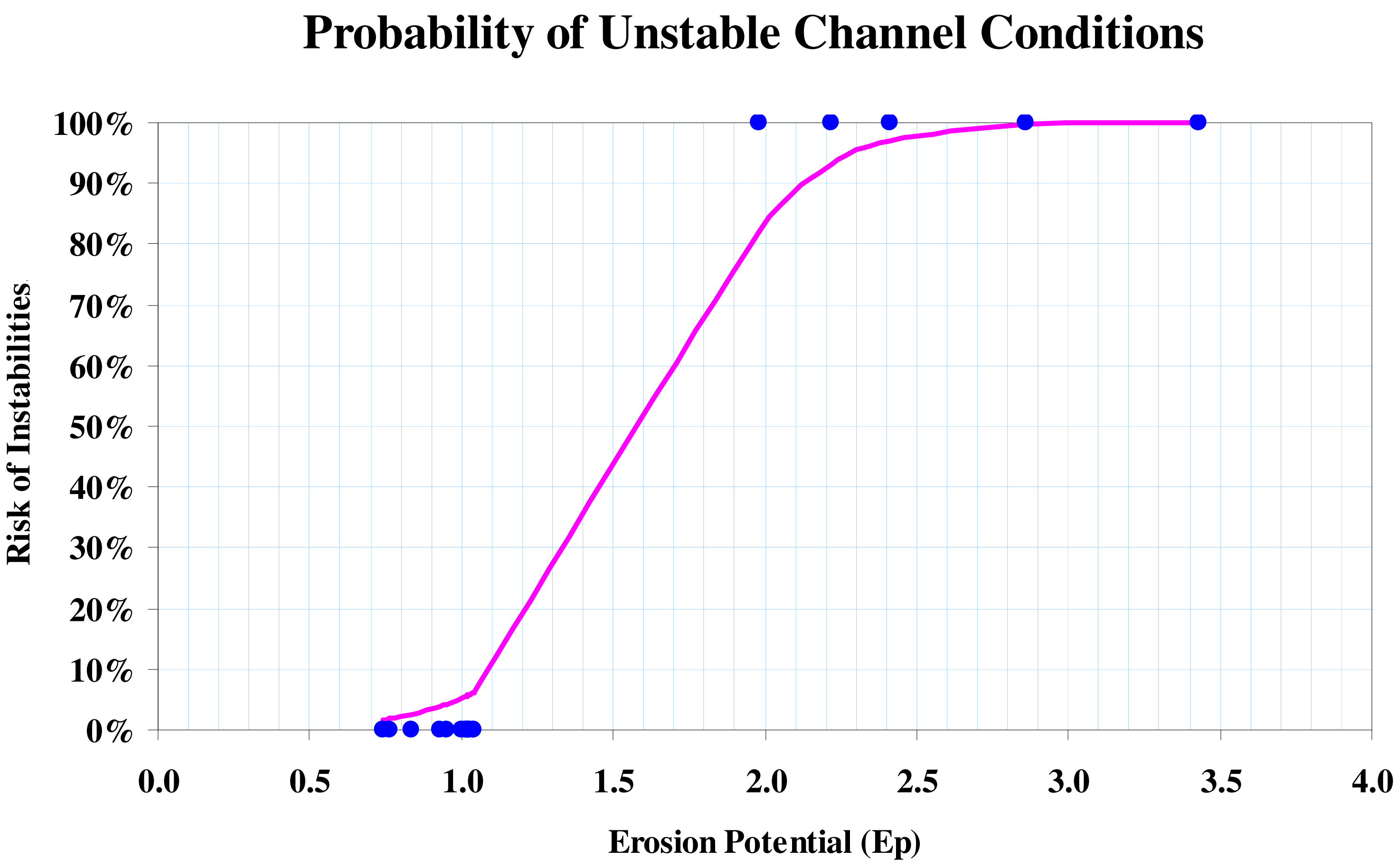

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Figure 4-4 – Probability of Unstable Channel Conditions for Laguna Creek

Table 4-3. Summary of Estimated Erosion Potentials under Future Development

Location		Slope	Future %IMP	Critical Shear Stress (lbs/sqft)	Erosion Potential (E_p)		Erosion Potential by Reach		
					WORK INDEX		Mean	Median	Std Dev
					(unitless)	(ft-lbs/sqft)	(ft-lbs/sqft)	(ft-lbs/sqft)	(ft-lbs/sqft)
Reach 1	G.S. XS-1	1.0%	5.2		1.04	1.04	1.04	1.04	
	G.S. XS-2	1.0%	15.6	0.38	1.47	1.47	1.34	1.28	0.11
	G.S. XS-3	0.60%	11.4		1.27	1.28			
	G.S. XS-4	0.60%	11.4		1.26	1.27			
Reach 2	G.S. XS-5	0.50%	47.3	0.20	1.89	1.93	2.06	2.13	
	G.S. XS-9	0.40%	49.4		2.24	2.32			
	G.S. XS-6	0.10%	28.8		1.64	1.66	1.58	1.60	0.09
	G.S. XS-7	0.15%	28.8		1.61	1.64			
	WLA Site 1	0.10%	29.0		1.55	1.57			
	WLA Site 2	0.20%	27.5		1.46	1.46			
Reach 3	WLA Site 4	0.24%	25.2	0.38	1.41	1.41	1.41	1.42	0.01
	WLA Site 6	0.35%	25.2		1.41	1.42			
	WLA Site 7	0.22%	25.2		1.42	1.42			
	WLA Site 8	0.24%	25.2		1.40	1.40			
Reach 4	WLA Site 10	0.07%	25.2	0.20	3.44	3.39	3.91	3.98	0.49
	WLA Site 12	0.07%	25.4		4.70	4.36			
	WLA Site 13	0.07%	25.4		3.91	3.98			
	WLA Site 15	0.10%	26.3		1.42	1.41			
Reach 4	WLA Site 16	0.07%	25.5	0.18	1.37	1.37	1.36	1.36	0.04
	WLA Site 17	0.10%	25.5		1.37	1.39			
	WLA Site 18	0.06%	25.2		1.33	1.35			
	G.S. XS-8	0.05%	22.1		1.28	1.31			
Trib.1	WLA Site 19	0.15%	12.5		2.24	2.64	2.36	2.36	
Trib.1	WLA Site 20	0.15%	12.5		2.00	2.07			

5 Conclusions of Future Conditions Assessment

This chapter presents the conclusion of the future conditions assessment and discusses the effects considering the unique physiography and geology of the Laguna Creek watershed.

1) This analysis suggests that a level of development of 5% to 7% imperviousness would not cause a hydrologic condition of concern. The results at WLA-19 and 20 (11.4% IMP) suggest a threshold based on percent imperviousness may be on the order of 10% - a common value reported in the literature.
2) On the basis of the land use assumptions, Future development will increase the percent imperviousness to 12% to 50% depending on location within the watershed – all greater than a presumed 10% threshold.
3) The range of flows to manage begins at the critical flow for bank toe erosion. This low flow is estimated to be 25% of the 2-year peak flow in Laguna Creek as determined from the continuous simulation model[3]. All flows greater than this have the power to erode bank material and carry fines downstream to depositional areas. The upper limit on the range of flows to be managed is the 10-year peak flow as determined from the continuous simulation model.
4) The increase in runoff volume and duration of flows is not as dramatic as Geosyntec has seen on other projects in California. The reason is that Laguna Creek has a relatively high amount of runoff naturally given the soil and geologic character of the watershed (hardpans) and fairly resistant channel materials. Under existing conditions, rainfall is held in the shallow soil layers overlaying hardpans, and is slowly released to the creek via interflow forming broad hydrographs with smaller peak flows. Urbanization creates flashier hydrographs with higher peaks and shorter event durations.
5) Work Curves illustrate changes in the distribution of work done contributing to erosion, deposition and transport. Results for Laguna generally show typical changes observed from urban development; that is the largest increases in work occur in the low to moderate flow ranges and less in the high flow range.
6) The most unstable portion of Laguna Creek (Appendix A) is the upper segment of Reach 4, which was historically dredged to increase flood conveyance. Investigation into the results indicates that the primary cause of instability and high erosion potentials is *channelization*. Channelization (dredging, deepening and straightening) has increased the capacity of the active channel and disconnected it from its floodplains. The full range of flows are contained within the active channel, increasing the amount of work by as much as 3 times. In this

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[3] The 2 year peak flow should not be computed using a flood management approach, such as a design storm with annual series. The appropriate 2 year peak flow is computed from the continuous simulation using a partial duration series.

reach, excessive shear erosion along the toes of banks and channel incision are observed, in addition to bank slumping.

7) Change in the relative amount of work done is not as large as what Geosyntec has observed on other projects. It is not uncommon to predict Ep values of 5, 10 or even 20 times the pre-developed condition. In the Laguna Creek watershed the highest estimated Ep is 2.3 (at 40% IMP) for the smaller channels receiving stormwater discharges from the Jackson Corridor area; and about 4 for the upper segment of Reach 4 that was historically dredged compounding the effects from hydromodification.

8) Future development will create *Erosion Potentials* (Ep) generally ranging from 1.3 to 4.4 – greater than the threshold reported by Geosyntec for Bay Area streams, as well as the value computed for the small tributary in Reach 4.

9) Hydromodification management strategies will be required for all new and significant re-development projects discharging stormwater to Laguna Creek and its tributaries upstream from Waterman Road.

10) Maximum applied shear stresses do not exceed the *critical* shear stress value listed for duripan/hardpan. So it would appear that hardpan exposed along the creek bed is resistant to the effects of hydromodification. However, other processes, such as changing the creek from ephemeral to perennial and dissolution of the material may be contributing to channel incision, specifically in Reach 3 and possibly elsewhere.

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