Sediment Deposition Relations to Watershed Land Use and Sediment Load Models Using a Reference Stream Approach to Develop Sediment TMDL Numeric Targets for the San Lorenzo River and Central Coast California Streams

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Executive Summary

TMDL targets for sediment can be derived using relatively undisturbed reference streams to set standards. Streams least exposed to riparian road density and catchment human land use, define reference conditions in this study, and these are used to determine impairment by sediment for streams within and adjacent to the San Lorenzo River, and for other streams on both the Pacific and interior valley drainages of the central coast range. Exceedance of the 75th and 90th percentiles of the reference distribution for 7 metrics of stream bed deposition measures were used as criterion levels for defining impaired condition. In addition to using reference conditions to define the natural background, we also employed hydraulic predictions of expected particle size distributions in streams, and sediment load models that simulate conditions in the absence of human disturbance. We observed significant differences in a variety of sediment indicators between reference and test stream groups, and also found that sediment in study streams was related to stream power, land use cover and roads, and was reduced by natural vegetation cover. Minimum deposition levels could be predicted by sediment load models. The results of these studies provide a multi-indicator approach to defining sediment TMDL targets based on percentiles of the reference range conditions where most sediment occurred. Finding sediment in test sites that exceed these levels shows that land use-related erosion can produce sediment impairment. Applications include listing and de-listing of 303(d) streams, and assessment of sediment impairment or attained habitat quality in the San Lorenzo River and other central coast watersheds.

PROJECT BACKGROUND AND OBJECTIVES:

The goal of this project is to provide a comprehensive picture of aquatic health of the San Lorenzo River and its tributaries with respect to sediment loading. This report synthesizes results from local watershed and regional assessments to develop preliminary stream bed sediment targets for the San Lorenzo watershed, and set the foundation for benthic invertebrate indicators of impairment. Determination of acceptable levels of sediment that do not degrade habitat is based here on reference conditions within the watershed and adjacent drainages that provide standards for developing multiple numeric targets of water quality attainment. The initial phase of this project quantified the relationship of watershed land use disturbance to the amount of sediment observed at an array of study sites. Natural background levels of erosion at reference sites were defined on the basis of these sites having minimal exposures to land use disturbances. These references were contrasted with a gradient of test sites exposed to increased levels of disturbance. The final phase of the project, detailed in a separate biological report,, examines the relationship of sediment deposition to benthic invertebrate indicators of ecological integrity as a means of defining measures of attainment of unimpaired stream habitat. These studies are also supplemented with data on the relation of sediment deposition to some keystone species in coastal streams – the large native rainbow trout or steelhead salmon, and invasive crayfish.

The science of fluvial geomorphology has devoted considerable attention to understanding the sources, transport, and distribution of sediments in streams (e.g. Leopold et al. 1964, Knighton 1998, Rosgen 1996, Nash 1994, Trimble and Crosson 2000). The extent to which natural erosion processes and sediment delivery to stream channels are exacerbated by land use disturbances is of concern to water resources regulators not only because of problems such as water quality degradation by turbidity and sediment accumulation in reservoirs, but because excessive deposition impairs aquatic habitat and beneficial life uses protected by the Clean Water Act. The TMDL (total maximum daily load) goal in this context is to define linkages between land surface disturbance and the excessive loading and deposition of sediments, and identify the biological consequences that impair beneficial use for the cold freshwater habitat category (including invertebrate aquatic life).

Some studies have documented how varied levels of cumulative land use and development affects the distribution of sediments along stream courses, showing increases in fine sediment deposition with less forested land cover or conversely with greater urban or agricultural land uses (Wang et al 1997; Sponseller et al. 2001; Roy et al. 2003; Larsen et al. 2009). Many studies of land use on streams have also linked degraded habitat conditions to detrimental biological effects on fisheries and macroinvertebrate communities (Allan 2004). In addition to evaluating effects of land use coverage, the objective of this initial phase project report is to contrast physical habitat quality between reference and test streams, and to model predicted quantities of sediment loading to streams resulting from land use practices that aggravate natural processes of erosion and sediment transport. As the changing flow regime of the river basin may be a contributing factor to changes in the sediment regime over time, we also assess the extent of hydrologic alteration on the San Lorenzo River, based on gauging records from before and after the 1960s-70s when extensive road building and development occurred in this watershed.

Environmental Setting

The San Lorenzo River basin is approximately 350 km^2 in area, covering an elevation range from sea level to near 3,000 ft (1,000 m). Geology is dominated by sedimentary rock in eastern drainages and smaller areas of granitic rock to the west. Average rainfall is nearly 120 cm, falling primarily in winter. With dense redwood forests, the region has a history of logging in late 19th century, low-density rural/recreational development through the first half of the 20th century, followed by rapid increase in population and urbanization over the past 50 years. Increased rates of erosion and sediment production have been attributed mainly to construction and roads (cited in CCRWQCB 2002). A primarily concern has been deteriorating conditions for the support of steelhead and salmon population native to the San Lorenzo watershed (Alley 2007). Despite sediment control measures and stabilized growth and development in the region, assessment of stream bed conditions suggest that habitat conditions have not much improved.

There have been 3 major reports relating to sedimentation in the San Lorenzo River basin in the last 7 years. The "San Lorenzo River Watershed Siltation TMDL" (CCRWQCB 2002) assessed current watershed conditions and sediment sources, proposed potential sediment control solutions, and developed numeric targets and implementation strategies for developing a TMDL. Suggestions include repeat field measurements to gauge change in watershed health according to numeric targets, and identifying major sediment point sources (mainly roads but also other human land uses) and attempting to improve conditions and reduce sediment runoff. The "San Lorenzo Valley Water District Watershed Management Plan, Rev. 1.3" (SLVWD 2007) is similar in nature to the CCRWQCB report. It includes a thorough summary of the physiographic background and human activity in the San Lorenzo River basin, and the goals, objectives, and management strategies of the district. The report is currently an administrative draft, only "Part I: Existing Conditions" has been released to the public. Another report, "2006 Juvenile Steelhead Densities in the San Lorenzo, Soquel, Aptos and Corralitos Watersheds, Santa Cruz Country, California" (Alley 2007) focuses on watershed condition in relation to fish habitat. This work created a network of reach locations within these watersheds, and physical and biological data were collected at these sites on an annual basis. Alley found that stream conditions are generally not improving in the San Lorenzo and continue to be impaired in terms of providing sufficient habitat for a healthy steelhead population. Many of the sites in our study are co-located or are at least in proximity to some of the established monitoring stations used in the Alley study.

<u>Preliminary Studies</u>

In May of 2007, as part of a broader geographic survey of stream sedimentation, 24 streams of the Pacific and interior sides of the Central Coast Range were surveyed, including five streams within the San Lorenzo drainage that formed a preliminary data set. The field methods used and analysis of the complete data set are detailed in a separate report, but reference criteria conform to San Lorenzo streams, and are used here to evaluate between-year variability and examine stream conditions across a larger geographic context. Three of the five sites in 2007 were repeated in 2008 and 2009, and using the techniques described in this report, we compare data for these sites between years, and apply sediment impairment criteria to the sites sampled in 2007.

Table 1. Listing of the 40 study sites (R=reference site, T=test or dose site) used in developing geomorphic and biological indicators for the San Lorenzo River sediment TMDL (last 12 sites listed are in adjacent watersheds). **Sites also surveyed in 2009.

Code & Stream Name (Reference or Test)	Catchment Area (km^2)	Reach Slope (%)	Lat.	Long.	Elev. (m)	Human Land Use	Riparian Road Density (km / km^2)	Alley Site Code	TMDL Listed?
0 San Lorenzo River (T) above city intake**	276.40	0.16%	36.99	-122.03	3	14.71%	4.18	0b	Pathogens
1 San Lorenzo River (T) Paradise park**	274.48	0.65%	37.01	-122.04	8	14.58%	4.15	1	Pathogens
2 San Lorenzo River (T) lower HC park**	264.61	0.22%	37.03	-122.06	63	14.27%	4.10	3	Pathogens
3 San Lorenzo River (T) below HC bridge**	256.22	0.03%	37.04	-122.07	68	14.08%	4.07	4	Pathogens
4 San Lorenzo River (T) below San Lo Way bridge**	181.31	0.30%	37.06	-122.08	73	11.41%	3.74	6	Pathogens
5 San Lorenzo River (T) above Hwy 9**	149.96	1.36%	37.09	-122.09	90	9.82%	3.76	7	Pathogens
6 San Lorenzo River (T) above E.Lomond bridge**	135.34	1.52%	37.13	-122.12	120	9.29%	3.54	9	Pathogens
7 San Lorenzo River (R) above Brimblecom**	52.22	0.78%	37.14	-122.13	156	6.69%	2.52	10	Pathogens
8 San Lorenzo River (R) lower Castle Rock SP**	20.44	1.16%	37.20	-122.15	182	7.25%	1.82	12a	Pathogens
9 Zayante Creek (T) above RR bridge**	70.10	1.12%	37.05	-122.06	71	19.25%	4.86	13a	Sediment
10 Zayante Creek (T) above Quail Hollow Rd	43.26	0.09%	37.07	-122.06	79	15.77%	5.07	13c	Sediment
11 Lompico Creek (T)	7.15	1.29%	37.08	-122.05	108	21.44%	4.36	n/a	Pathogens
12 Zayante Creek (T) below Zayante market bridge	29.12	0.97%	37.09	-122.05	108	8.68%	4.21	13d	Sediment
13 Bean Creek (T) at Locatelli Rd**	25.22	0.38%	37.05	-122.05	92	23.37%	4.36	14a	Sediment
14 Bean Creek (T) above Morgan Run Rd**	10.02	0.70%	37.07	-122.02	143	15.03%	5.05	n/a	Sediment
15 Love Creek (T)	7.93	0.91%	37.09	-122.09	90	14.22%	4.01	n/a	Sediment
16 Fall Creek (R) **	12.78	1.73%	37.05	-122.08	78	9.15%	1.55	15	Sediment
17 Jamison Creek (R)	4.35	1.68%	37.15	-122.16	231	5.00%	2.14	n/a	No
18 Boulder Creek (T) below Hwy 9**	29.71	1.06%	37.13	-122.12	133	10.10%	3.72	17a	Sediment
19 Boulder Creek (R) Hwy 236 marker 4.0	13.00	0.55%	37.16	-122.16	243	10.47%	2.98	n/a	Sediment
20 Kings Creek (R) **	20.04	1.39%	37.16	-122.12	157	2.75%	1.87	19a	Sediment
21 Bear Creek (T) Eurella**	41.97	0.52%	37.13	-122.11	140	10.64%	3.67	18a	Sediment
22 Bear Creek (R) above treatment plant**	38.93	0.69%	37.14	-122.09	149	10.03%	3.15	18b	Sediment
23 Newell Creek (T)	4.07	0.97%	37.09	-122.08	83	27.56%	5.15	16	Sediment
24 Carbonera Creek (T) **	17.84	0.32%	37.00	-122.02	17	51.02%	5.27	20b	Pathogens
25 Branciforte Creek (T) Delaveaga park**	20.67	0.77%	37.00	-122.00	27	16.49%	4.25	21a	Sediment
26 Branciforte Creek (T) below Shady Brook bridge	10.02	1.32%	37.03	-121.99	53	12.13%	3.42	21b	Sediment
27 Shingle Mill Creek (T)	1.72	3.14%	37.04	-122.07	70	27.77%	6.26	n/a	No

External Watersheds – Table 1 continued

Stream Name (Ref or Test)	Catchment Area (km^2)	Reach Slope (%)	Lat.	Long.	Elev. (m)	Human Land Use	Riparian Road Density (km / km^2)	Alley Site Code	TMDL Listed?
28 Aptos Creek (R) **	28.66	1.80%	36.98	-121.91	10	3.55%	0.75	3*	Sed + Path
29 Waddell Creek (R)	61.70	0.72%	37.11	-122.27	0	3.67%	1.14	n/a	No
30 W. Waddell Creek (R)	24.69	0.70%	37.14	-122.27	25	1.86%	0.44	n/a	No
31 E. Waddell Creek (R) above confluence	30.72	0.90%	37.13	-122.27	25	4.48%	1.55	n/a	No
32 E. Waddell Creek (R) above treatment plant	26.66	1.54%	37.16	-122.23	51	4.64%	1.45	n/a	No
33 Little Creek (R)	5.10	5.17%	37.06	-122.23	11	0.85%	0.45	n/a	No
34 Scott Creek (R) upper tributary	23.00	0.32%	37.08	-122.25	22	2.31%	0.68	n/a	No
35 Scott Creek (R) below Little Creek	71.75	0.53%	37.06	-122.23	7	1.71%	0.47	n/a	No
36 Pescadero Creek (R) above Cloverdale bridge	139.92	0.47%	37.25	-122.37	6	6.63%	2.34	n/a	Sediment
37 Pescadero Creek (R) at Oakland YMCA	101.32	0.77%	37.28	-122.28	61	5.39%	1.91	n/a	Sediment
38 Pescadero Creek (R) below Sequoia trail	75.94	0.64%	37.25	-122.22	104	5.62%	1.98	n/a	Sediment
39 Peters Creek (R)	25.47	1.06%	37.26	-122.22	112	8.59%	2.91	n/a	No

Table 1. Continued – Central Coast Streams used in combination with San Lorenzo studies to expand geographic coverage.

Code Stream Name	Site Name	GPS Lat	GPS Long	Slope (%)	Elev (m)	Stream Order	Area (km)	Roadedness (km/sqkm)	% Human Land Use	Reference or Test
000 Big Sur River	Coyote Flat	36.28084	121.83337	0.27	13	3	146.323	0.72	1.7	Test*
001 Kings Cr	County Land	37.16	122.12448	0.58	166	3	20.1339	1.87	2.8	Reference
002 San Lorenzo R	Upper Camp Campbell	37.16358	122.13559	0.29	166	3	30.0276	2.59	8.7	Reference
003 San Lorenzo R	Cowell Park - below RR bridge	37.03078	122.05637	0.19	64	4	287.644	3.85	13.3	Test
004 Bear Cr	Scout Camp	37.13113	122.1049	0.85	154	3	39.1257	3.67	10.2	Test
005 Soquel Cr	Upper	37.07835	121.94168	0.47	51	3	83.4642	2.43	10.0	Reference
006 Zayante Cr	Above Graham Hill Bridge	37.0499	122.06515	0.61	73	3	70.4259	4.86	19.3	Test
007 Scott Cr	Swanton Ranch - CalPoly	37.04361	122.22637	0.06	4	3	77.3532	0.49	1.9	Test*
008 Stevens Cr	Above Reservoir	37.28111	122.07458	1.67	172	3	36.9522	1.86	5.9	Reference
009 Soquel Cr	Lower	36.97832	121.95666	0.23	9	3	107.279	2.83	15.1	Test
010 Aptos Cr	Below Valencia Confluence	36.97499	121.90204	0.29	10	3	63.6867	2.53	19.1	Test
011 Carmel R	Bluff Camp	36.36161	121.65597	1.52	378	3	87.6195	0.06	0.1	Reference
012 Corralitos Cr	Above Hames	36.99028	121.80366	1.03	79	3	56.2302	2.65	19.8	Test
013 Arroyo Seco R	Above Green Bridge	36.28072	121.32317	0.56	114	4	628.546	0.76	2.2	Test*
014 Arroyo Seco R	Above day use area	36.23549	121.48767	0.70	250	4	285.694	0.51	0.8	Reference
015 Tassajara Cr	Horse Pasture trail crossing	36.21855	121.51468	1.60	318	3	69.7122	0.59	0.6	Reference
016 Waddell Cr	Above Alder Camp	37.11528	122.26983	0.17	13	4	62.0289	1.14	3.6	Reference
017 San Antonio R	Above Interlake Bridge	35.89391	121.09031	0.22	267	3	559.572	1.93	7.0	Reference
018 Nacimiento Cr	Below Campground	36.003	121.38885	1.06	475	2	22.518	1.17	1.7	Reference
019 Sespe Cr	Lion Campground	34.56228	119.16647	0.94	925	4	221.383	0.78	1.9	Reference
020 Sisquoc R	Above Dam	34.84222	120.1663	0.34	195	3	731.027	0.15	0.4	Reference
021 Salinas R	Above Pozo CDF Station	35.29372	120.38835	0.28	425	3	125.605	1.17	1.4	Reference
022 Santa Rosa Cr	Behind High School	35.56669	121.06738	0.66	25	3	56.4444	1.82	6.7	Test*
023 San Simeon Cr	Above Fence	35.61448	121.07036	1.73	48	3	34.2216	1.26	1.6	Reference

*Sites that met reference criteria but were excluded because of local disturbance factors, so were classified as test sites. Arroyo Seco above green bridge excluded as a large gravel quarry exists upstream, Scott Crk excluded due to local agriculture and tidal influence, lower Big Sur River excluded because of historic mudflows and channel dredging/clearing after the Marble Cone fire and winter storm surges of sediment and debris, and Santa Rosa Creek excluded due to development within the reach.

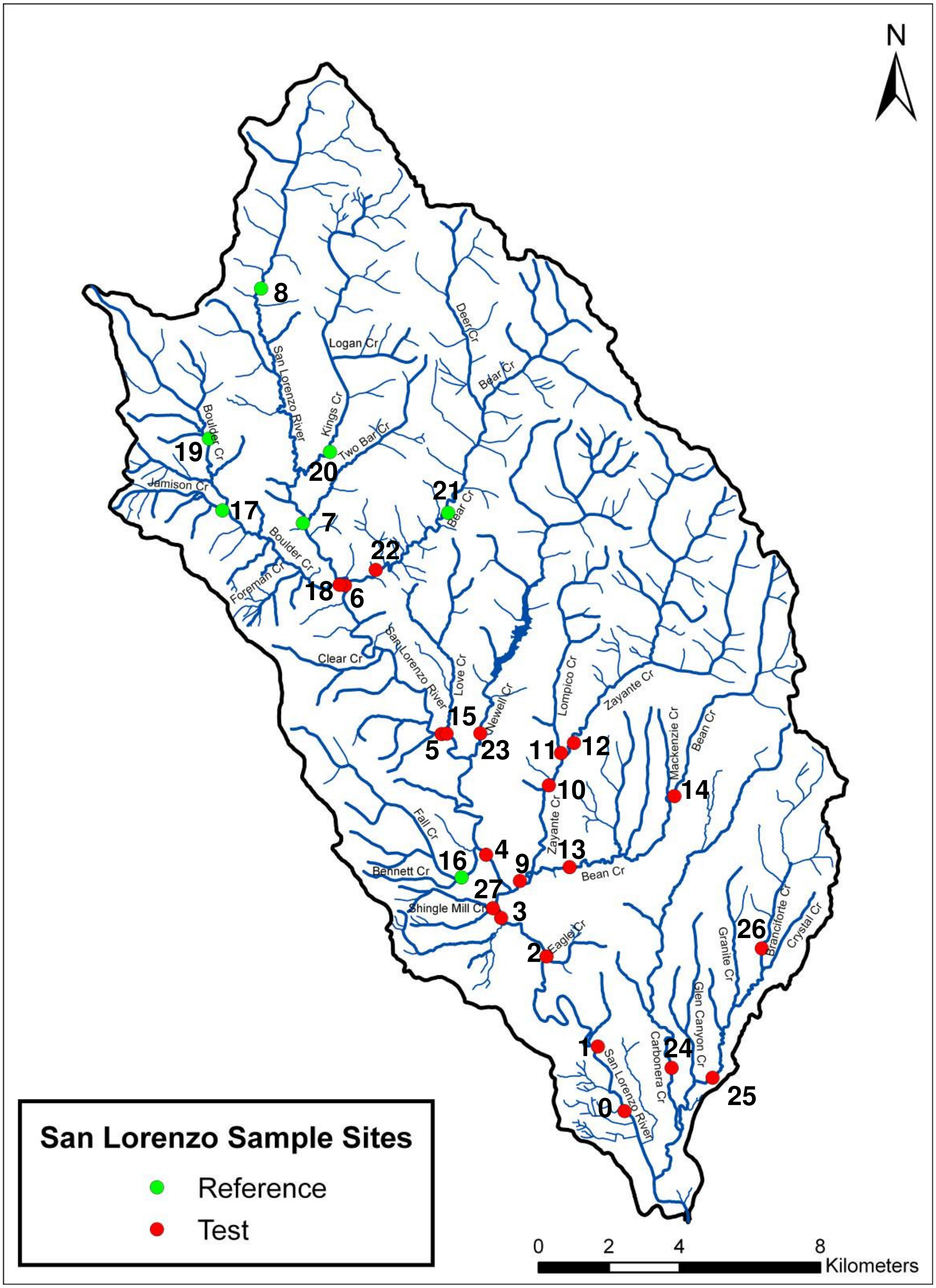

Figure 1. San Lorenzo River watershed and bioassessment monitoring stations for sediment TMDL development (2008 & 2009). Reference selection based on primary screen of watersheds with <10% human land use, and secondary on buffer road density <3 km/km^2 (see text). Site numbers correspond to the code listings in Table 1.

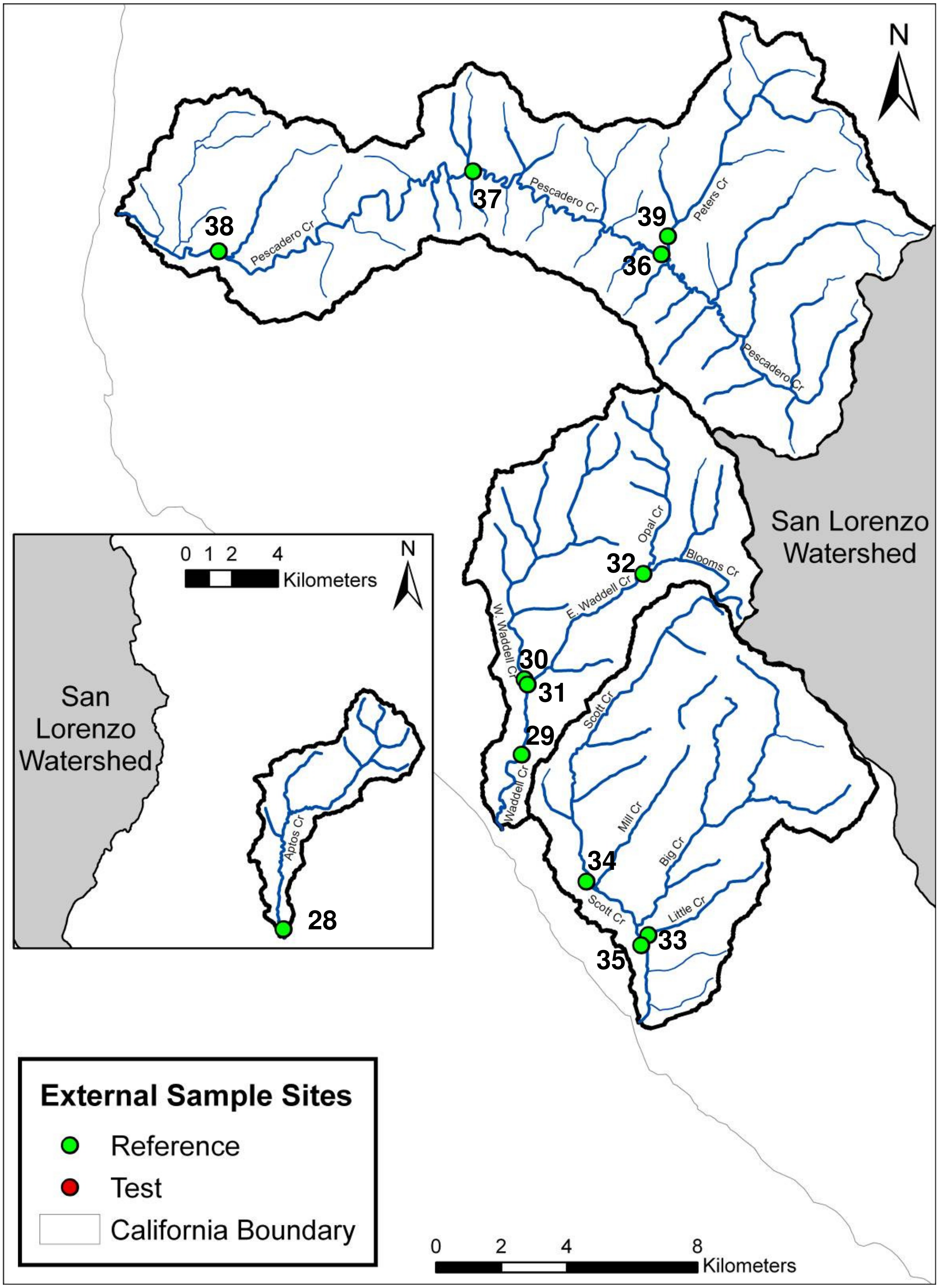

Figure 2. External watershed study sites for the San Lorenzo River regional assessment (2008 & 2009). Includes Aptos, Scott, Waddell, and Pescadero Creeks (gray area the boundary of the San Lorenzo). Site numbers correspond to the code listings in Table 1.

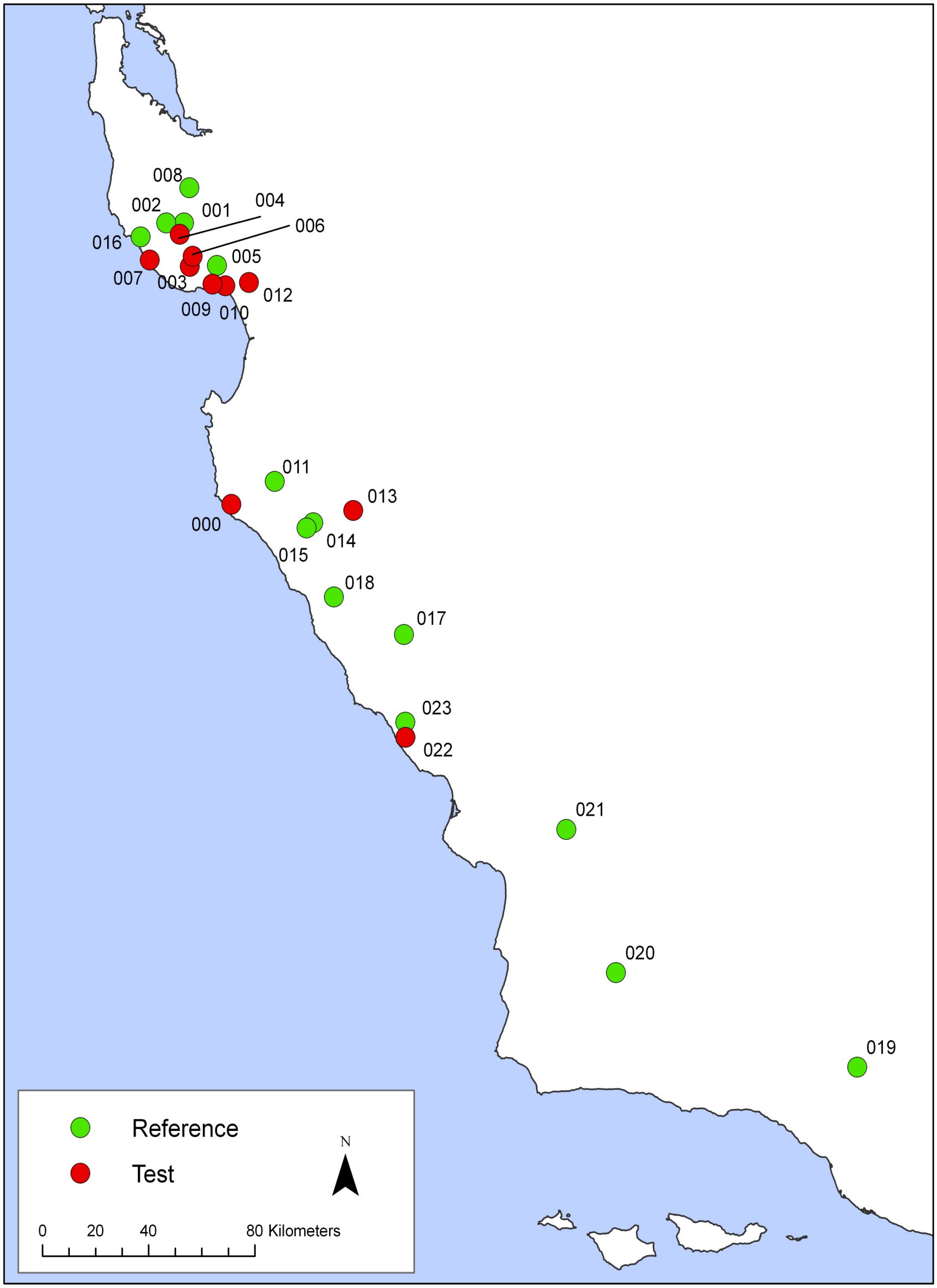

Figure 3. Sites surveyed throughout the Central Coast Region during May 2007. Code numbers correspond to stream name listing in Table 1.

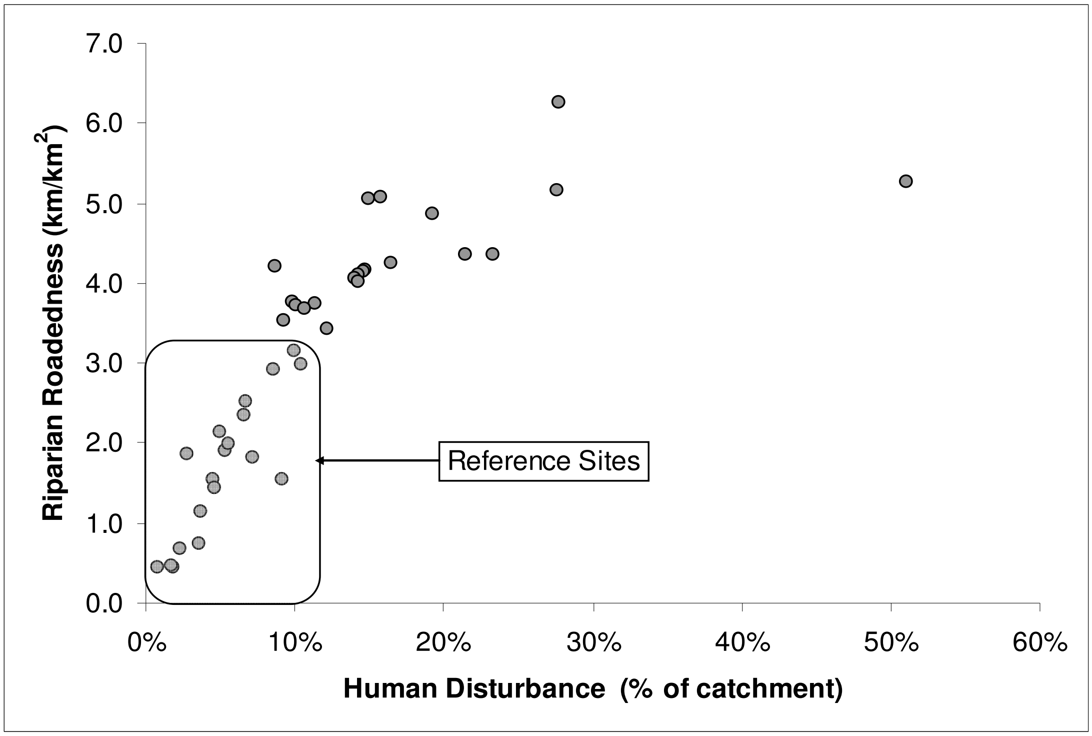

Figure 4. Partitioning of reference and test sites for SanLorenzo studies 2008-2009, based on discontinuity in plot of human disturbance measures. References represents least-disturbed state for this population of study sites (≤10% human influence, and ≤3 km /km^2 roads in riparian area; some marginal exceptions).

<u>Repeat Surveys and Combination with other Central Coast Region Streams</u>

After conducting surveys of the 40 stream sites studied in 2008, repeat sampling was conducted at 20 of these sites in 2009, all within the target San Lorenzo watershed (except Aptos Creek). In order to expand the application of these data to the central coast region (San Francisco to Santa Barbara), the 60 surveys from the San Lorenzo and adjacent watersheds were combined with data collected in 2007 from 24 streams throughout the region. In addition to expanding the geographic scope of the analysis, combining data also provides a larger reference site sample size that improves the accuracy of representing the unimpaired condition for defining sediment criteria.

METHODS AND DATA ANALYSIS

Overview of Study Design:

We selected 40 research sites, consisting of 50-m length reaches with mixed flow-depth features present in each, situated in the San Lorenzo River watershed and in four adjacent watersheds used as reference comparisons. San Lorenzo stations were located at or near 28 existing sample sites used to document fish habitat (Alley 2007), covering nearly all tributaries and most of the main stem river (Table 1 and Figure 1). In addition, 12 sites in separate watersheds (Pescadero Creek, Scott Creek, Waddell Creek, and Aptos

Creek) were surveyed to document reference conditions in less disturbed landscapes (Figure 2). The group of sites surveys across the central coast region are shown in Figure 3 and listed in Table 1 (continued portion). The partitioning of stream segments into reference and test groups was done by considering the exposure to human-related sources of sediment input (defining reference in the sense of Least-Disturbed Condition or LDC, Stoddard et al. 2006). As an initial screen, GIS analysis of human land use (HLU) at or below 10% partitioned sites into a low exposure group, and a secondary screen of roadedness within a 100 m stream zone buffer of ≤3 km/km^2 further minimizes the road disturbance effect within streams with less than 10% HLU upstream. All of the external watershed sites (Pescadero, Waddell, Scott, Aptos) conform to this reference standard, and 7 of 28 within the San Lorenzo. This partitions a total of 19 reference and 21 test sites (2008 data set). These thresholds were selected at an inflection in the distribution of sites (Figure 4), and to represent the lowest levels of disturbance within the data set (Stoddard et al 2006), but which covered a similar representative range of physiography to test sites. Test sites covered a moderate to high range of potential exposure to erosion and sediment from land use disturbances. With the repeat surveys of 2009 at 6 of the San Lorenzo reference sites, and 14 references in the 2007 central coast surveys, there were a total of 39 references and 45 tests in the full data set.

GIS Methodology

I. Analysis Scales

GIS analysis for the San Lorenzo TMDL project was conducted at three nested spatial scales. This was done to capture the importance of spatial proximity of landscape disturbances to sampling location. The usefulness of analyzing hierarchical nesting of watershed spatial scales is reviewed in Allan (2004). Our 3 spatial scales consisted of:

- **Catchment:** the entire watershed area upstream from the sample point, taken from Digital Elevation Model (DEM) based delineations provided by the National Hydrographic Dataset (NHD). Metadata for NHD can be found here.
- **Riparian:** a buffer of 100 meters on both sides of all stream segments upstream from the sample point, for a total buffer width of 200 meters. Stream network data was taken from NHD.
- **Reach:** the riparian buffer zone within 1 kilometer upstream of the sample site.

II. Land Use, Land Cover, and Environmental Features

Population Density - Development Footprint

The development footprint is a measure of population density created by the California Department of Forestry and Fire Protection (FRAP). This layer is a hybrid using both U.S. Census Bureau and NLCD data in an attempt to correctly estimate population density in areas where either layer is thought to be inaccurate. The layer assigns pixels to 1 of 4 classes of population density based upon a set of rules that interpret the two source datasets. The output data is the mean value of the population class rankings at each spatial scale. Metadata for the development footprint layer can be found here.

Roadedness

Roadedness was calculated using the Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset produced by the U.S. Census Bureau. This layer was clipped at all three spatial scales, and the total road length at each scale was divided by the area. Output data is in km / km^2. Metadata for TIGER can be found here.

Road Crossings

Road Crossings were calculated using TIGER road data and the NHD stream network at both stream scales. Additionally, we looked at the subset of streams that are classified by NHD as being perennial. The number of intersections was divided by the upstream channel length, and the final output is a density measurement of road crossings / km.

Land Cover

The National Land Cover Dataset 2001 (NLCD), created by the Multi-Resolution Land Characteristics Consortium (MRLC), was used to analyze the percentage of landscape activity for each site at all 3 spatial scales. The dataset was reclassified to broad categories to look at percentages of human land use, urbanization, and natural vegetation. The criteria for lumping categories together can be found in Appendix A. Metadata for the NLCD can be found here.

Imperviousness

Imperviousness is a measure of the inability of landscapes to absorb water, and is calculated from the MRLC Imperviousness layer. This layer is derived from the same source imagery as the NLCD, but uses a different algorithm and method for assigning pixels to a class of imperviousness (does not simply reassign NLCD codes). Output data is the percentage of an area that is deemed impervious. Metadata for the imperviousness layer can be found here.

Land Use Land Cover

The Multi-source Land Cover Dataset from FRAP was used to augment our NLCD analysis. This dataset has poorer resolution than NLCD, but provides more detailed information on the current use (not just the cover) and the ownership data. We re-calculated similar measures as for the NLCD (percent urban, percent forested) and also calculated the percent of land that was privately-owned for each site. Metadata for the Multi-source Land Cover Dataset can be found here.

Soil Detachability

Soil Detachability (K-factor) was calculated from the Soil Survey Geographic (SSURGO) Database, created by the Natural Resources Conservation Service (NRCS). K-factor is a measure of a soil layer resistance to erosion, and the value was spatially averaged over each spatial scale. Metadata for SSURGO can be found here.

Landslides

Digitized landslide data from the United States Geological Survey (USGS) was used to calculate the areal percentage of landslides within the 3 spatial scales. Metadata for the landslide data can be found here.

Hillslope

Hillslope was calculated using the DEM from the NHD. Percent slope is calculated for each pixel, and the final output is the mean value of percent slope for each spatial scale.

Channel Relief Ratio

Channel Relief Ratio was calculated by extracting the main upstream stem for each site from the NHD. The total distance and the maximum and minimum elevation values for each stem were calculated using GIS, and the Channel Relief Ratio is the Total Distance / (Maximum Elevation – Minimum Elevation).

III. Model Calculations

1. AGWA2

The Automated Geospatial Watershed Assessment Version 2 tool (AGWA2) is an interface for performing spatially-distributed hydrologic models, and was developed by the U.S. Environmental Protection Agency (EPA) and U.S. Department of Agriculture (USDA). AGWA2 implements two existing models, the Soil and Water Assessment Tool (SWAT) and the Kinematic Runoff and Erosion Tool (KINEROS2). KINEROS2 is only appropriate for single storm events that occur in smaller watersheds (<100 km^2), while SWAT is a long-term yield model without watershed size limits, and was the appropriate model for this project. SWAT calculates a variety of output factors for each watershed, including total sediment yield and average sedimentation rate. Sediment calculations are made using the Modified Universal Soil Loss Equation (MUSLE). The load units are in metric tons (Mg) per year.

Required Inputs

- Digital Elevation Model (DEM): the DEM determines drainage delineation, runoff direction and slope length, and slope steepness. We used 30-meter DEM coverage from the NHD.
- Land Cover: landscape cover determines the ability of each pixel to produce and/or capture water and sediment. We used the 1992 NLCD because AGWA is not calibrated for the more current 2001 NLCD.
- Soils: soil data determines the erodibility and permeability of each pixel. We used the U.S. General Soil Map (STATSGO2) database from the USDA.
- Precipitation: precipitation determines runoff and transmission of water and sediment. We used the Rocky Mountain Climate Generator from the USDA Forest Service, which estimates daily precipitation values interpolated from weather stations and from the Parameter-elevation Regressions on Independent Slopes Model (PRISM).

Model Notes

The model was designed to compare spatially-proximate watersheds, typically over a time span (before-after type contrasts). All 40 sites are proximate, so a single climate was used for the study area. AGWA2 does not specifically account for road sediment production, except for roads that are significant enough to appear in the NLCD. Since road sediment production is a main source of anthropogenic sediment in forested watersheds, we overlaid the NLCD data with road data from the TIGER dataset. We ran AGWA2 with both the original NLCD and the road-enhanced version. During analysis, the estimated sediment yield was distributed throughout the stream network by dividing each site by the upstream length. This assumes that sediment is distributed throughout the system, rather than located entirely near the pour point of the watershed.

Model Documentation

Burns, I.S., S.N. Scott, L.R. Levick, D.J. Semmens, S.N. Miller, M. Hernandez, D.C. Goodrich, and W.G. Kepner, 2007. Automated Geospatial Watershed Assessment 2.0 (AGWA 2.0) – A GIS-Based Hydrologic Modeling Tool: Documentation and User Manual; U.S. Department of Agriculture, Agricultural Research Service. Available at http://www.tucson.ars.ag.gov/agwa/.

2. FOREST

The FORest Erosion Simulation Tools (FOREST) model calculates changes in sediment regime due to natural background and anthropomorphic disturbances, and was developed by Lee MacDonald and Sam Litschert at Colorado State University. The model attempts to predict the cumulative effects of watershed disturbances over time and space in terms of both sediment production and sediment delivery. The output for FOREST is a yearly sedimentation estimate, and the individual sediment sources can be parsed out from one another. The load units are in metric tons (Mg) per year. “Natural” sediment production was assumed to be equivalent across all landscape types and was modeled simply as a fixed amount of 0.1 Mg/ha/yr and so scales with area.

Required Inputs

- Digital Elevation Model: the DEM determines runoff network and slope steepness. We used 30-meter DEM coverage from the NHD.
- Streams: the streams layer provides a network for analyzing the amount of yearly sediment that is delivered to streams. We used the hydrography layer from NHD.
- Roads: the roads layer is used to estimate yearly road sediment production, which is adjusted for road slope. We used the TIGER dataset.
- Fires: the fire layer is used to estimate sediment impact and recovery from a forest fire. No fires of record occurred recently in the study area, so this impact was not included.
- Logging: the logging layer is used to estimate sediment impact and recovery from logging activities. Logging was not used as a model input because specific harvesting data was not available from the private sector.
- Climate: the climate file is used to estimate annual sediment delivery for each pixel based on disturbance, soil type, and slope. FOREST requires the creation of climate files using the Water Erosion Prediction Project (WEPP) interface created by the National Soil Erosion Research Laboratory (NSERL), a unit of the U.S. Department of Agriculture. The WEPP interface assigned an expected sediment response for each pixel configuration based on a weather generation system and regional climate data.
- Soils: soil data is used to separate each landscape pixel into either clay-silt loam or sandy loam category. We used the SSURGO database, and the K-Factor (soil detachability) as a cutoff for the two categories, based on empirical evidence.

Model Notes

The model was designed to compare spatially-proximate watersheds, typically over a time span (pre-logging or fire versus post, e.g.). All 40 sites are close, so a single climate was used for the study area. Because ”natural” sediment production was a fixed proportion of catchment area, delivery simply models the relative effects of slope, landscape vegetation cover, and soils in downslope transport of this area-defined load. In addition to this “natural” hillslope sediment delivery, road-derived sediment production was determined from the summed products of road segment lengths x (road gradient)^2 x fixed coefficient (Luce and Black 1999). To equalized different source areas, the estimated sediment yield was distributed throughout the stream network by dividing load outputs by the total upstream perennial channel length. This assumes that sediment is distributed over the network, rather than located entirely at the watershed pour point.

Model Documentation
FOREST documentation and a user's manual are available at http://welcome.warnercnr.colostate.edu/~leemac/model.htm.

3. RUSLE

The Revised Universal Soil Loss Equation (RUSLE) model is a standard method for estimating erosion potential that was created for agricultural areas but has been revised for use in forested watersheds. We used a set of computational GIS scripts developed by Rick Van Remortel of Lockheed Martin Environmental Services to run RUSLE analyses for our study areas. These scripts also included Spatially Explicit Delivery Model (SEDMOD) estimates for sediment delivery, based on the results from the RUSLE analysis. The load units are in metric tons (Mg) per catchment area per year.

Required Inputs

- Digital Elevation Model: the DEM determines runoff network and slope steepness. We used 30-meter DEM coverage from the NHD.
- Streams: the streams layer provides a network for analyzing the amount of yearly sediment that is delivered to streams. We used the NHD hydrography layer.
- Land Cover: landscape cover determines the ability of each pixel to produce and/or capture water and sediment. We used the NLCD, 1992 version, provided by the MRLC. 1992 is the most recent version acceptable for the RUSLE scripts.
- Soils: soil data is used to create an entire matrix of physical soil properties for each watershed. RUSLE requires using the STATSGO2 database.
- Climate: the climate files were provided by RUSLE for the watershed area, and were used to estimate rainfall intensity.

Model Notes
Many studies have been critical of the use of "slope length" as a dominant erosion factor in forested watersheds of low disturbance, and suggest that RUSLE, despite being modified from its agricultural origins, still performs poorly in forested mountain landscapes. The two main outputs of RUSLE are the estimated annual erosion and delivery rates using RUSLE and SEDMOD models. The scripts also provided a great deal of information about the physical landscape and soil characteristics.

Model Documentation
This particular model is unpublished and was received from the programmer. General information on RUSLE and its history can be found here:
http://www.ars.usda.gov/Research/docs.htm?docid=5971

4. CCRWQCB Method

The CCRWQCB method refers to the analysis used in the CCRWQCB 2002 report, which is based upon previous erosion estimates measured in the San Lorenzo River basin. This is a non-distributed model; sedimentation is estimated by summing landscape parameters for entire watersheds rather than on a pixel-by-pixel basin.

Required Inputs

- Digital Elevation Model: the DEM determines road steepness. We used 30-meter DEM coverage from the NHD.
- Streams: the streams layer is used to estimate road sediment delivery based on stream proximity. We used the hydrography layer from the NHD.

- Landslides: the landslides layer is used to estimate mass wasting sediment and delivery. We used digitized landslide data from the USGS.
- Geology: geology is used to estimate channel erosion. We did not use geology for reasons discussed below.
- Timber Harvest Plans: THP's are used to assign differing rates of erosion to land and road types. We did not use THP's for reasons discussed below.

Model Notes
Previously, estimates on channel erosion were developed by taking one small study and extrapolating the results over the entire San Lorenzo River basin, with the only factor being the presence/absence of Santa Margarita Sandstone or alluvium. Since our study area included external watersheds and was even larger than the SLR basin, this extrapolation was deemed to be even less reliable. Therefore, we used the constant that was estimated for "Other Geologic Units" in the CCRWQCB report for estimating channel erosion. Timber Harvest Plans are used in the model to apply slightly different estimates for road and land erosion. Most of the logging in our study area is done on private lands, and we could not gain access to GIS data for logging activities that was current enough and/or covered our entire spatial study area. Therefore, we used the constant that was estimated for "Other lands" in the CCRWQCB report for estimating road and landscape erosion. As we calculated it, the CCRWQCB method is the sum of annual erosion from roads, the landscape, landslides, and channel erosion.

Model Documentation
The specific parameters for the model are laid out in detail in Appendix B of the San Lorenzo River Watershed Siltation TMDL (CCRWQCB 2002).

Index of Hydrologic Alteration (IHA) Methodology

Measures of hydrologic alteration in the San Lorenzo River basin were analyzed by using the software package Indicators of Hydrologic Alternation (IHA) developed by The Nature Conservancy (TNC 2007). IHA analyzes temporal trends in stream gage data, and looks for key components that impact biological health and affect stream geomorphic processes. The U.S. Geological Survey maintains a stream gage on the main stem of the San Lorenzo River at Big Trees, which is located near the town of Felton. This gage has a continuous period of record from October 1st, 1936 to the present day.

The most common use of IHA has been comparing watershed alteration after a significant, permanent impact (usually dam installation or removal). Since extensive changes in the San Lorenzo River basin occurred during the 1960s through the 1970s (population growth and land use development), we instead chose to compare a period of time from the early part of the record to the latest part (before/after 60s-70s), as suggested in the software. This method sets thresholds for expected ranges of variation based on the earlier period, and computes the deviation from those expected values for the later period. Our application of IHA improves understanding of how changes in flow regime after land development and population expansion may alter sediment flux dynamics. Comparing a 25-year periods before and after the time of greatest population expansion and development in the basin (1937-62 vs. 1982-2007), we computed an Index of Hydrologic Alteration (Richter et al. 1996).

Physical Habitat Surveys

Surveys of the physical habitat of the 50-meter reach length of study sites emphasized measures of sediment deposition taken concurrent with benthic invertebrate samples in order to link both habitat and biological response variables to the land use and sediment loading of each catchment compared. We documented sedimentation for use in setting TMDL targets in the following ways (illustrated in Figure 5):

1. The substrate particle size distribution (intermediate of sieve-axis diameter) within the section was measured by a set of ten 10-point transects taken over the entire reach at 5 m intervals. These samples permit the calculation of (a) deposited percent fines (F), sand (S) and gravel (G) on the stream bed, and (b) D-50 particle size and cumulative particle distributions. These provide standard cover estimates of substrate composition and an important predictor of impaired condition of benthic invertebrate communities in streams.

2. Grid-frame counts taken at 20 locations, alternating combinations of right-center-left positions (1 at top and bottom reach boundaries and 2 at 9 transects inside the reach), were used to generate high-resolution data on fine particle distribution within the reach segment. Separate counts of fine and sand particles were made at the intersecting grid line points of the frame (Figure 6) for a total of 500 point-counts in each reach. Eleven of these grids corresponded to the macroinvertebrate samples locales, and the other 9 filled the offset sampling array (Figure 5).

3. Cobble substrate embeddedness (n=25 samples per reach) was estimated as the volume of rocks of cobble size (64-250 mm) that were buried by fines and/or sand. This provides a direct measure of the extent to which interstitial microhabitat spaces are occluded by deposited fine and sand material.

4. Stream bed facies maps showing patch distributions over riffles and pools for the 50 m reach. Sediment patches and pool areas covered by fines can be mapped with simple grid sketches to estimate the composition and dynamics of stream bed particles that occur in more-or-less uniform clusters. Gravel facies may also be used as an indicator of potential area available for salmonid spawning (redds).

In addition to these sediment deposition measures, we also measured the depth profiles across all transects, channel slope at 0-25 and 25-50 meter segments, bankfull channel width, and temperature, conductivity and pH (Oakton con10 meter). Photos were taken from the channel center at 0 m upstream, 50 m up and down, and 100 m downstream. GPS coordinates were recorded to provide a georeference point for each study reach.

Bankfull estimations from wetted width measurements

At each reach transect we measured the height from the water surface to the bankfull level. Depth of water measurements were taken at equally spaced points across each transect bankfull width. For the wetted locations, the final bankfull depth was simply the water depth plus the bankfull height above water. For the dry locations, we had to make assumptions about the channel profile. For dry locations that were on the edges of the transect, we assumed that the channel elevation profile followed a linear path between the last wetted point and the bankfull elevation. Dry locations that were between wetted points were assumed to be relatively close to the water surface, and we assigned the water surface elevation to these points.

Bedrock along transect

Our study reaches were not bedrock dominated, but there were cases of bedrock measurements along our substrate transects. In these cases the substrate measurement was marked as bedrock, and during database analysis it was given the value of the bankfull width divided by the transect count number (always 10). This insured that a single section of bedrock that was counted and re-counted would not ever add up to have substrate that was wider than the actual channel.

Watershed Coverage

The only drainage within the San Lorenzo watershed that is impounded is Newell Creek, where Loch Lomond is located. As this reservoir may be regarded as a sediment trap, we excluded all area above Loch Lomond from any land use or model analysis. The site below this was therefore examined only in terms of land use disturbance within the catchment draining below the outlet of the reservoir. This upper drainage represents a small area of the overall watershed (about 6 percent), and is mostly undisturbed land (HLU of 1.4% and 95.5% natural vegetation cover) that would have minimal effect in assessment of cumulative impacts.

Methods Used for the Central Coast Region Stream Surveys of 2007

In contrast to the 50 m reaches used in the San Lorenzo surveys, the reach lengths for surveys of central coast streams in May of 2007 were 150-250 meters, depending on stream width (<10 m or > 10 m, respectively). Cross-channel transects of substrate composition were taken for twenty 5-point measures (rather than ten 10-point measures), and the patch-scale grid measures of fines and sand, and facies maps, were not made in 2007. Otherwise, the methods and calculations used were the same.

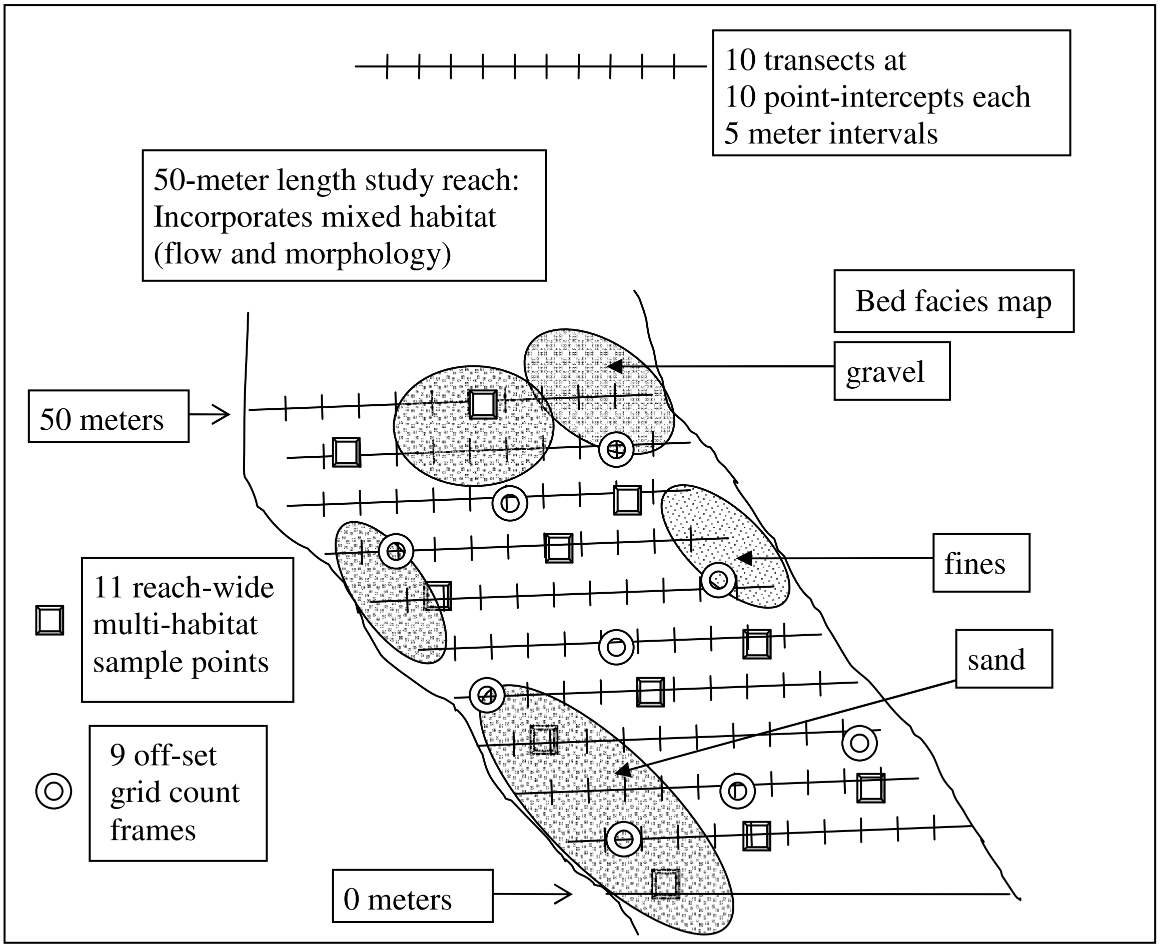

Figure 5. Transects for determination of particle size distribution and embeddedness, bed facies maps, and locations of grid counts of fines/sand (and invertebrate sample points).

Table 2. Selected measures of sediment deposition, predicted and observed responses to erosion disturbance from land use, and p-values for one-tailed Mann-Whitney U-test (non-parametric test) of reference vs. test groups. [** p<0.05, * p<0.10] See text for further detail. [For 2008 surveys]

Variable	Predicted Response	Observed Response	p-value
Pct.FS	+	+	0.006 **
Pct.FSG<8 mm	+	+	0.018 **
Pct.FSG<16 mm	+	+	0.035 **
D50	–	–	0.033 **
Geometric Mean	–	–	0.034 **
Embeddedness	+	+	0.125
Pct.Thalweg FS	+	+	0.022 **
Pct.Grid FS	+	+	0.002 **
Pct.Facies FS	+	+	0.086 *
Relative Bed Stability D50	–	–	0.104
Excess FS	+	+	0.003 **
Excess FSG<8 mm	+	+	0.038 **
Excess FSG<16 mm	+	+	0.015 **

Table 3. Correlations among physical habitat variables measuring sediment deposition and selected channel dimensions. Pearson R^2 values for each relationship. [for 2008 San Lorenzo surveys]

	Transect FS	Transect FSG	Transect d50	Geo Mean	RBS (d50)	Excess FS	Embedd	Thalweg FS	Facies FS	Grid FS	Slope	Bankfull Area	Hydraulic Radius
Transect FS	1	0.79	-0.49	-0.56	-0.47	0.95	0.14	0.45	0.59	0.55	0.00	0.09	0.17
Transect FSG	0.79	1	-0.60	-0.61	-0.45	0.80	0.09	0.28	0.59	0.36	0.00	0.10	0.07
Transect d50	-0.49	-0.60	1	0.88	0.65	-0.49	-0.04	-0.13	-0.29	-0.11	0.00	-0.02	-0.01
Geo Mean	-0.56	-0.61	0.88	1	0.61	-0.55	-0.07	-0.20	-0.31	-0.17	0.00	-0.03	-0.02
RBS (d50)	-0.47	-0.45	0.65	0.61	1	-0.33	-0.03	-0.13	-0.21	-0.08	-0.08	-0.01	-0.04
Excess FS	0.95	0.80	-0.49	-0.55	-0.33	1	0.14	0.45	0.62	0.59	-0.04	0.15	0.18
Embedd	0.14	0.09	-0.04	-0.07	-0.03	0.14	1	0.06	0.12	0.15	0.00	0.00	0.00
Thalweg FS	0.45	0.28	-0.13	-0.20	-0.13	0.45	0.06	1	0.11	0.32	0.00	0.17	0.08
Facies FS	0.59	0.59	-0.29	-0.31	-0.21	0.62	0.12	0.11	1	0.52	-0.01	0.03	0.13
Grid FS	0.55	0.36	-0.11	-0.17	-0.08	0.59	0.15	0.32	0.52	1	-0.03	0.06	0.25
Slope	0.00	0.00	0.00	0.00	-0.08	-0.04	0.00	0.00	-0.01	-0.03	1	-0.16	-0.04
Bankfull Area	0.09	0.10	-0.02	-0.03	-0.01	0.15	0.00	0.17	0.03	0.06	-0.16	1	0.52
Hydraulic Rad.	0.17	0.07	-0.01	-0.02	-0.04	0.18	0.00	0.08	0.13	0.25	-0.04	0.52	1

Transect measures are from 100 point-counts of fines (F) and sand (S) and gravel (G) in this case with gravel less than 16 mm axis width; Geo mean is geometric mean particle size; RBS is relative bed stability; Embedd is embeddedness of cobble (%burial by FS); thalweg is the deepest point on each of the 10 transects and associated FS; facies are the mapped clusters of similar particle groups; grids are the patch-counts of FS from 20 frames; slope is reach gradient; bankfull area is the cross-sectional area defined by bankfull height, and hydraulic radius is cross-sectional area to wetted perimeter across bottom of channel at bankfull. See text for details.

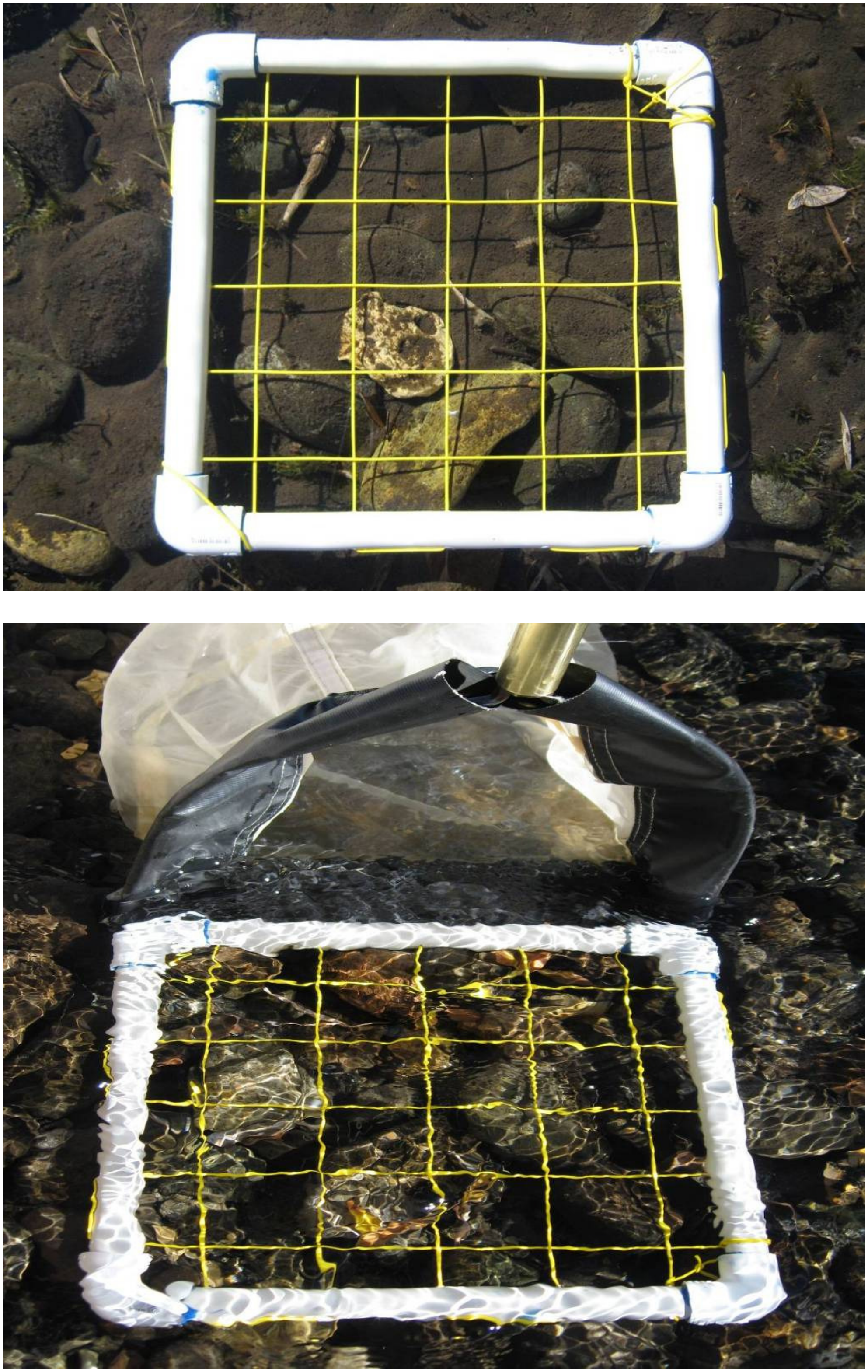

Figure 6. Quadrat grid-frame for particle counting of substrate composition (upper) and with D-frame net positioned for sampling benthic macroinvertebrates (lower).

Fine Sediment Pollution Indicators

We compared our GIS analysis results with instream sediment measures collected during our stream sampling. The first category of measures are standard geomorphic measurements taken during a bankfull pebble count, including percent sands and fines, percent sands, fines, and gravel, D50 median grain size, and embeddedness. The second category is taken from the grid sampling and facies mapping procedures specific to this project, and includes the percent of sands and fines coverage measured at random grid sample sites and the percent of sand and fines visually estimated by facies mapping. A third category, relative bed stability and excess sand and fines, involves comparing the difference between the expected particle size distributions (based on theory of stream hydraulic power effects on particles) and those observed.

Our methodology for calculating Relative Bed Stability (RBS) and excess sediment was taken from the USEPA monitoring protocols (Kaufmann et al 1999). These measures calculate the departure of substrate conditions from what is the expected condition, based on reach slope and geometry. The equation for Relative Bed Stability:

> RBS = $[D_{50}] / [13.7 * R_{bf} * S]$, where D_{50} is the median grain size (mm), R_{bf} is the mean reach hydraulic radius, and S is reach slope.

The calculation of excess fines and sands (FS) was taken from a presentation by the author of the EPA methodology (Kaufmann 2004). We regressed the percent of fines and sands found at our reference sites against the log-10 transformation of the expected median grain size (denominator of the RBS equation) using the reference site data. For the reference sites, the excess FS value is the actual residual (±) from the regression line. For test sites, excess FS is the observed %FS minus expected %FS (Y), that is obtained from the reference regression line equation $Y = m (\log10(13.7 * R_{bf} * S)) + b$, as calculated specific to each test site.

Data Analysis for Reference and Test Comparisons

At the outset of the study, we hypothesized that our measures of sediment deposition in the study reaches would change in predictable ways with land use disturbance and sediment loading (Table 2). Many of the variables exhibited non-normality in distribution, so we applied nonparametric Mann-Whitney U-tests to the comparisons (according to one-tailed tests specified by the expectations). We did not apply Bonferroni corrections to p-values for the multiple comparisons as these had been set out as planned *a priori* hypotheses of the study.

Estimating natural conditions using models

FOREST model sediment delivery was compared between reference streams as an estimate of natural background sediment delivery, to that in disturbed test streams. FOREST also makes independent estimates of road-based contribution to sediment yield (based on road lengths and slopes) from the entire catchment or just the riparian zone. RUSLE and AGWA model outputs were also partitioned into reference and test groups to estimate the average differences that can be attributed to higher levels of land use disturbances.

RESULTS

Land Use Relation to Reach-Scale Sediment Deposition

GIS coverages of human land use (Figure 7), and roads (Figure 8), are an important foundation for contrasting distributions of reference and test sites and how these landscape disruptions may be related to observed sediment deposition. Many interactions are possible among the different landscape and reach habitat variables, so it is necessary to use some representative examples of associations between land use and response measures examined at different scales rather than give an exhaustive presentation of all possible combinations. Some NLCD land covers use overlapping classes (see Appendix A) and so cannot be combined with one another. While closely related (correlations, Table 3), the many measures of sediment deposition that were taken for each reach reflect different aspects of how and where deposits collect. We examined spatial distribution of deposition pattern by collecting data at different scales – at the scale of points (on transects), patch (with 20x20 cm grid frames), and facies (with maps). Each measure represented a larger and coarser scale of area covered by sediment.

Increased human influence land use cover (NLCD classes 21, 22, 23, 24, 81, 82) is associated with increased levels of fine and sand deposition, with reference sites having significantly lesser amounts than test sites (Figure 9 and Table 2). Similar significant differences between reference and test groups exist for many other measures of deposition, at point, patch, and facies map levels of resolution (Table 2). A reversal of this pattern of sedimentation was observed for stream reaches where there was greater coverage of natural vegetation (made up mostly by NLCD forest classes 41, 42, 43; and other vegetation covers 52, 90, 95), with fines and sand declining as cover increases (Figure 10). At the reach scale was the widest range of vegetation cover, and while test sites showed increasing loss of cover as scale was reduced, most references retained high levels of protective cover (and sediment-filtering capacity) even at the local reach scale.

Impervious cover and roads were also associated with increased sedimentation. Among sediment indicators used were embeddedness, a measure of the extent to which pebble and cobble-size substrates are buried by sand and/or fine particles, and percent fines, sand and gravel less than 8 mm size. Increasingly embedded conditions and higher %FSG<8mm were observed as impervious cover or roads increased, though this was less evident at the reach scale (Figures 11 and 12). At the reach scale, most test sites had exceeded 2% impervious cover and few were less than 30% embedded. Populated areas are best quantified according to population density and the cover of private land, and here the relation to the percent cover of fines and sand within the grid-frame patches, and on facies maps again showed increasing sediments at higher levels of population density (development footprint) and private land cover (Figures 13 and 14).

Relation of Sediment Load Model Output to Instream Sediment Deposition

Sediment load estimates from the three erosion models (RUSLE, AGWA, FOREST) produced total annual loads for each sub-catchment. These values were then divided by the upstream channel length over which the load generated could be distributed, and then normalized by an index of stream power at each reach (bankfull area x slope) to account for local forces operating on the modeled load received at the reach segments surveyed. All three models showed predicted load was related to increases in patch-scale fines and sand present at study reaches (Figure 15). Other deposition measures showed similar patterns but are not shown here (refer again to the high correlations among sediment measures in Table 3).

Departure from the Natural Sedimentation Regime

The increase in sediment deposition levels above natural background conditions was evaluated in several ways:

- Comparing sediment distributions between reference versus test sites.
- Models predicting sediment load for natural landscape factors, and that added by considering the effects of land use disturbances (FOREST roads sediment compared to natural hillslope delivery predicted by model, and reference-test contrasts for all model outputs, including AGWA and RUSLE)
- Particle composition based on channel geometry - the particle size (D50) expected based on calculated stream power for a channel relative to that observed (relative bed stability, RBS); and the excess fines and sand present in relation to that in reference streams
- Examining natural factors that could account for high sediment levels (Table 4)

Along with our finding that most of our measurements of sediment deposition showed significant differences ($<p=0.05$) between reference and test site groups (presented in Table 2 with hypothesized expectations), the load models predict sediment delivery rates were on average 2-4 times as high in test than reference streams (Table 5). Modeled loads attributable to roads relative to natural erosion processes provides another estimate of the amount of sediment entering as a pollutant. The percent increase in sediment load from roads above background from the FOREST model showed that if all catchment roads were considered, about half the mean total sediment load of test streams can be accounted to this source (Table 5). AGWA predicts test sites to have a mean load 3X higher than references, but RUSLE shows test sites elevated only about 0.5X higher than reference and the actual load values are much higher than for the other models, and may be large overestimates. Examining the roads sediment load component of FOREST showed that as this increased, so did the cover of fine and sand sediment (Table 5 and Figure 16). AGWA and RUSLE outputs were also correlated with %FS, but not as high as for FOREST roads estimates (Table 5 and Figure 17). Cumulative sediment loading in the San Lorenzo basin has previously been estimated with non-distributed data sources (CCRWQCBB 2002), and we used this for contrast with our distributed models and found a similar relation to FS deposition (Figure 18), showing that above 1000 tons/yr/km^2/spi, there is higher probability of elevated stream bed deposition of above 30% FS (see conclusions showing this is near the criterion level for impairment).

The Log of RBS (the ratio of observed median particle size D50 to that expected) indicates smaller-than expected particles (net sediment accumulation) as values become more negative, and equilibrium sediment flux for values centered on zero (±0.5). Plotted against the excess fines and sand calculation, the regression line for test sites showed more negative Log RBS values and at higher excess of FS compared to the reference regression line (Figure 19). This shows test site disturbances are associated with accumulating sediment deposits compared to reference sites.

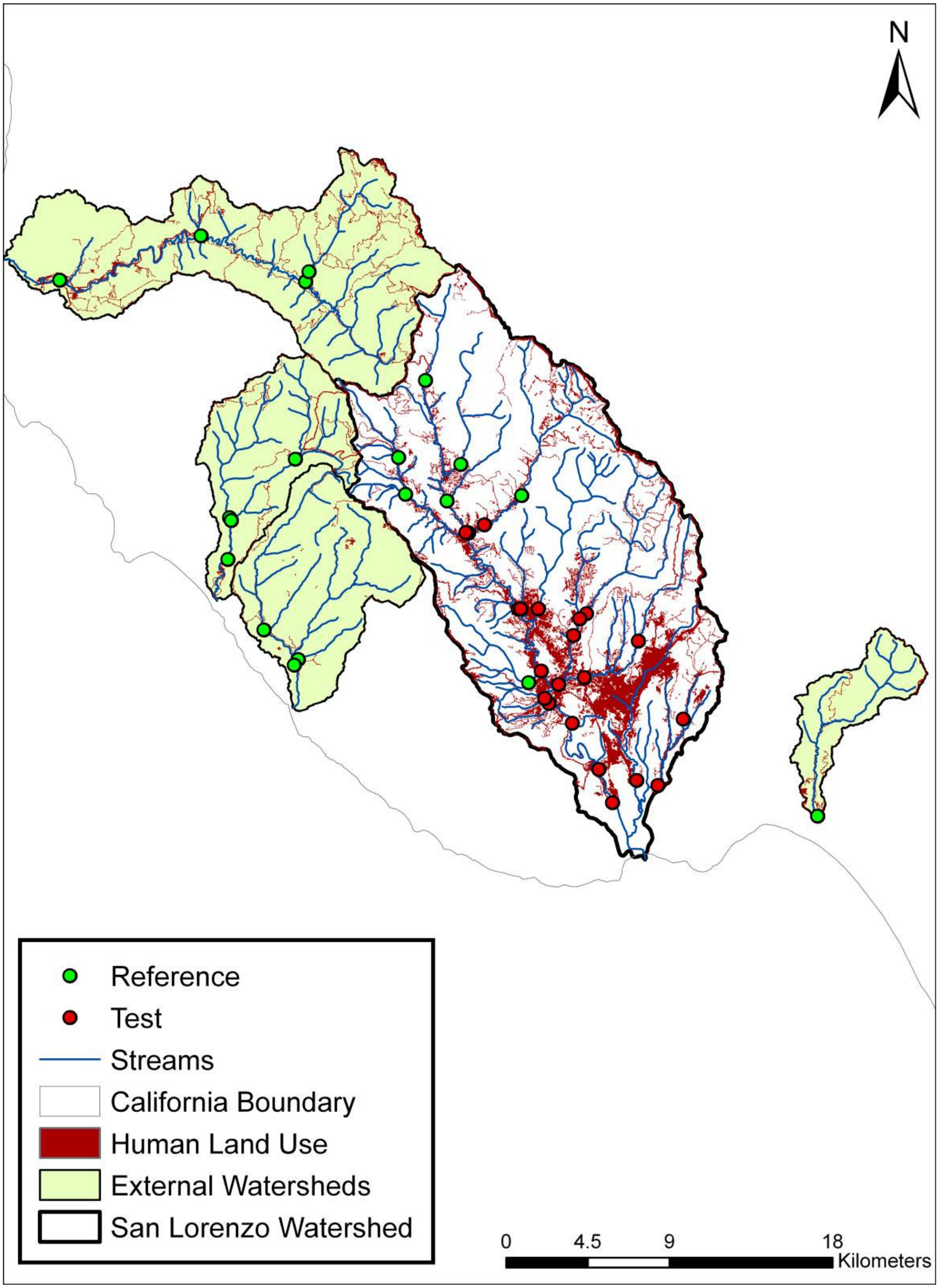

Figure 7. Human land use coverages in the San Lorenzo River watershed and adjacent reference drainages.

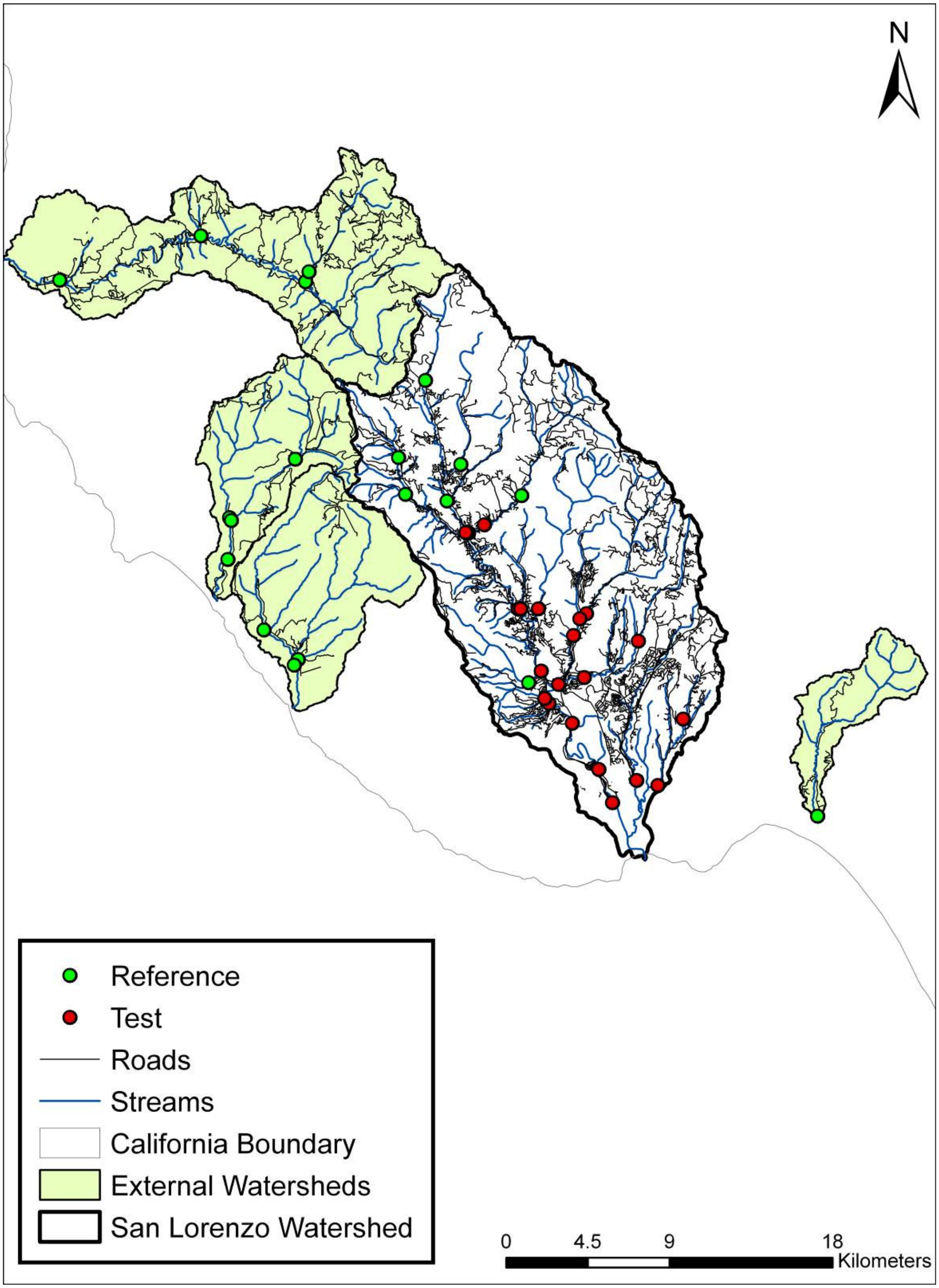

Figure 8. Road networks in the San Lorenzo River watershed and adjacent reference drainages.

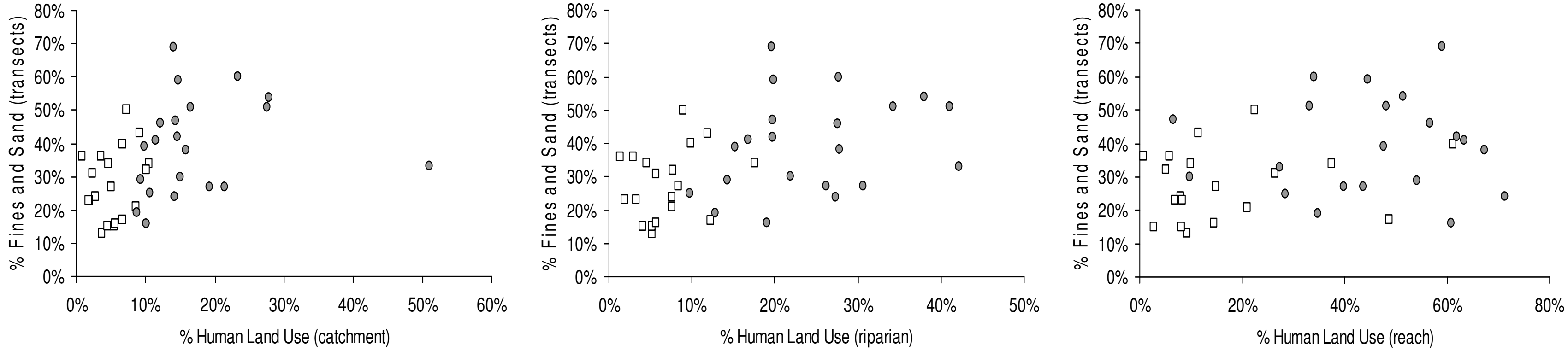

Figure 9. Scaled influence of human land use influence on reach sediment deposition (catchment left, riparian center, reach right)

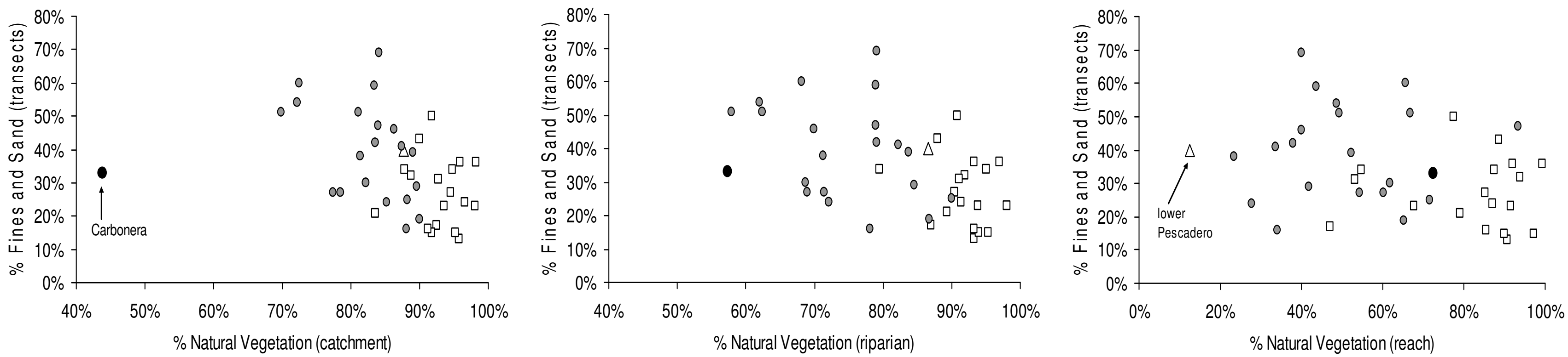

Figure 10. Scaled influence of natural vegetation cover on reach sediment deposition (catchment left, riparian center, reach right)

[In all graphs shown in Fig. 9 & 10, and elsewhere, reference sites = open squares, and test-dose sites = closed circles]

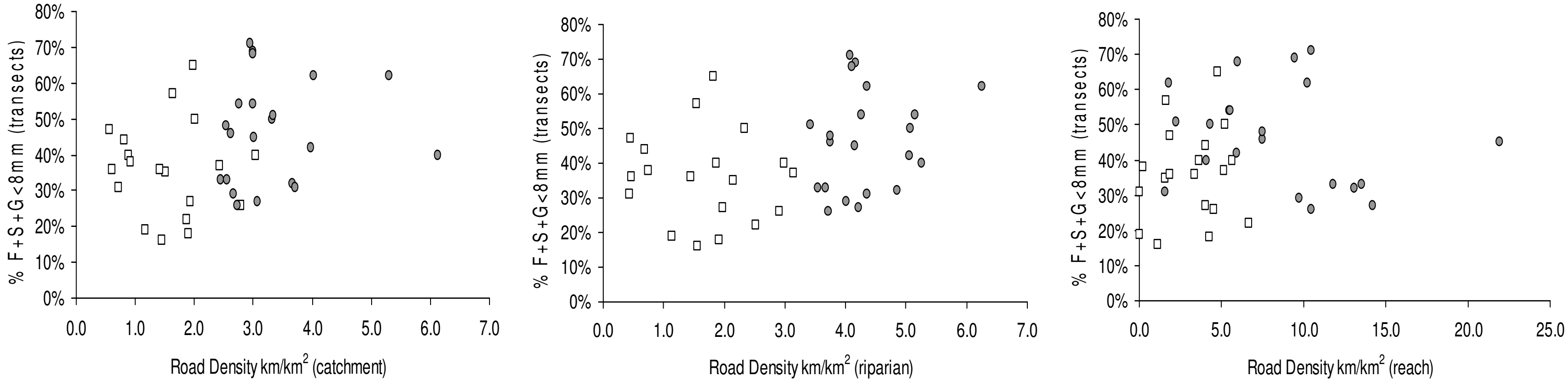

Figure 11. Scaled influence of road density (km length/km^2) on percent fines, sand, and gravel less than 8 mm in size.

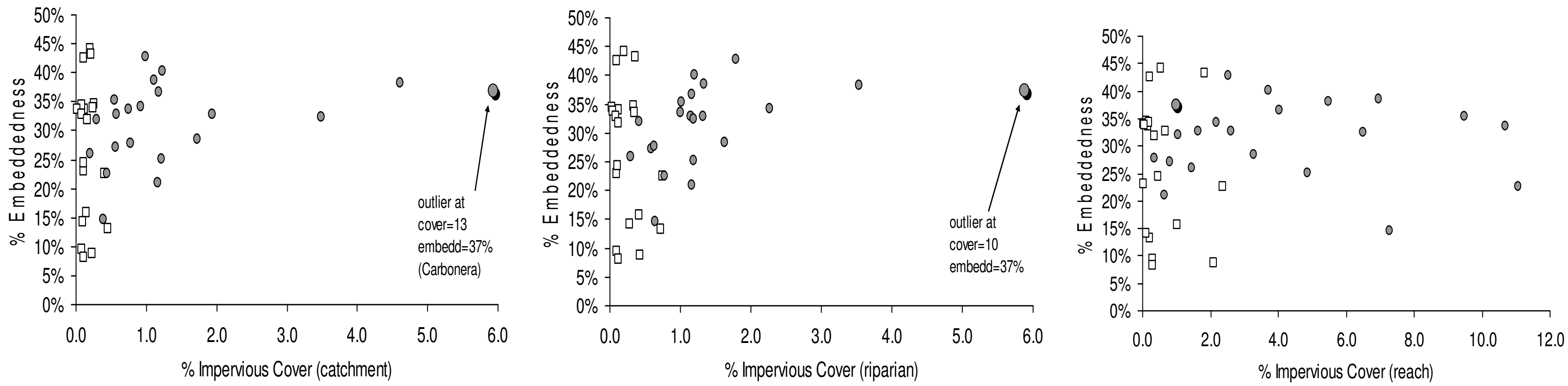

Figure 12. Scaled influence of impervious cover on embeddedness of pebble and cobble substrate.

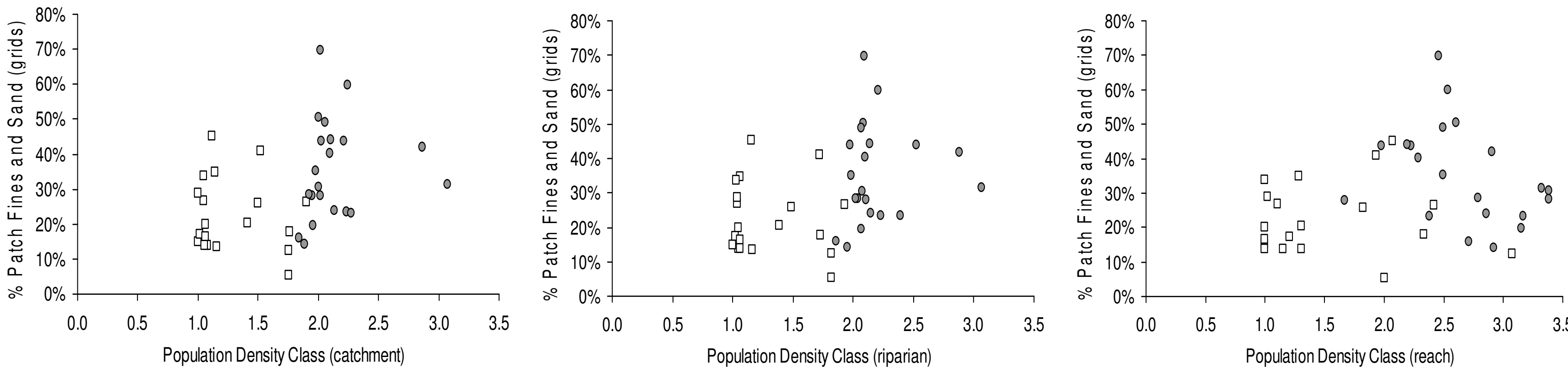

Figure 13. Scaled influence of population density class on percent sand + fine from patch-grid frame counts

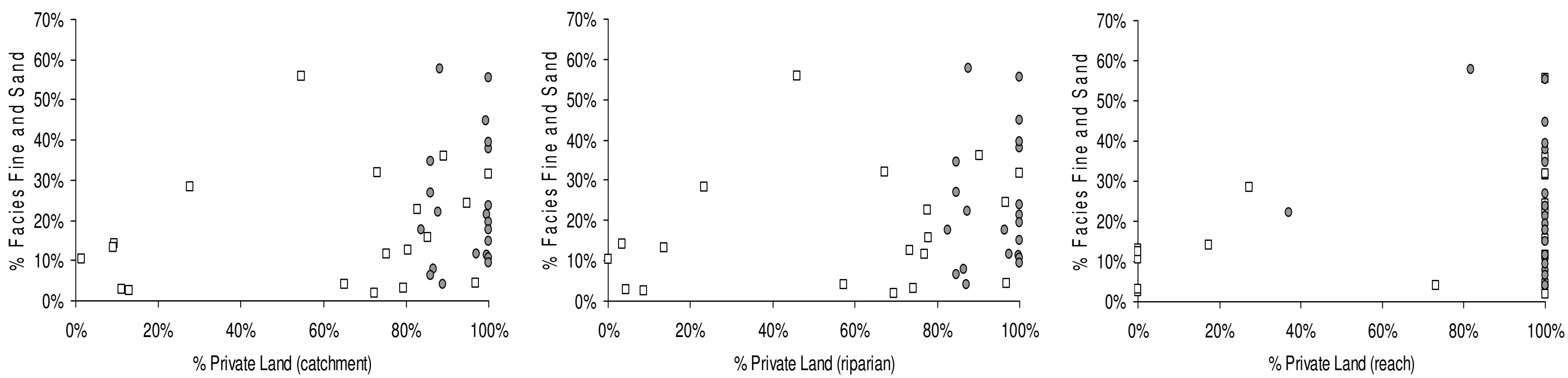

Figure 14. Scaled influence of private land cover on percent sand + fine deposition areas from facies maps

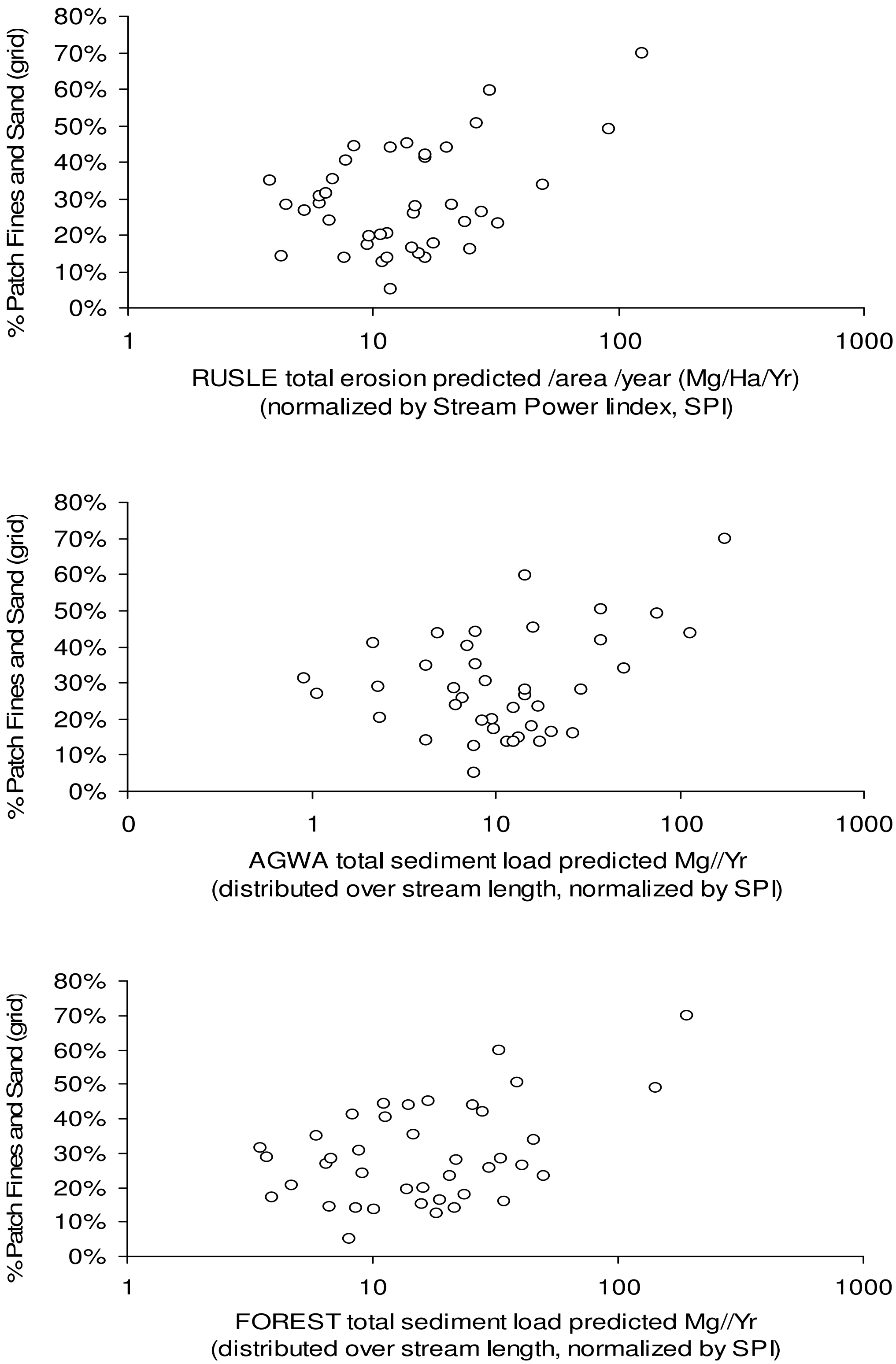

Figure 15. Comparison of sediment load models (load distributed over km length normalized by stream power index) and FS cover (San Lorenzo region sites only).

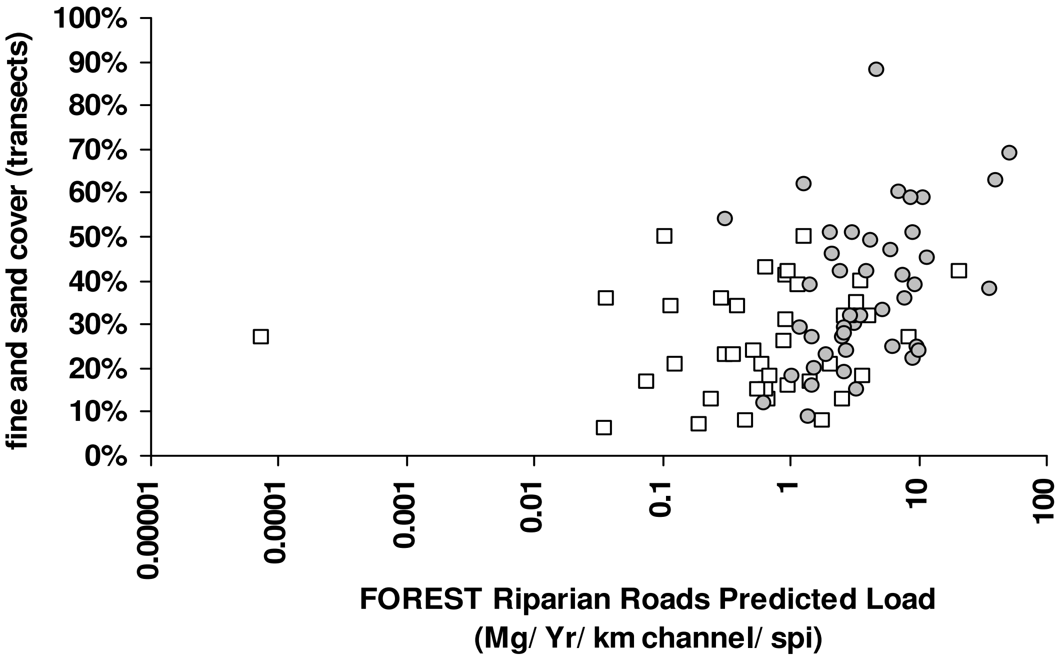

Figure 16. Transect fines and sand cover in relation to predicted sediment load delivered from roads in the riparian zone (100 m either side of stream) based on the FOREST model. Open squares reference, filled circles test. Showing combined coast region data.

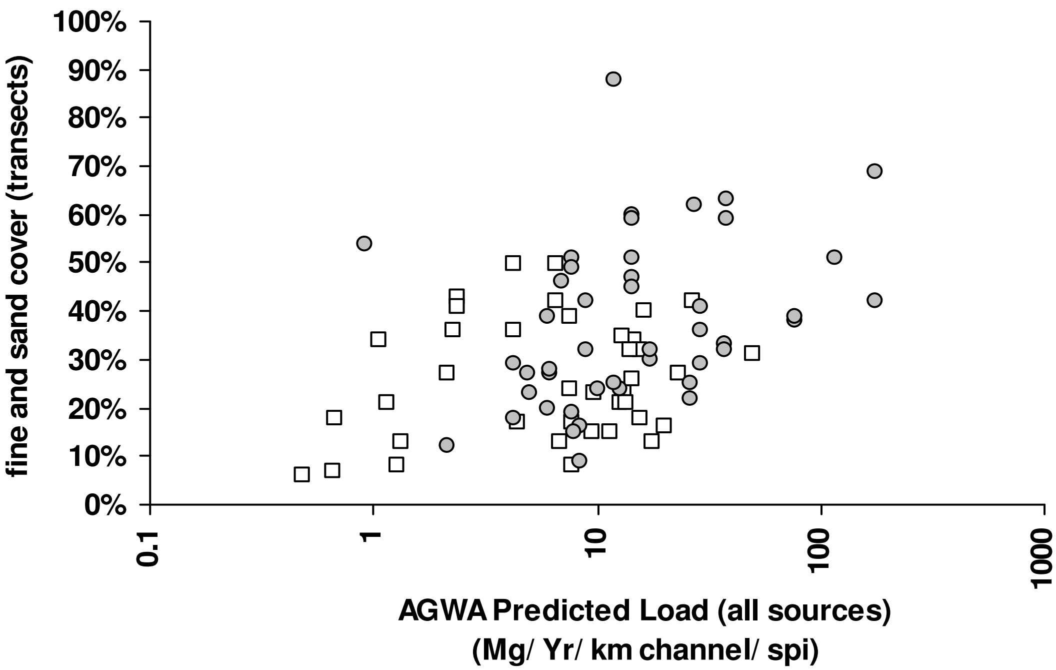

Figure 17. Transect fines and sand cover in relation to predicted sediment load delivered from based on the AGWA model. Open squares reference, filled circles test. Showing combined coast region data.

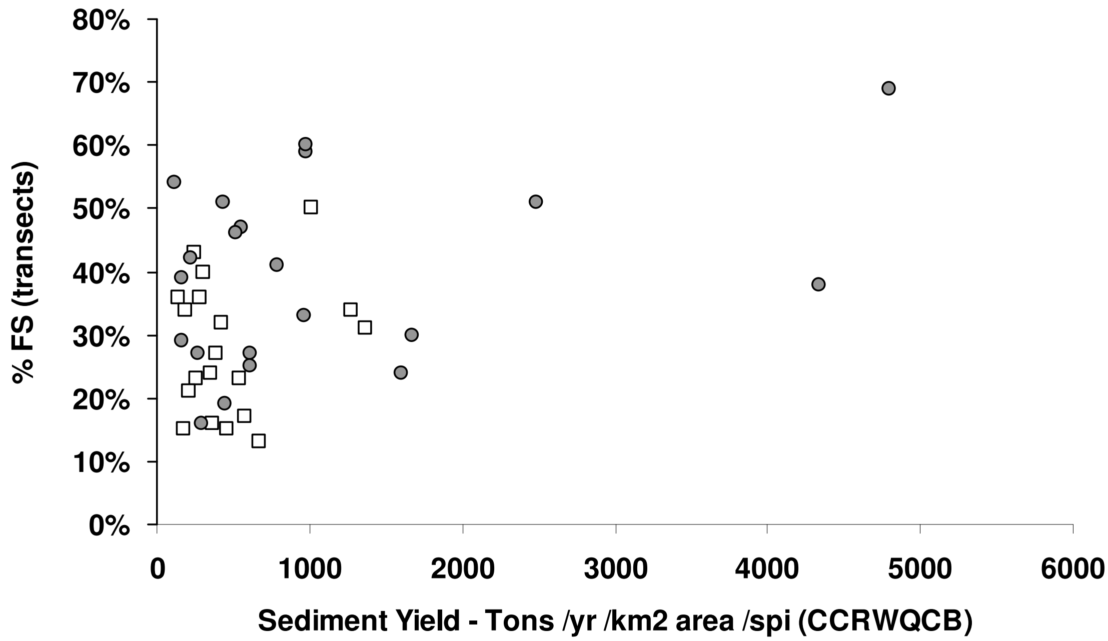

Figure 18. Method used by central coast regional water quality board to estimate cumulative sediment load in the San Lorenzo and FS deposition.

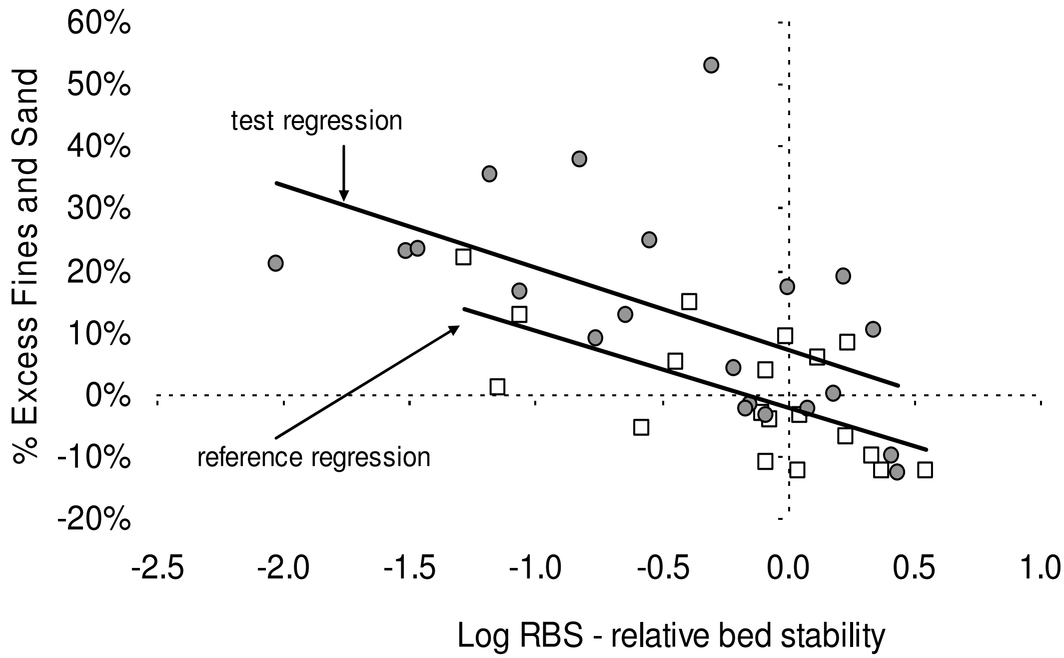

Figure 19. Relationship of excess fine and sand to relative bed stability (see methods for derivation of these values), contrasting reference and test regressions.

Indicators of Hydrologic Alteration

The analytical framework of IHA takes a baseline period of flow records and creates thresholds that establish low (below average), normal (average), and high (above average) category ranges (the RVA's) for the expected condition of different flow parameters. Another later period of record (post-impact) is then analyzed for changes in the frequency (the observed term) for which the flow features reach low, normal, and high RVA. The metric Hydrologic Alteration is the departure from the expected occurrence in each category, calculated as (observed value – expected value) / (expected value). Comparing the first 26 years of the record (1937-1962) to the most recent 26 years (1982-2007), three important trends appear: (1) median flows are more frequently in a lower range during the dry season (May-October), (2) minimum flows are more often lower and maximum flows are less frequently above average, and (3) high pulse flow events are more flashy (Figure 20, upper, middle and lower panels, respectively). For each month of the dry season there are consistently more below average flows observed than expected (the low flows have become lower), showing that there has been a reduction in overall baseflow. Processes that work to control stream geomorphology and substrate have also been altered, with (1) maximum flows (7-d duration shown in middle panel) occurring less often in a high range, and (2) high pulse floods having more rapid rise rates of shorter duration, and occur with an increased frequency in the above average range. In addition, flows during the autumn minimum have decreased and come later (by nearly 20 days), prolonging the dry season. It is noteworthy that there is unlikely to be any influence of differences in precipitation between the periods of time compared. The 1937-62 time frame averaged 32.3 inches per year of rainfall, compared to 30.9 inches per year for 1982-2007. No statistically significant difference was found and the ranges observed (17-60 inches/year) were the same for both periods.

A sediment rating curve, predicting the amount of sediment transported as total suspended solids (SLVWD 2007) shows less sediment would be exported from in-channel deposits because of reduced flows/transport capacity indicated in IHA analysis. Converting change in mean annual flows in the pre- vs. post-development period contrast, and using the relation: total sediment load (tons) = $6 \times 10^{-8} * (\text{acre-feet/yr})^{2.47}$, the amount of sediment transport would be reduced by about 8 percent. In addition, flows over 500 cfs are thought to be required before sediment transport becomes significant in the San Lorenzo River (SLVWD 2007), and these would have occurred a total of 92 days in 1937 to 1962, but only 79 days for the same number of years from 1982 to 2007.

Preliminary Surveys from 2007

Of the five sites surveyed in 2007, three were repeated in 2008 and 2009, and data were consistent in all three years, with two sites showing no sediment impairment and one site (San Lorenzo River in lower Cowell State Park below RR bridge) showing impairment (Appendix C). Across years the indicator metrics were mostly in agreement in being above or below criterion levels. These data indicate that conditions were fairly stable between years and that detection of long-term trends of improvement or degradation will require continued monitoring.

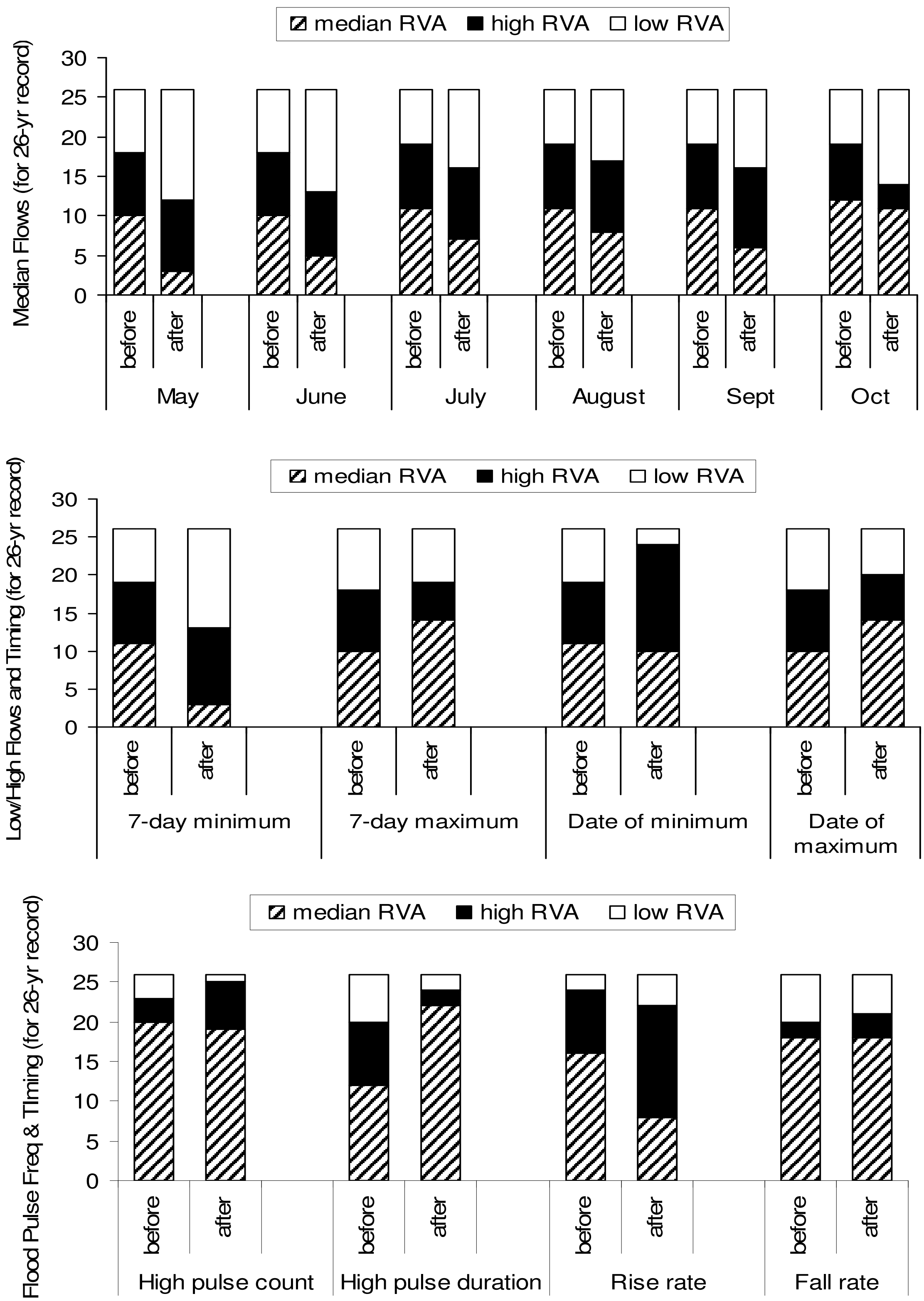

Figure 20. Hydrologic alterations of flow regime (median dry season flows, min/max flows, and floods) on the San Lorenzo River contrasting baseline period of 1937-1962 to 1982-2007, before and after the most rapid expansion and development of the watershed.

Combined Data Sets from San Lorenzo and Central Coast Region

Using the full complement of stream surveys from 2007-2008-2009, it can be seen that the patterns observed above for the 40 San Lorenzo surveys of 2008 are reinforced in the combined data set. Increased exposure to human land use disturbance and roads at the riparian scale provides the clearest evidence of impact on sediment deposition (Figures 21, 22). As the area and intensity of these disturbances increase, the minimum level of sediment deposition also increases (as shown by quantile regression of the 10th percentile of the distribution). This suggests that a dynamic equilibrium between sediment imported and exported is altered such that sediment accumulates where source inputs exceed the capacity of a channel to transport load downstream. From the equation of the quantile regression lines, we conclude from this coastal data set that the minimum %FSG<8mm increases over 4% for each km/km^2 increase in road density, and 5% for each 10% increase in human land use.

Examining the Log RBS and %FS relation from the combined data set (Figure 23), shows that most reference sites cluster near zero Log RBS, with greater numbers of test sites having lower Log RBS values and higher %FS cover. Models of Log RBS under differing conditions suggest that whether in sedimentary or volcanic geology, streams in undisturbed reference-condition catchments should tend towards values in the range of -0.7 to +0.5 (Kaufmann et al. 2009). With progressive human land use disturbance, the Log RBS values will decline to a greater extent in the more erodible sedimentary geology than volcanic rock, with small streams of low power being especially vulnerable. Our empirical data support this model, with disturbed test sites of low power having the highest levels of %FS cover compared to reference sites at similar low levels of stream power (Figures 24 and 25).

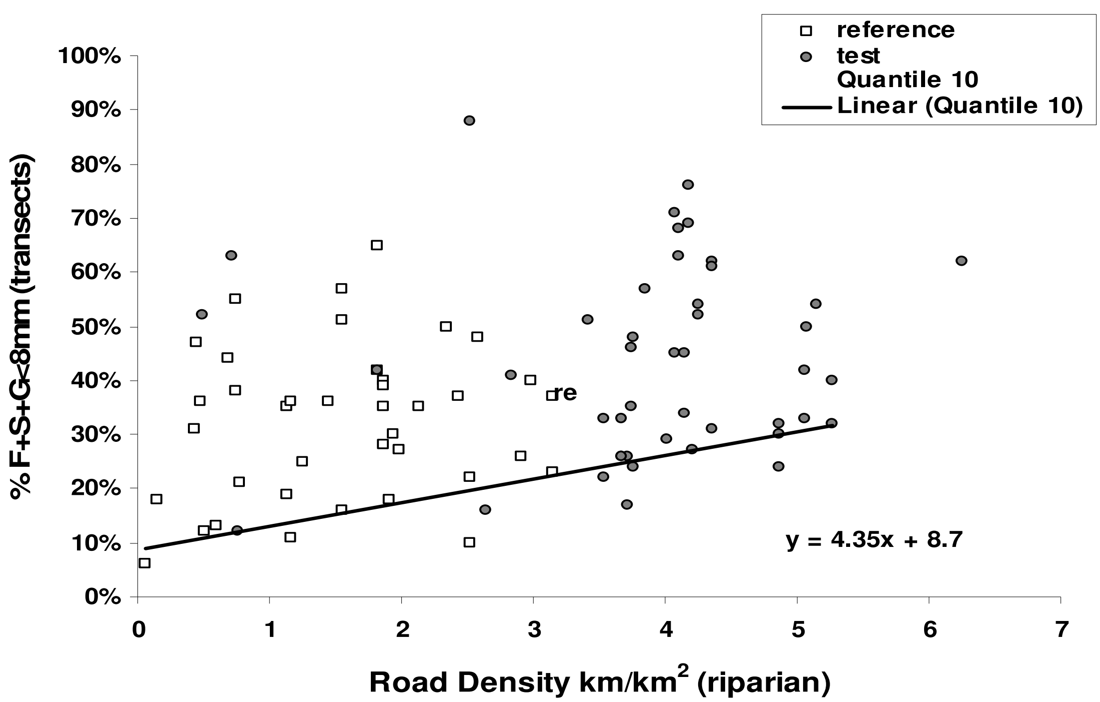

Figure 21. Influence of increased road density on sediment deposition (%FSG<8mm), showing quantile regression of 10th percentile (excluding the far right point).

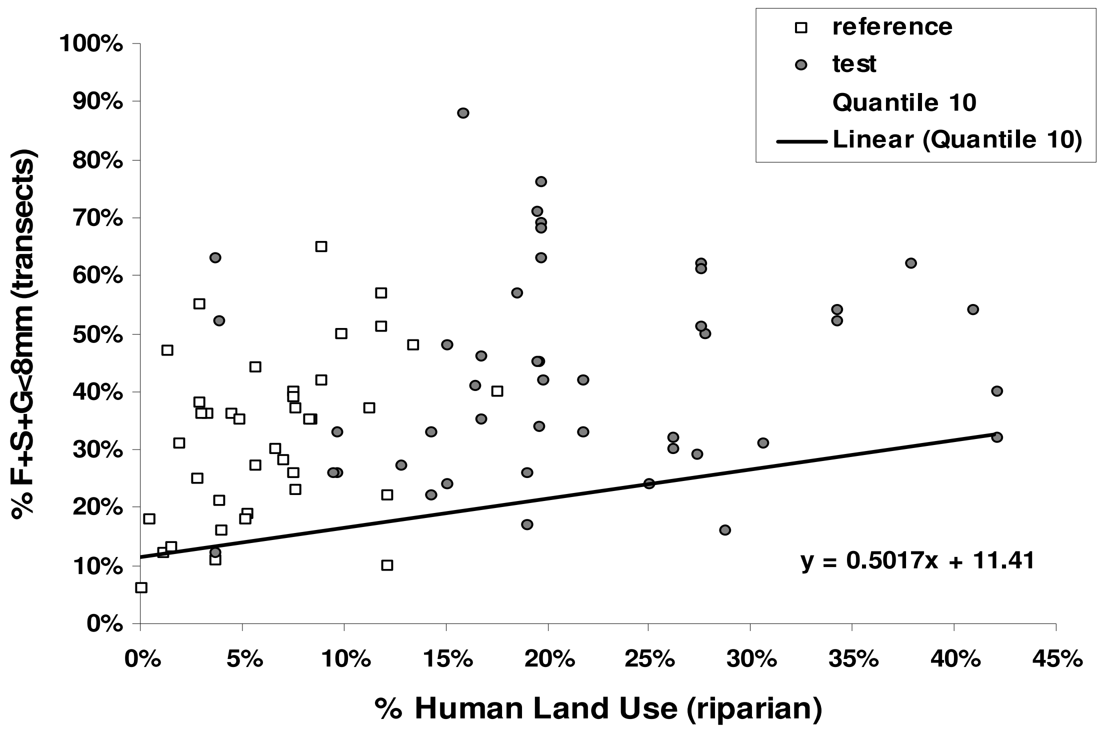

Figure 22. Influence of increased human land use cover on sediment deposition (%FSG<8mm) showing quantile regression of the 10th percentile.

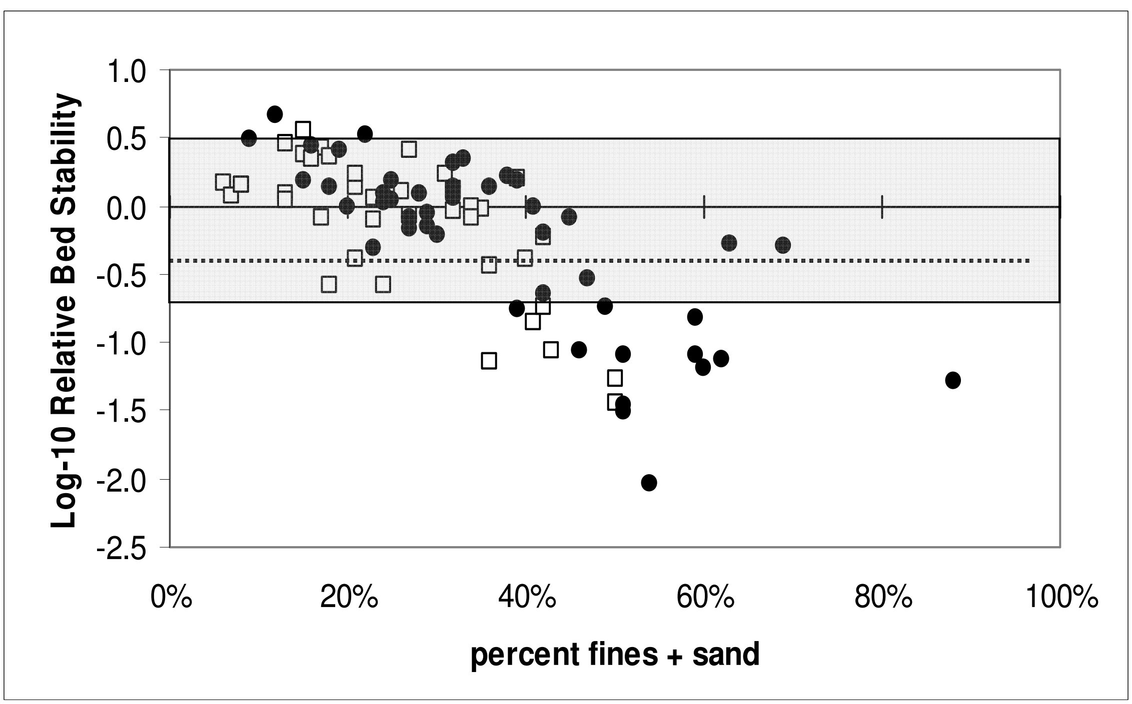

Figure 23. Log RBS and %FS for all central coast region sites. Shaded area from +0.5 to -0.7 is modeled reference range (Kaufmann et al. 2009). Impairment below -0.39 is the 25th percentile impairment criterion for the combined central coast region streams.

DISCUSSION AND CONCLUSIONS

EPA guidance on the sediment TMDL process has emphasized that sediment as a pollutant is difficult to characterize as it is not intentionally discharged, is derived from natural sources, and problems originate only when increased erosion from land use exceeds the capacity of a watershed to transport load (USEPA 1999). Assessment of sedimentation problems require evaluation of the extent to which existing conditions diverge from the natural state, enabled through comparisons to reference streams.

Multiple lines of evidence support the conclusion that deposited stream sediments at reaches throughout the San Lorenzo and other central coast watersheds are in excess of contributions from erosion related to natural sources, and may be impaired by those additional sediments. Using a reference site approach, the results establish significant increases in many reach-scale measures of deposition for the collective grouping of test sites (Table 2). The potential sediments received as load in different subcatchments was also shown through GIS models to exceed natural background in many cases. Combined results further show that the degree to which sediments accumulate may be attributed in large part to consistent relations between land use coverage in upstream catchments and increased sediment deposition at downstream monitoring reaches. Disturbance sources could be described as many interrelated factors including human land use, population density, roads, impervious cover, and private land. The coverage of natural vegetation also appeared to reduce the extent of sediment deposition, particularly at the local reach scale. These coordinated measures of sedimentation, landscape estimates of sources, and contrast of reference and test groups provides a foundation for identifying multiple criteria for TMDL guidance. These results pertain only to geomorphic conditions of stream bed substrates and will be complemented by associated biological data on macroinvertebrates in the companion report to this project.

A primary control on how stream sediments are distributed is stream power, which determines the ability of streams to do the work of sediment transport (Mount 1995). Particles are moved as a function of forces produced in a channel at bankfull flow, and at any scale of measurement (point, patch, facies), we found that the depositional environment of stream reaches reflected these differences in power, with finer particles persisting at low powers (Figure 24). Examined in terms of the amount of excess fines and sand (relative to reference background) it is clear that test sites of lower power have the greatest levels of deposition relative to reference conditions (Figure 25), while test/disturbed sites with high power do not hold as much accumulated sediment.

The data collected here sometimes showed single or a few outlier points at extremes of the observation range for many of the landscape-habitat associations, and these reflect the expectation that there are site-specific idiosyncrasies that alter the type of response observed. Individual site characteristics vary, and how each local reach segment responds at different scales to larger upstream areas of landscape conditions and disturbance will not be the same across sites. Often the data show wedge-shaped distributions with upper “ceilings”and lower “floors” in the response that serve to frame the boundaries of the relationship, and can be analyzed using quantile analysis (Cade and Noon 2003) as shown in Figures 16, 17, 21 and 22. While reduced cover of sediments were most typically found at low levels of disturbance (or high natural landscape cover), as disturbance increased the minimum deposition observed became confined to higher levels of coverage, suggesting that under constraints of greater erosion inputs from land use, stream reaches may no longer have the capacity to achieve low levels of sediment cover (i.e., there is net deposition). The broad range of deposition cover observed at lower levels of disturbance indicates that there are other varied natural factors that control sedimentation when not exposed to land use disturbance. For example, among the 5 reference sites in the San Lorenzo River region (selected *a priori* according to lowest catchment human land use and riparian road densities) with the highest levels of fine-sand-gravel sediment deposits (>50%), each had some natural features making them vulnerable to erosion (Table 4). Though there was no single explanation for problems at these sites, contributing factors including soil detachability (k-factor); local mass-wasting and instable slopes; structures built within or near the reach; and for one or more of the sites, the highest levels of landslides, and rainfall erosivity. One of the sites, lower Pescadero Creek, is a site that fits the criteria for a reference site at the catchment scale but has locally poor natural vegetation cover (and adjacent agriculture). This shows the tradeoff for choosing reference sites based on their entire watershed as there is the potential for local conditions creating outliers in the dataset. The high deposited sediment cover at this site may be due to reduction of protective natural vegetation cover at the reach scale (but not at riparian and catchment scales, see Figure 9). Another example of an outlier and site-specific interpretation is Carbonera Creek (a test site), which is located within a watershed that has substantial human population upstream (far right of catchment and riparian scales of Figure 8) in the town of Scotts Valley. The actual reach is located 5 km downstream from Scotts Valley, and there is increasing forested land cover from the catchment- to the reach-scale (44 to 73% cover, Figure 9) providing increased filtration potential (the reverse of that on lower Pescadero Creek).

Land use factors contributing most to higher sediment deposition at stream reaches within the San Lorenzo watershed may be discerned from their correlation coefficients (Table 5). These indicate that combined human land use and imperviousness are important sources, and that associated deposition was evident across spatial scales. Point- and patch-scale estimates of deposition gave the best spatial resolution for detecting land use and sediment loading effects, but the facies maps produced low correlations. Urban land use accounts for most of Human Land Use (see Appendix A NLCD classes), but interrelated population density and roads also separately correspond to the overall human disturbance that can be related to sedimentation. Private land use showed least relationship to measures of deposition. Natural vegetation cover at the riparian scale in particular appears to reduce the deposition of sediment, but local reach-scale filtering of sediment appeared to be important in explaining higher or lower than expected deposition levels for some outliers. High correlations to sediment measures for FOREST and AGWA predicted loads, and test sites with loads 3-4X in excess of references support the conclusion that increasing levels of catchment disturbance degrade stream habitat quality (Table 5). The RUSLE model produced lower correlations with sediment, much higher absolute loads, and less increase in test over reference background. Other studies have shown RUSLE predictions exceed observed sediment yields (Boomer et al. 2008). Loads from roads can be compared to sediment load above "natural" from the simulated hillslope component of the FOREST model, but the road sediment is a total yield whereas the hillslope sediment delivery comes from a constant input (0.1 Mg/ha/yr) that scales with catchment area and then is routed through a series of downslope model grid cells that modify delivery into the stream according to slope and land cover (vegetation and soils). If these assumptions are accepted, then at least the relative difference in load going to streams from all catchment roads is a mean of 8.3 Mg of sediment at reference sites, increasing to 26.7 at test sites, representing 36% of all reference sediment and 50% of all sediment at test sites. Road-related loads only (from the FOREST model) partitioned by subcatchment, can also show localization of problem areas on Zayante Creek and some of the middle tributaries of the San Lorenzo (Figure 26 and Table 6). The AGWA model does not explicitly model road inputs, but gave total delivered load estimates in the same range as FOREST natural delivery (Table 5).

The load estimates given in the CCRWQCB (2002) sediment yield analysis may be the most realistic as they are based on actual measurements of total suspended solids from different parts of the San Lorenzo watershed and partition sedimentation sources as 42% from mass wasting, 14% channel erosion, 30% from roads (mostly timber harvest), and 15% from urban and rural lands. These data are in agreement then with the FOREST model suggesting roads over all sites may yield about 40% of load, and with test streams having at least twice the load of the reference background. Load estimates from CCRWQCB were about an order of magnitude higher than for AGWA / FOREST (tons are about 90% of metric tons=Mg), indicating either inaccuracy in the study on which these results were based, or that actual sediment delivery derived from the distributed models underestimate true loads and need to be calibrated with empirical erosion data. Despite this uncertainty, all loads predicted were reflected in the field measurements of bed sediments deposited in the study reaches (Figure 19). Although absolute load estimates of the models may not have been accurate, the relative loads distributed by stream length and normalized by stream power, showed reasonable correspondence to actual deposited sediments observed, especially at minimum levels (Figure 15). Sediment load models provide an improvement over simple land use cover percentages in predicting sediment deposition levels in streams, but both show that as load or land use increase, streams cannot avoid rising base levels of sediment buildup.

Any increase above natural background erosion creates a potential sediment pollution source. In order to determine what level of sediment deposition was indicative of impairment, we used sediment levels found in reference streams as a standard, so that where exceeding the 75th percentile of the reference range, we defined a reach as sediment-impaired (Appendix B). Using multiple measures of depositional environment provides for a more robust assessment and increased certainty in decisions of impaired or unimpaired condition, progress towards attainment, or further degradation. We used 8 sediment quantity indicators, and judged degree of site impairment based on the number of exceedances of reference criterion thresholds. This process identified 19 test sites and 9 reference sites with more than half of criteria in excess of the criterion level (Appendix B). Declaration of some references as impaired results from the procedure of eliminating extremes of the reference range as accurate indicators of the unimpaired state. Had we used only sediment levels outside the full reference range, the effect of outliers in the reference distribution would introduce increased chance of making statistical errors of interpretation. Type II errors, or false negatives, are the misjudgments of not rejecting the null hypothesis when it is in fact false (failing to detect impairment when and where it occurs). In that TMDL standards are intended to protect natural resources, reference standards are typically set at some tail of the distribution to eliminate outliers and unaccounted impairment sources (e.g. local-level disturbances or unknown pollution sources)– this is also consistent with incorporating a margin of safety (MOS) as a standard procedure in TMDL development (USEPA 1999 sediment TMDL protocol). It should further be noted that in using an expanded number of reference sites that have some level of existing impact from land use and roads, the criteria are not as stringent as had we selected lower thresholds for defining the reference state. Therefore this is also a conservative assessment of impairment that uses a lenient definition of reference so that test sites are fairly represented (see Appendix D, decision rationale for criterion levels).

Previous TMDL numeric criteria for the San Lorenzo were borrowed entirely from studies conducted in north coast watersheds, were based mainly on fish habitat, and none are comparable to the reach-wide sampling we conducted.
1) % Fine Fines in Spawning Gravels - taken from Garcia River Sediment TMDL (14%) base value, then multiplied by (1/0.67) to account for fine sediment removal during Redd construction, for a limit of 21% fines (<0.85 mm) as measured by a McNeil sampler.
2) % Coarse Fines (<6 mm) in Spawning Gravels - taken from other studies where 30% is determined to be an impairment to steelhead and Coho.
3) Residual Pool Volume – (Garcia River TMDL): <= 0.21 (mean) and <= 0.45 (max).
4) D50 (> 37mm minimum and > 69 mm mean) - taken from Redwood Creek Sediment TMDL. These particle measures were based on sampling from “riffle crest” surfaces.

Using 7 operational metrics that are readily measured (adding %S and dropping embeddedness and facies fines of appendix B), provided good separation between reference and test sites, and were most sensitive to measures of land disturbance (road density measures and human land use cover), we recommend that CCRWQCB staff use this multi-parameter set of indicators for assessment of sediment-impaired stream bed habitat. These are based on exceedances of the 75th and 90th percentiles of the reference distribution for metrics that increase with deposition, and below the 25th and 10th percentiles for those metrics expected to have lower values indicating sedimentation. Using multiple indicators and these criterion levels provide a balance between errors of false positives and negatives in reducing the chance of unwarranted determinations of impairment while still protecting stream habitat resources, but also permit judging levels of impairment. These are the same criterion levels used in other studies of sediment and habitat stressors in the western United States (Bryce et al. 2008, Stoddard et al. 2005).

Sites would be considered impaired as follows:

Sediment Indicator	Moderately Disturbed [partially supporting] (75/25)	Disturbed [not supporting] (90/10)
1. Percent Fines (F) on transects	>8.5%	>15.2%
2. Percent Sand (S) on transects	>27.5%	>35.3%
3. Percent FS on transects	>35.5%	>42.0%
4. Percent FSG<8mm on transects	>40.0%	>50.2%
5. D50 median particles size	<15 mm	<7.7 mm
6. Percent patch-scale grid FS	>28.8%	>38.5%
7. Log RBS (relative bed stability)	<–0.39	<–0.90

As sediment conditions are improved at impaired sites through transport of smaller particles, recovery might proceed in the order of F to FS to FSG<8mm, enabling the tracking of progressive recovery as erosion sources and sediment delivery are reduced.

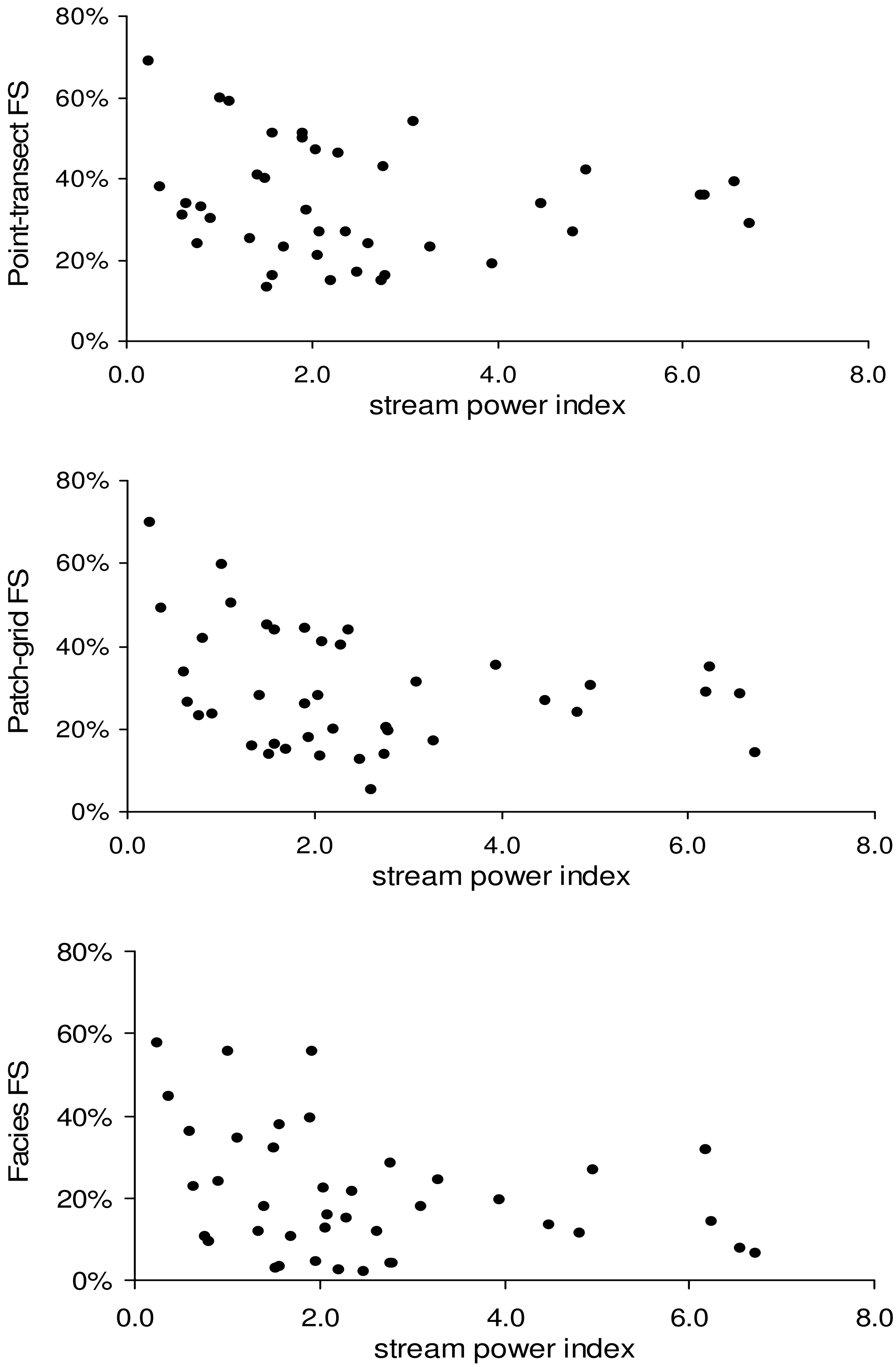

Figure 24. Influence of stream power on deposited fines and sand measured at three scales (points – upper; patches – middle; and facies – lower).

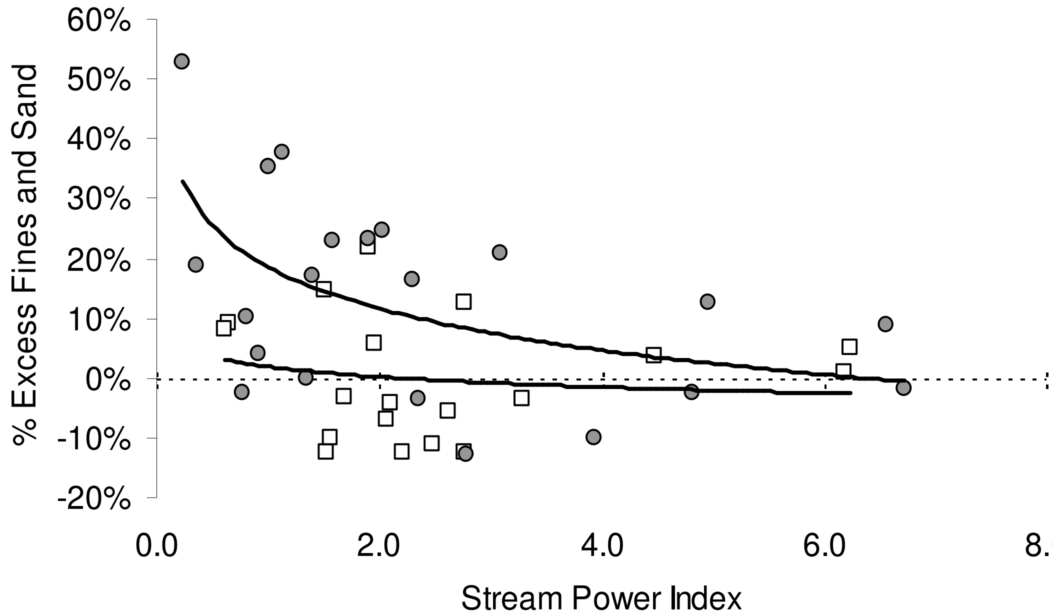

Figure 25. Excess sediment deposition calculated for study reaches as a function of stream power index (product of bankfull cross section area and reach slope).

Table 4. Natural factors accounting for 5 reference sites with highest sediment cover.

Stream (Site)	**% FSG**	**Explanation for High Sedimentation**
San Lorenzo River (Lower Castle Rock S.P.)	71%	Catchment-scale landslide coverage 2nd highest of all sites (35.5%); highest reach SSURGO-based soil detachability factor (K-Factor = .294)
Pescadero Cr (Cloverdale Road Crossing)	66%	Reach-scale natural vegetation cover lowest of all sites (12.4%) – Figure 10, right
Fall Cr (Henry Cowell S.P.)	62%	Highest rainfall erosivity factor (R-Factor) of all sites (from RUSLE model calculations)
Kings Cr (above Kings Cr Rd. bridge)	52%	Local mass wasting of unstable slopes (photo documented); reach SSURGO K-factor higher than 75% of all sites (.276)
Little Cr (above Swanton Rd. bridge)	51%	Highest catchment landslide cover of all sites (38.5%); steep site; locally disturbed by downstream control (weir)

Table 5. Correlations between GIS measures of land cover, land use, sediment load models and measures of sediment deposition, and reference-test differences in load.

Spearman Rank R^2 coefficients	Sediments (San Lorenzo region)				
Land Cover or Use	Transect FS	Transect D50	Grid FS	Facies FS	Excess FS
Catchment Population Dens	0.21	-0.14	0.23	0.06	0.24
Riparian Road Density	0.16	-0.09	0.25	0.06	0.20
Road Crossing Density	0.16	-0.10	0.12	0.02	0.20
Catchment Human Land Use	0.27	-0.16	0.25	0.08	0.31
Catchment Imperviousness	0.36	-0.23	0.28	0.09	0.39
Catchment Urban Land Use	0.27	-0.16	0.26	0.09	0.32
Catchment Private Land	0.09	-0.05	0.21	0.10	0.10
Riparian Natural Vegetation	-0.26	0.19	-0.30	-0.13	-0.28
Reach Natural Vegetation	-0.09	0.06	-0.14	-0.08	-0.10
Modeled Load (Mg/yr/km/spi)	Central Coast Region Combined Data				
	%FS	Reference (mean)		Test (mean)	
FOREST – All Roads Yield	0.40	8.3		26.7	
FOREST - Riparian Roads Yield	0.43	1.8		7.0	
FOREST - Natural Load Delivered	0.27	16.1		31.2	
AGWA – Total Load Delivered	0.34	10.0		26.9	
RUSLE - Total Load Delivered	0.26	393.1		560.9	

GIS Measures & Load Models

In addition to land use disturbances, some insight to reasons for sediment accumulation in the San Lorenzo can also be gained from hydrologic alterations. The decrease of median flows during the dry season is an expected result of increasing human land use in the watershed. Pumping for human consumption draws water out of the hydrologic budget, and an increase of impervious surfaces reduces the potential for groundwater recharge. During the part of the year when stream flow is nearly completely dependant upon groundwater, these alterations manifest as an increase in median flows that are classified as being lower than average (Figure 20 upper panel).

High pulse events shape the physical character of the river channel and control substrate sizes. IHA indicates that median high pulse occurrence has remained steady at 5.5 per year, but the median duration has gone from 4 to 2 days. Additionally, the highest of the high pulses have actually become more frequent, but their duration has greatly decreased. High pulses are the period during which a stream adjusts to excesses by altered channel profile and flushing out fine sediment pollution during sustained flows. High maximum flow periods, and their sediment transporting capacity, have also declined. Without these events the San Lorenzo River does not maintain a dynamic equilibrium between import and export, and this contributes to fine sediment being trapped in the system. Imperviousness is a likely cause for the diminishing high pulses, as water flows overland rather than becoming part of the groundwater recharge that can sustain high flows. Rapid rises of short duration are more likely to bring sediment into the system than provide flushing removal flows. In short, while erosion and sediment inputs to the watershed have increased, the capacity for cleansing has declined.

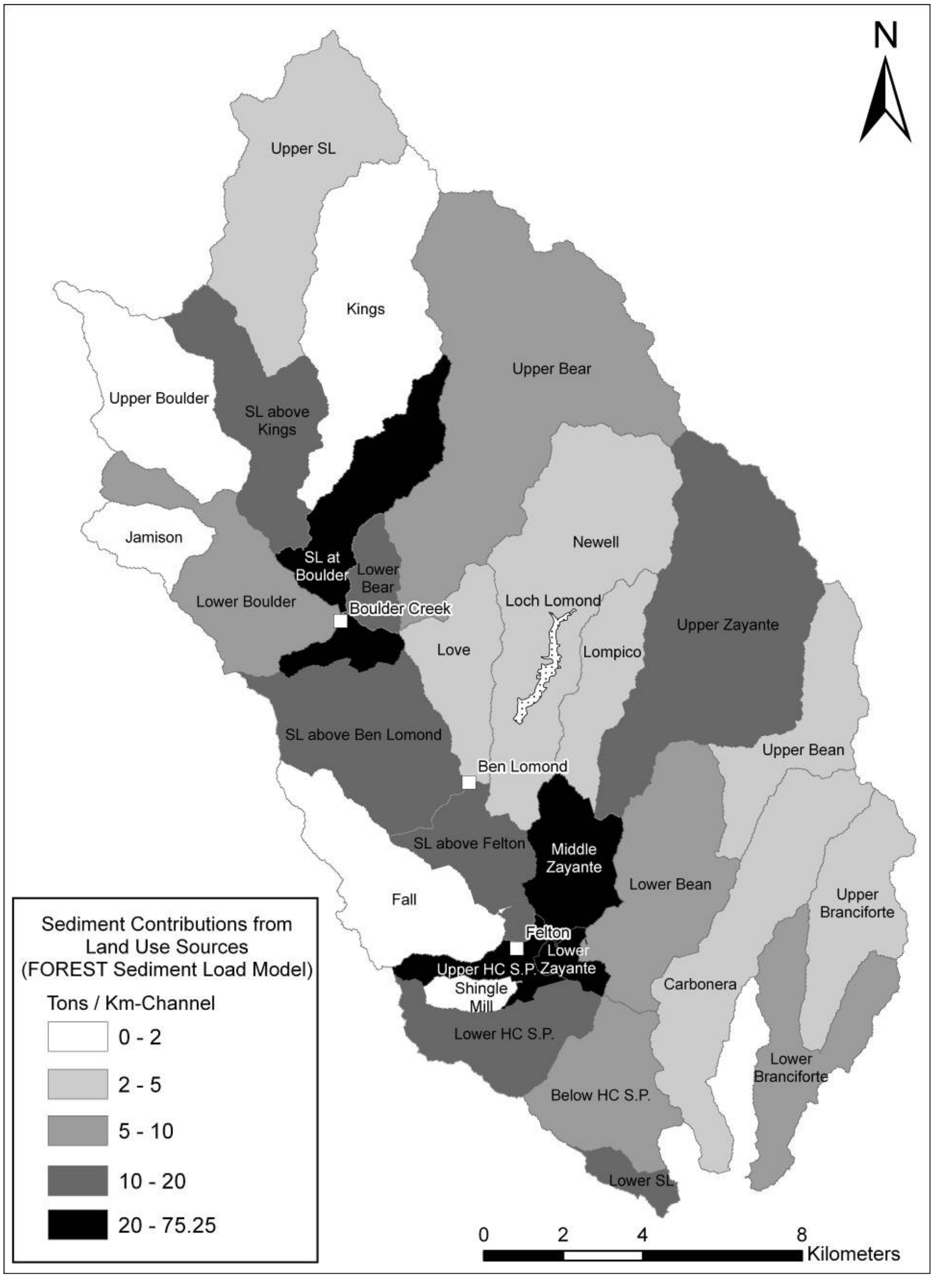

Figure 26. Map of San Lorenzo watershed showing road-related sediment load levels.

Table 6. Highest Sediment Producing Catchments from Land use – FOREST sediment load model road component

Subcatchment	Tons/ km channel	Subcatchment	Tons/ km channel
San Lo. at Boulder	36.40	SL Above Kings	10.27
Middle Zayante	45.55	Lower SL	10.42
Lower Zayante	62.74	Upper Zayante	10.52
San Lo. Upper HC S.P.	75.29	Lower Bear	12.02
		Lower HC S.P.	16.03
		SL Above Ben Lomond	17.27
		SL Above Felton	19.60

Applications:
Utility of the data set for continued monitoring of change (improvement where erosion control plans underway) will provide for an adaptive management approach to erosion control and management in the watershed. The numeric targets identifying potential thresholds of exposure to sediment cover beyond geomorphic capacity of the channel (in the sediment transport sense) establish standards for determining when and where attainment of standards has been achieved, or further remediation is required. Water Board staff can use these numeric targets to evaluate impairment and TMDL attainment (listing and de-listing of sites). Use of reference sites and models also permits determination of the natural range of deposition and loading, and identification of some of the potential causes of erosion and accumulation (roads, land uses, impervious cover, altered hydrograph). Maps of loading and sites of impairment further permit prioritization of problem areas by subcatchment and locales where erosion controls could be most beneficial and cost effective (using detailed GIS spatial information).

Recommendations for management, control, and further studies:

- Adopt multi-parameter standards (7-criteria) for attainment of natural sediment levels, and couple these to biological standards
- Implement erosion controls for the following:

1. >3 km/km^2 roads within riparian zone (Fig.s 11 and 21)
2. >1% impervious cover within riparian zone (Fig. 12)
3. <80% natural vegetation cover within riparian corridor (Fig. 10; increase cover at both riparian and reach-local levels to improve sediment filtering capacity)

- Goal of sediment load reductions in areas of roads and land use impairment in order to attain reduced loads and deposition of fines and sand (Fig.s 16 and 17)
- Target problem areas identified by FOREST road model to achieve overall load and deposition reductions in the lower watershed (Fig. 26)
- Modify standards as appropriate when biological data become available, and identify threshold responses over sediment deposition gradients at differing spatial scales
- Plan for further monitoring of subset of station established in this study
- Develop linkages with salmonid populations and food web alterations
- Improve the calibrations of load models with empirical data on suspended sediments from subcatchments throughout the basin, and enhance the resolution of GIS data inputs where available
- Update roads-related load models with details on surface type and use levels to provide more accurate predictions of loading from these sources
- Incorporate data for model calibrations with TSS monitoring and sediment yield measurements (sediment capture fences) in different subcatchments

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Appendix A: NLCD 2001 Classes

Class Value	Description
11	Open water
12	Perennial Ice/Snow
21	Developed, Open Space
22	Developed, Low Intensity
23	Developed, Medium Intensity
24	Developed, High Intensity
31	Barren Land
41	Deciduous Forest
42	Evergreen Forest
43	Mixed Forest
52	Shrub/Scrub
71	Grassland/Herbaceous
81	Pasture/Hay
82	Cultivated Crops
90	Woody Wetlands
95	Emergent Herbaceous Wetlands

Lumped Category	Classes
Human Land Use	21, 22, 23, 24, 81, 82
Urban	21, 22, 23, 24
Natural Vegetation	41, 42, 43, 52, 90, 95

For **2001 NLCD**, roads are not included in only one class, it depends upon the surrounding landscape (these are 30 m x 30 m pixels, so roads only cover part of a pixel in most cases). The 2001 classes:
21. Developed, Open Space - Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
22. Developed, Low Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.
23. Developed, Medium Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.
24. Developed, High Intensity - Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.

For overlapping roads data in NLCD in the San Lorenzo area, most of the rural roads are in class 21, but as the roads become more urban they trend into classes 22, 23, and 24.

For **1992 NLCD** (which drives AGWA and RUSLE) the classes are different, and the wording does specifically mention roads in class 23. That is why for the roads-enhanced layers used in AGWA and RUSLE, a roads layer was added to class 23.

21. Low Intensity Residential - Includes areas with a mixture of constructed materials and vegetation. Constructed materials account for 30-80 percent of the cover. Vegetation may account for 20 to 70 percent of the cover. These areas most commonly include single-family housing units. Population densities will be lower than in high intensity residential areas.

22. High Intensity Residential - Includes highly developed areas where people reside in high numbers. Examples include apartment complexes and row houses. Vegetation accounts for less than 20 percent of the cover. Constructed materials account for 80 to100 percent of the cover.

23. Commercial/Industrial/Transportation - Includes infrastructure (e.g. roads, railroads, etc.) and all highly developed areas not classified as High Intensity Residential.

Appendix B: Sediment deposition values for REFERENCE reaches and impairment exceedances of 75^{th} reference criterion levels.

Year	Stream Name	Site Name	R / T	%F	%FS	%FSG<8	D50	Embedd.	%Facies.F	%FS.Grid	LRBS.D50	#Ex	Imp
2008	San Lorenzo R	Above Brimblecom Rd.	R	1%	17%	22%	34	9%	0.6%	12.4%	-0.081	0	
2008	San Lorenzo R	Lower Castle Rock State Park	R	3%	**50%**	**65%**	**2.125**	**44%**	0.9%	25.8%	**-1.277**	5	x
2008	Fall Creek	Cowell Unit H.C. State Park	R	7%	**43%**	**57%**	**6**	13%	**7.5%**	20.4%	**-1.056**	5	x
2008	Jamison Creek	Next to fire station	R	3%	27%	35%	70	16%	2.7%	**41.0%**	-0.072	1	
2008	Boulder Creek	Highway 236 – Mile marker 4.0	R	8%	34%	40%	19	23%	0.0%	26.4%	-0.003	0	
2008	Kings Creek	Above Kings Creek Road Bridge	R	1%	24%	40%	**14.5**	14%	1.0%	5.2%	**-0.578**	2	
2008	Bear Creek	Above treatment plant	R	**9%**	32%	37%	35	**35%**	0.5%	17.8%	0.121	2	
2008	Aptos Creek	Below Aptos Rancho trail	R	**21%**	**36%**	38%	29.5	**34%**	3.3%	**34.8%**	**-0.438**	5	x
2008	Waddell Creek	Above Alder Camp	R	4%	13%	19%	24	34%	0.1%	13.8%	0.040	0	
2008	W. Waddell Creek	Above confluence	R	4%	23%	31%	20	**34%**	0.9%	15.0%	-0.104	1	
2008	E. Waddell Creek	Above confluence	R	7%	15%	16%	118	23%	0.4%	20.0%	0.547	0	
2008	E. Waddell Creek	Above treatment plant	R	**21%**	34%	36%	55	**43%**	**10.9%**	26.8%	-0.086	3	
2008	Little Creek	Above Swanton Rd. bridge	R	0%	**36%**	**47%**	**14.5**	**34%**	0.6%	28.8%	**-1.145**	5	x
2008	Scott Creek	Upper tributary	R	1%	31%	**44%**	21	9%	**13.8%**	**33.8%**	0.236	3	
2008	Scott Creek	Below Little Creek (OSH property)	R	7%	23%	36%	31	33%	**6.7%**	17.2%	0.051	1	
2008	Pescadero Creek	Above bridge Xing @ Cloverdale	R	4%	**40%**	**50%**	**8.5**	**43%**	0.6%	**45.2%**	-0.388	5	x
2008	Pescadero Creek	At Oakland YMCA Camp	R	0%	15%	18%	78.5	24%	0.1%	13.8%	0.371	0	
2008	Pescadero Creek	Below Sequoia nature trail	R	3%	16%	27%	55	8%	0.1%	16.4%	0.338	0	
2008	Peters Creek	Above campground	R	1%	21%	26%	66.5	32%	0.0%	13.6%	0.233	0	
2009	Aptos Creek	Below Aptos Rancho trail	R	**15%**	**50%**	**55%**	**1.625**	28%	**9.7%**	**50.2%**	**-1.443**	7	x
2009	Fall Creek	Cowell Unit H.C. State Park	R	**10%**	**41%**	**51%**	**6.5**	16%	**5.3%**	24.2%	**-0.861**	6	x
2009	Bear Creek	Above treatment plant	R	4%	18%	23%	69	**44%**	1.2%	19.0%	0.362	1	
2009	San Lorenzo R	Above Brimblecom Rd.	R	0%	8%	10%	54.5	13%	0.0%	5.4%	0.159	0	
2009	San Lorenzo R	Lower Castle Rock State Park	R	**16%**	**42%**	**42%**	**9**	23%	0.5%	**33.0%**	**-0.748**	6	x
2009	Kings Creek	Above Kings Creek Road Bridge	R	**10%**	**39%**	39%	40	29%	0.3%	26.4%	0.207	2	
2007	Kings Creek	County Land	R	**9%**	27%	28%	50	0%			0.406	1	
2007	San Lorenzo R	Upper Camp Campbell	R	**23%**	**42%**	**48%**	**8**	12%			-0.229	4	X
2007	Soquel Creek	Upper	R	5%	35%	37%	25	24%			-0.027	0	
2007	Stevens Creek	Above Reservoir	R	5%	21%	35%	19	18%			**-0.393**	1	

Year	Stream Name	Site Name	R / T	%F	%FS	%FSG<8	D50	Embedd.	%Facies.F	%FS.Grid	LRBS.D50	#Ex	Imp
2007	Carmel River	Bluff Camp	R	0%	6%	6%	145	6%			0.168	0	
2007	Arroyo Seco R	Above Arroyo Seco day use area	R	0%	7%	12%	82.5	15%			0.079	0	
2007	Tassajara Creek	Horse Pasture trail crossing	R	1%	13%	13%	70	3%			0.081	0	
2007	Waddell Creek	Above Alder Camp	R	1%	32%	35%	16	33%			-0.035	0	
2007	San Antonio R	Above Interlake Bridge	R	0%	13%	30%	15	18%			0.459	0	
2007	Nacimiento Creek	Below Campground	R	0%	8%	11%	69	**36%**			0.157	1	
2007	Sespe R	Lion Campground	R	8%	21%	21%	80	**38%**			0.137	1	
2007	Sisquoc Creek	Above Dam	R	**12%**	17%	18%	36.5	29%			0.422	1	
2007	Salinas R	Above Pozo CDF Station	R	3%	26%	36%	15	8%			0.113	0	
2007	San Simeon Ck	Above Fence	R	1%	18%	25%	30	6%			**-0.583**	1	

Appendix B (con't): Sediment deposition values for TEST reaches and impairment exceedances of 75th reference criterion levels

Year	Stream Name	Site Name	R / T	%F	%FS	%FSG<8	D50	Embedd.	%Facies.F	%FS.Grid	LRBS.D50	#Ex	Imp
2008	San Lorenzo R	Above city intake	T	8%	**59%**	**69%**	**1.25**	**40%**	**4.2%**	**50.4%**	**-0.823**	7	x
2008	San Lorenzo R	Paradise Park	T	2%	**42%**	**45%**	**12**	25%	0.4%	**30.6%**	**-0.642**	5	x
2008	San Lorenzo R	Lower H.C. State Park below RR	T	6%	**47%**	**68%**	**3**	21%	**3.4%**	28.0%	**-0.541**	5	x
2008	San Lorenzo R	Below H.C. entrance bridge	T	**11%**	**69%**	**71%**	**1.25**	**37%**	**5.2%**	**69.8%**	-0.296	7	x
2008	San Lorenzo R	Below San Lorenzo Way Bridge	T	3%	**41%**	**46%**	15.5	34%	**4.3%**	28.2%	0.001	3	
2008	San Lorenzo R	Above Hwy 9 - Ben Lomond	T	**9%**	**39%**	**48%**	**11.5**	23%	0.9%	28.4%	**-0.761**	5	x
2008	San Lorenzo R	Above East Lomond Rd. Bridge	T	**11%**	29%	33%	55.5	15%	0.5%	14.2%	-0.147	1	
2008	Zayante Creek	Above Railroad Bridge	T	3%	27%	32%	39.5	33%	1.2%	24.0%	-0.165	0	
2008	Zayante Creek	Above Quail Hollow Rd. bridge	T	**13%**	**38%**	**50%**	**8.5**	**34%**	**21.4%**	**49.0%**	0.223	7	x
2008	Lompico Creek	Above Lompico Cr. Rd. bridge	T	1%	27%	31%	57	27%	1.3%	**43.8%**	-0.086	0	
2008	Zayante Creek	Below Zayante Market bridge	T	2%	19%	27%	125.5	26%	**5.3%**	**35.2%**	0.415	2	
2008	Bean Creek	At Locateli Rd.	T	5%	**60%**	**62%**	**1.25**	32%	**10.0%**	**59.8%**	**-1.182**	6	x
2008	Bean Creek	Upstream of Morgan Runs Rd.	T	0%	30%	**42%**	**14.5**	28%	**5.4%**	23.4%	-0.212	3	
2008	Love Creek	Below Glen Arbor St. bridge	T	4%	24%	29%	34.5	**39%**	0.9%	23.2%	0.085	1	
2008	Boulder Creek	Below Highway 9	T	**9%**	16%	26%	130	**35%**	0.8%	19.6%	0.439	2	
2008	Bear Creek	Eurella	T	0%	25%	33%	30	32%	2.0%	16.0%	0.182	0	
2008	Newell Creek	Above Rancho Rio Rd.	T	**37%**	**51%**	**54%**	**1.25**	**38%**	**32.2%**	**43.8%**	**-1.506**	8	x
2008	Carbonera Creek	Above Carbonera Rd.	T	**12%**	33%	40%	26	**37%**	**4.6%**	**41.8%**	0.342	4	
2008	Branciforte Creek	DeLaveaga Park	T	**33%**	**51%**	**54%**	**1.25**	**43%**	**31.2%**	**44.2%**	**-1.461**	8	x
2008	Branciforte Creek	Below Shady Brook bridge	T	5%	**46%**	**51%**	**5**	33%	**7.9%**	**40.2%**	**-1.060**	6	x
2008	Shingle Mill Creek	Above Hwy 9	T	7%	**54%**	**62%**	**1.25**	28%	**4.7%**	**31.4%**	**-2.029**	6	x
2009	San Lorenzo R	Paradise Park	T	**11%**	32%	34%	50	8%	**3.8%**	**34.6%**	0.059	3	
2009	San Lorenzo R	Above city intake	T	**20%**	**63%**	**76%**	**1.25**	32%	**13.2%**	**57.0%**	-0.280	6	x
2009	San Lorenzo R	Lower H.C. State Park below RR	T	**12%**	**45%**	**63%**	**4.5**	34%	2.7%	**40.8%**	-0.093	5	x
2009	Bean Creek	At Locateli Rd.	T	**12%**	**59%**	**61%**	**1.25**	**42%**	2.0%	**50.8%**	**-1.100**	7	x
2009	Bean Creek	Upstream of Morgan Runs Rd.	T	1%	32%	33%	30	22%	0.0%	21.0%	0.140	0	
2009	Carbonera Creek	Above Carbonera Rd.	T	**12%**	32%	32%	58.5	21%	**4.2%**	**55.2%**	0.306	3	
2009	Branciforte Creek	DeLaveaga Park	T	**32%**	**49%**	**52%**	**5**	**36%**	**20.3%**	**40.4%**	**-0.737**	8	x
2009	San Lorenzo R	Below H.C. entrance bridge	T	**18%**	**42%**	**45%**	21.5	18%	1.6%	**60.2%**	-0.203	4	
2009	San Lorenzo R	Below San Lorenzo Way Bridge	T	**9%**	29%	35%	39	9%	**4.0%**	17.8%	-0.052	2	

Year	Stream Name	Site Name	R / T	%F	%FS	%FSG<8	D50	Embedd.	%Facies.F	%FS.Grid	LRBS.D50	#Ex	Imp
2009	Boulder Creek	Below Highway 9	T	4%	9%	17%	150	21%	0.9%	20.6%	0.483	0	
2009	Bear Creek	Eurella	T	6%	22%	26%	45.5	**37%**	3.0%	12.8%	0.514	1	
2009	Zayante Creek	Above Railroad Bridge	T	1%	28%	30%	68.5	17%	0.4%	15.6%	0.091	0	
2009	San Lorenzo R	Above Hwy 9 - Ben Lomond	T	5%	20%	24%	65	20%	0.5%	27.0%	-0.009	0	
2009	San Lorenzo R	Above East Lomond Rd. Bridge	T	6%	18%	22%	120	16%	0.0%	9.2%	0.143	0	
2007	Big Sur River	Coyote Flat	T	**34%**	**62%**	**63%**	**1.25**	**40%**			**-1.127**	6	x
2007	San Lorenzo R	Cowell Park - below train bridge	T	**17%**	**51%**	**57%**	**1.25**	27%			**-1.096**	5	x
2007	Bear Creek	Scout Camp	T	7%	25%	26%	40	10%			0.042	0	
2007	Zayante Creek	Above Graham Hill Bridge	T	0%	24%	24%	42.5	**35%**			0.023	1	
2007	Scott Creek	Swanton Ranch - CalPoly	T	**14%**	**39%**	**52%**	**5**	4%			0.184	4	X
2007	Soquel Creek	Lower	T	8%	**36%**	**41%**	15	9%			0.139	2	
2007	Aptos Creek	Below Valencia Confluence	T	0%	**88%**	**88%**	**1.25**	**59%**			**-1.293**	5	x
2007	Corralitos Creek	Above Hames	T	4%	15%	16%	60	5%			0.191	0	
2007	Arroyo Seco R	Above Green Bridge	T	0%	12%	12%	155	**45%**			0.661	1	
2007	Santa Rosa Creek	Behind High School	T	4%	23%	**42%**	**14.5**	28%			-0.304	2	

Criterion Level	**8.5%**	**35.5%**	**40.0%**	**15.00**	**33.7%**	**3.3%**	**28.8%**	**-0.390**
Indicator	**%F**	**%FS**	**%FSG<8**	**D50**	**Embedd.**	**%Facies.F**	**%FS.Grid**	**LRBS.D50**
Impaired Direction	**>**	**>**	**>**	**<**	**>**	**>**	**>**	**<**
Test Site Exceedances	19	22	24	23	15	18	19	14

Definitions:

%F	percent fines (transects)
%FS	percent fines + sand (transects)
%FSG<8	% FS + gravel<8mm (transects)
D50	median particle size mm
Embedd.	embeddedness
%Facies.F	percent fines on facies maps
%FS.Grid	percent FS on patch-scale grids
LRBS.D50	Log relative bed stability for D50

#Ex = number of exceedances
Imp = sediment impaired

Note that surveys conducted in 2007 did not include patch-grids or facies maps

Appendix C: 2007 study sites within the San Lorenzo watershed & criteria exceedances (>75th reference percentile)

Year	Stream Name	Site Name	R / T	%F	%FS	%FSG<8	D50	Embedd.	%Facies.F	%FS.Grid	LRBS.D50	#Ex	Imp
2007	**Kings Creek**	County Land **	**R**	**9%**	27%	28%	50	0%	Not collected		0.406	1	
2007	**Zayante Creek**	Above Graham Hill Bridge **	**T**	0%	24%	24%	42.5	**35%**	"	"	0.023	1	
2007	**San Lorenzo R**	Upper Camp Campbell	**R**	**23%**	**42%**	**48%**	**8**	12%	"	"	-0.229	**4**	**X**
2007	**San Lorenzo R**	Cowell Park - below train bridge **	**T**	**17%**	**51%**	**57%**	**1.25**	27%	"	"	**-1.096**	**5**	**x**
2007	**Bear Creek**	Scout Camp	**T**	7%	25%	26%	40	10%	"	"	0.042	**0**	

Sites with ** were re-sampled in 2008 and 2009, and consistent with these 2007 surveys, Kings and ZayanteCreek was not impaired, but San Lorenzo in lower Cowell SP below the RR bridge was impaired in all years.

Appendix D. Decision Rationale for Selecting Bedded Sediment Criteria:

Criterion Level of Reference Range	Advantages	Disadvantages	Statistical Implications
>50th percentile (indicator level most restrictive)	Requires test streams to be at least as good as the mid-range of all reference sites and protects stream inhabitants that depend on substrate quality that has low levels of sediment deposition.	Many streams that have natural high levels of loading would be judged impaired, including half of the reference streams. TMDLs might be required in many situations, creating high costs to the State.	Increases chances of Type I errors (unimpaired streams might be declared to exceed standards)
>75th percentile (indicator level intermediate)	Protects designated aquatic life uses in streams while limiting the number of circumstances where elevated sedimentation of test streams would be judged impaired when this is either marginal, not true, or due to natural causes.	There remains some chance of errors in assessing impairment but these may be offset by use of multiple indicators including benthic biological measures. Distinguishing natural causes from human sources would still be necessary.	Minimizes Type II error =false negatives (it is probable that truly impaired streams are detected, but if distinguished as partially supporting of standards in the 75-90 range, indicates these may be sites that are only partly degraded)
>90th percentile (indicator level least restrictive)	Only a few references judged impaired and minimal chance that test sites would be judged impaired when they are not or when natural sources cause most sedimentation.	Less protection afforded stream habitats and biota because reference extremes allow excessive levels of sediment to be acceptable. Degradation could go unchecked.	Minimizes Type I error =false positives (but partly degraded streams may go undetected if this is the only criterion used; but if used with the 75th, this distinguishes sites that are most severely degraded)