Development of Sediment TMDL Guidance Indicators: Relation of roads and land use disturbances at different spatial scales to the depositional environment of streams in the Sierra Nevada and Central Coast of California

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Report 1 of 4

Contract # 05-179-160-0

EXECUTIVE SUMMARY

The process of developing guidance for total maximum daily load (TMDL) limits on stream sedimentation is complicated by the difficulty in distinguishing what is natural from what is human-caused. Sediment occurs in both suspended and deposited forms, and may be identified as a pollutant only to the extent that it results from human activities that produce erosion and entry paths into stream channels. Sediment coming from land use disturbances is typically a non-point source pollutant and is usually not intentionally discharged. Problems can develop as increased erosion and delivery exceeds the capacity of a stream to transport load, resulting in disequilibrium of net deposition. Assessment of sedimentation problems requires evaluation of the extent to which existing conditions diverge from the natural state. The approach taken here to define natural expectations is through comparisons to the bedded or deposited sediments of reference streams.

The goal of this research was to study linkages between land use disturbance, natural erosion, instream depositional features, and benthic invertebrate indicators that define how deposited sediments impair beneficial use of the cold fresh water habitat category (including invertebrate aquatic life). The study design consisted of comparing reference and test streams of similar geomorphic type (gradient <2%, riffle-pool form) to contrast natural background conditions (least-disturbed references) with varied watershed exposures to landscape disturbances expected to increase erosion and sediment production. Land use disturbance was used to separate reference and test groups in the Sierra Nevada according to roadedness (known to be a major source of erosion and used to measure cumulative watershed land use exposure), along with aggregate human land use coverage in streams of the central coast region of California. Catchments with varied levels of road density were selected to cover a range of potential erosion and sediment supply in order to develop dose-response relationships.

Over this varied geographic area, data were gathered at multiple spatial scales to relate deposition within stream reaches to local, riparian, and catchment landscapes, providing insight to which measures of sedimentation are most closely connected to the pattern of watershed disturbance. Coordinated measures of sediments, GIS estimates of disturbed land use covers, and contrast of reference and test groups provided a foundation for identifying multiple stream bed sediment parameters for TMDL guidance that distinguishes where accumulated sediment deposition was in excess of background.. This first report provides background on site selection and survey methods relating sediment deposition to land use, followed by a second report using models of sediment loading to predict deposition, a third report on responses of benthic invertebrate communities over sediment gradients, and a fourth report using experimental stream mesocosms to study effects of sediment dose and duration on invertebrates.

Multiple lines of evidence support the conclusion that increases in deposited sediments can be related to road network density and combined land uses. There were significant increases in measures of sedimentation in test streams from both the Sierra Nevada and central coast compared to reference streams. Sediment dispersion patterns in streams were determined by reach-scale stream power, but land use or roads raise the minimum level of accumulated deposition, especially in low power streams. Sediment indicators were identified using the 75th & 90th percentiles of the reference distribution as numeric criteria levels for impairment, and showed that sediment limits would be lower in the Sierra (>15-27% fines and sand) compared to the central coast region (>27-34%).

INTRODUCTION

Degradation of physical habitat of streams through increased supply of sediment is a major cause of impaired biological integrity in streams (Waters 1995, Stoddard et al. 2005). Sediment is one of the most prevalent, non-point source pollutants impacting water quality in streams in the United States (USEPA 2006), and has recently been implicated in some cases as a point-source delivered through channels and ditches into streams from logging roads (*Northwest Environmental Defense Center v. Brown*, 617 F.3d 1176 (9th Cir. 2010)). In California, 30.5 percent of stream miles listed as impaired under the Clean Water Act in 2002 were listed for sediment, and sediment was cited more than any other pollutant, impairing nearly 17,000 river miles (SWRCB 2005). Assessing, managing, and restoring streams affected by sedimentation resulting from land use activities, and differentiating natural sediment levels, is one of the most difficult challenges faced by water quality managers. The extent to which natural erosion and sediment delivery to stream channels are exacerbated by land use disturbances is of concern for water resources regulation not only because of water quality degradation by turbidity or sediment accumulation in reservoirs, but because excessive deposition impairs aquatic habitat and beneficial life uses protected by the Clean Water Act. The goal of the TMDL process in this context is to characterize linkages between land use disturbance and the loading and deposition of sediments, and identify how this affects biological integrity of aquatic life. Developing criteria for suspended and bedded sediments will require a synthetic approach combining methods that define the limitations these stressors place on aquatic life, and detect where sediment loading and accumulation exceed levels found under natural reference conditions (USEPA 2006).

The advent of Geographic Information Systems (GIS) enabling detailed analysis of multiple categories of land use disturbances along with natural landscape features (geology, soils, slopes) has provided a means of expressing the cumulative influence of disturbances for multiple scales within the catchment of a stream (Allan 2004a). The effects of land use on stream habitat and biological integrity have often been presented in terms of urban land cover and impervious surfaces, or agricultural land cover and nutrient loading (Richards and Host 1994; Roy et al. 2003; Lammert and Allan 1999; Wang et al. 2001). In forested mountain landscapes where little urban or agricultural development occurs, the influence of roads has been identified as a significant source of erosion from slope instability and exposed land surface (Forman and Alexander 1998; Luce and Black 1999; Jones et al. 2000; MacDonald et al. 2004). Analyses of land use effects on streams have often been confined mainly to data sets involving few catchments, with limited geographic or physiographic variety, and emphasizing percent land cover classes rather than intensity of land uses (e.g. Richards et al. 1996, Roth et al. 1996; Nerbonne and Vondracek 2001, Sponseller et al. 2001; Bruns 2005, Stephenson and Morin 2008, Larsen et al. 2009). Although some of these and other studies have documented increases in measures of downstream habitat degradation and sediments with greater land use cover, they have come to conflicting conclusions about whether thresholds for impact exist, or at what spatial scale landscape changes can best be related to instream habitat or biotic conditions (reviewed in Allan 2004b).

Constructing sediment budgets to evaluate cumulative watershed effects (CWEs) of different land management practices (as required by the National Environmental Policy Act), has typically involved measures of hillslope erosion yield (e.g. silt fences, gully cross section changes), channel bedload movement (traps, dams), and suspended load (turbidity). How these yields transfer into the dynamic depositional regime of channels of the watershed network has less often been documented but has direct consequences to benthic stream habitat quality. Few studies have explicitly compared different quantitative or cumulative GIS measures of land use disturbances relative to reference conditions of natural background erosion, or utilized sediment loading models to explore the relation between potential sediment generation of the upstream watershed and the actual depositional environment observed in downstream reaches of mountain streams. CWEs and TMDLs are typically developed for the management of specific catchments or for particular stream segments designated as polluted on EPA 303(d) lists. This piecemeal approach is costly and yields criteria that vary from place to place, hindering development of general relationships between varied amounts of landscape disturbance and in-stream habitat quality that could provide general guidance for TMDL criteria and watershed resource management.

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, Rosgen 1996, Nash 1994, Trimble and Crosson 2000). Channel form classification has been used to describe how bedload and suspended load are distributed in different stream types (Schumm 2005), but there is still considerable uncertainty in predicting how streams and rivers respond to elevated erosion from land use activities, especially at local reach scales (Kinnell 2005, Pricope 2009). In studies conducted in the Klamath mountains of northern California (Cover et al. 2008), increased fine sediment in both pools and riffles was found to be related to soil-loss models predicting greater sediment supply. These results are difficult to generalize, however, as they were based on only six streams with low levels of sediment cover, and did not integrate measures of land use disturbance. A further limitation of this and other studies of landscape influence on sediment is that associated stream habitat surveys often examine only a few metrics of deposition such as percent fine and sand cover, mean particle size, or embeddedness. A comprehensive evaluation of land use effects on habitat and biota should include multiple descriptors of the depositional environment of reaches for different spatial scales, geologic settings, and types of upstream disturbance.

The conventional approach to developing TMDLs is to define the capacity of a waterbody to receive a pollutant load without degrading water quality standards (USEPA 1991). This typically involves defining mass loading rate, but sediment TMDLs present the complications of partitioning suspended and deposited load, natural from land use sources, undefined impairment levels for cumulative effects, and no uniformly accepted standards (USEPA 1999). Erosion and sediment production exhibit great spatial and temporal variability and contribute to the dynamic process of building, shaping, and renewing stream channels. Sediment can also be important to the ecological function of streams in providing habitat and cover for some organisms, substratum heterogeneity, and as a food resource to collector guild feeders (i.e., filterers and gatherers of organic sediment particles). It is excessive sediment, derived from human land use activities, that is of interest when evaluating ecological impairment in streams and developing a TMDL. Thus, the challenge of the TMDL process is to determine (1) what portion of the total sediment load differs from background levels in quantity or quality, (2) at what point does excessive sediment loading degrade habitat and ecological function, and (3) to identify indicators that can be used to define and quantify both the impairment and target conditions for recovery. Identifying these thresholds and indicators provide numeric targets for achieving control of the deleterious effects of excess sedimentation.

Alternative protocols that are being used to develop TMDLs for sediments (USEPA 1999) include modeling effects of sediment on specific designated standards (e.g., nutrients and dissolved oxygen), comparisons to historical conditions prior to sediment pollution where data is available, comparisons to reference conditions of natural or background sediment levels (upstream of nonpoint origins or in undisturbed watersheds), and experimental studies of sediment on target indicators. Incorporating a margin of safety (MOS) to account for uncertainty in the loading-water quality relationship is often used to ensure resource protection where statistical errors in endpoint indicators could lead to misjudged attainment of a standard. In a review of the conventional TMDL approach by the National Research Council (NRC 2001), the use of multiple criteria as water quality indicators – especially the integration of biological indicators –was identified as a critical need. Too often the indicators have relied only on chemical criteria, or in the case of sediment, on physical measures such as turbidity, TSS (total suspended sediment), and deposited fines. The NRC review further emphasized the need to establish linkages between specific stressors and impairment of designated aquatic life uses, and the cause-effect relationship of pollutant to response indicator. The sparse evidence on which many 303(d) listings have been made also argues that suspect water bodies should first be placed on a preliminary list and only after sufficient data has been gathered to substantiate a problem should the TMDL process be engaged. Informed by these needs and the shortcomings of previous studies, the goals of this study were to define multiple water quality targets using a reference watershed approach, identify sediment sources through GIS land use analysis, and provide quantitative linkage of source problems to both physical and biological indicators. Criteria for listing and de-listing sediment-impaired water bodies are one application of project results.

This report is intended to provide guidance on how land use and consequent alteration of erosion and sediment production affects the depositional environment of stream habitats. This part of the project was designed to achieve these objectives:

- Compare differences in the sediment deposition regime of stream reaches from watersheds exposed to a range of road density and other land use-disturbances relative to reference watershed streams representing the natural background condition of sedimentation within the differing geographic contexts of the Sierra Nevada and central coast region of California.

- Evaluate the influence of channel fluvial and hydraulic forces, and the spatial scale of watershed disturbance, on the patterns and particle size composition of sediment deposition within stream reaches.

- Develop endpoint indicator criteria for sediment TMDLs based on estimates of natural background sediment deposition at reference sites, the particle size distributions expected compared to those observed for streams of differing power and transport competence, and the excess levels of fines and sand in stream reaches within catchments disturbed by increasing levels of land use and roads compared to reference streams.

METHODS

Site Selection and Sampling

Stream reaches were selected to be of similar type, in terms of hydrology and fluvial geomorphology (e.g., gradient, flow regime, alluvial form). We identified stream reaches in the Sierra Nevada and Central Coast mountains of California to serve as candidate study sites that met the following criteria: (1) second to fourth-order size perennial streams; (2) less than or near two percent slope (riffle-pool geomorphology classification of Montgomery and Buffington 1997); (3) reach channels were unconfined and alluvial, with depositional bar formations; (4) absence of upstream reservoirs (dams), large lakes, or diversions that could act as sediment traps or affect the natural flow regime, and (5) confined sites in the Sierra Nevada to mid-elevation locations between 3000 and 8000 feet (ca. 1000 to 2500 meters) in elevation, while sites in the Central Coast Range were located above the tidal level influence and up to 3300 feet (1000 meters). Situated in these mid-watershed locations, these sites may also be considered zone 2 types (Schumm 2005), within a steady state transfer zone of transport and deposition of sediment, found in alluvial channel forms (Montgomery et al. 1996). Stratified by these stream types, our conclusions are primarily applicable to this classification of habitat type. After assembling a list of >300 candidate catchments that met these criteria based on inspection of 1:24,000 USGS topographic maps and screening for a range of road density coverages using GIS tools, we conducted ground-truthing visits to locate appropriate unconfined alluvial reaches. Because roads represent prerequisites for many forms of land use, and are conduits for sediment entry to streams, a range of road densities provided a means of sampling over a potential sediment “dose” gradient. Following site visits, about 200 candidates were eliminated owing to absence of appropriate geomorphology (e.g., boulder-controlled channels, local point-source pollution), were intermittent or of insufficient length, or were inaccessible. In total we surveyed 98 sites, 74 in the Sierra Nevada and 24 in the central coast range (Figure 1), with watersheds ranging in size from 12 to 731 km^2 (Tables 1 and 2). Some analyses were supplemented with prior data taken in similar stream surveys in the eastern Sierra.

Sampling began each year with sites in the southern regions of the mountain ranges and progressed north with the season. In 2006 we sampled 15 sites in the Sierra Nevada in July through September; in 2007 we sampled all 24 sites in the central coast range in May and 48 sites in the Sierra between June and September; and in 2008 we sampled 11 sites between July and September in the Sierra. These periods also represent a mix of flow conditions, with 2006 snowpack about 40% above average, 2007 near 50% below average, and 2008 near-average. In order to characterize error variation in physical habitat features measured, we performed complete repeat physical habitat surveys at 5 sites in 2008 (results not reported here).

Reference-Test/Dose Designations

Sites were partitioned into reference and test groups by identifying breaks or discontinuities in site distributions for co-plots of road density and road crossings in the Sierra, and road density and catchment human land use in the coast range (Figure 2). Separate criteria were used in recognition of differing geographic, geologic and climatic settings, as well as biogeographic distinctions and the dominant types and extents of land use. Road density was used to quantify a gradient of disturbed habitat conditions with the

Figure 1. Watershed boundaries of the 98 study sites in the Sierra Nevada and Central Coast mountains surveyed for sediment TMDL development.

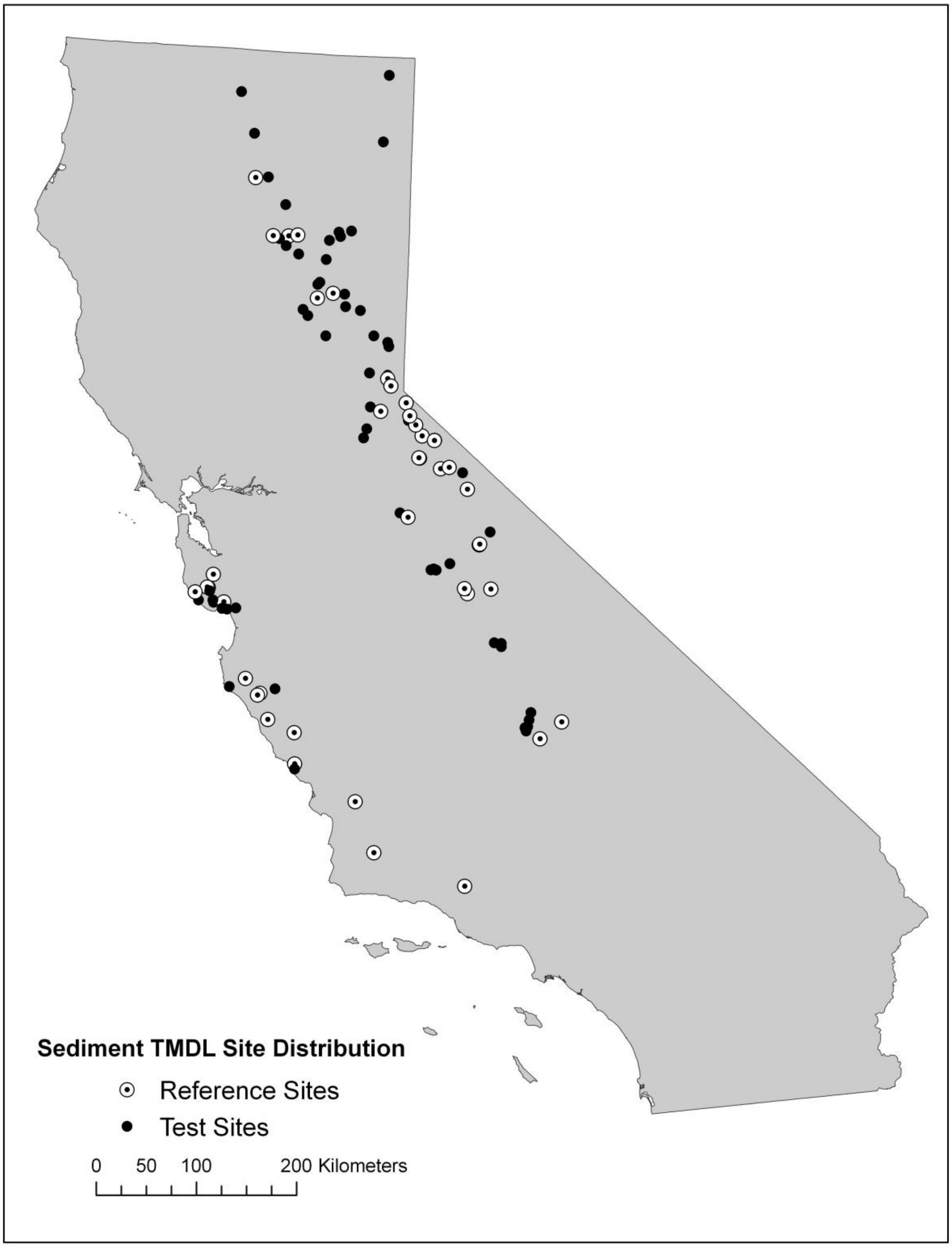


Figure 2. Study reach locations and designation as reference or test/dose status in the Sierra Nevada and Central Coast mountains.

Table 1. Sierra Nevada study sites and reach coordinates, slope, elevation, order, upstream catchment size, and road disturbance.

Stream Name	Site Name	GPSLat	GPSLong	Slope (%)	Site Elev (m)	Stream Order	Area (km)	Road Dens (km/sqkm)	Road Xings	Reference / Test
Deadman Cr	Above Road Crossing	37.7531	118.96453	0.61	2241	3	92.9088	2.12	0.654	Test
West Walker R	Above Leavitt Oxbow	38.31307	119.54842	0.30	2175	4	143.291	0.01	0.008	Reference
Lewis Fork	Below Cedar Valley	37.39932	119.62548	1.05	1006	3	42.8814	2.47	0.894	Test
Trout Cr	Above Pioneer Trail	38.89633	119.9657	0.13	1914	3	61.0047	0.71	0.295	Reference
Ward Cr	Top Avulsed Meadow	39.13902	120.18834	0.99	1982	2	28.7919	2.65	0.635	Test
Stanislaus R (Clark Fk)	Above Arnot	38.40397	119.79316	0.84	1879	4	104.158	0.21	0.045	Reference
Blackwood Cr	Below Barker Pass Road	39.10791	120.18952	0.44	1936	2	23.1192	1.02	0.344	Reference
West Carson R	Upper Hope	38.7391	119.93209	0.29	2171	3	71.1252	1.13	0.400	Test
General Cr	Above Loop Road	39.04283	120.14828	1.16	1964	2	20.1051	0.73	0.338	Reference
Arnot Cr	At Trailhead	38.40579	119.79781	1.81	1879	3	37.881	0.33	0.135	Reference
Jawbone Cr	Above Falls	37.9036	119.99539	1.07	1050	3	51.9597	3.42	0.954	Test
Nelder Cr	Below California Cr	37.41003	119.59538	1.31	1417	2	21.7422	1.88	0.817	Test
Tuolumne R (Middle Fk)	Below Mather Camp	37.86885	119.9028	0.97	1210	3	149.747	0.09	0.033	Reference
Pitman Cr	Below Highway 168	37.19512	119.20783	1.22	2170	3	65.2068	0.35	0.090	Reference
Home Camp Cr	Inside Wilderness	37.24059	119.24243	1.13	2200	3	16.6239	0.03	0.000	Reference
Dry Meadow Creek	Camp 4	36.00871	118.50607	2.14	1363	3	34.5582	1.65	0.675	Test
Nobe Young Creek	Camp Whitsett	35.99782	118.53639	1.01	1412	3	43.4133	1.41	0.528	Test
South Creek	Below Johnsondale	35.96983	118.52168	0.39	1409	3	58.8627	2.16	0.525	Test
Peppermint Creek	Above Lower Campground	36.06813	118.49105	2.24	1603	3	26.9181	1.14	0.815	Test*
Freeman Creek	Pyles Camp	36.13534	118.47314	0.58	1694	3	45.9819	0.34	0.191	Test
Kern River (South Fk)	Above Campground	36.05605	118.13082	1.09	1867	4	524.669	0.02	0.012	Reference
Willow Creek (North Fk)	Above Gray Mountain CG	37.40073	119.56684	1.03	1598	3	50.5584	1.93	0.502	Test
Boulder Creek	Above Florence Lake Trail	37.24082	118.94688	0.57	2245	3	37.9521	0.00	0.000	Reference
Tenmile Creek	Below Tenmile CG	36.75773	118.8951	0.51	1758	2	19.3833	1.51	0.649	Test
Salmon Creek	Horse Meadow CG	35.90079	118.36854	1.04	2241	2	30.1113	0.57	0.349	Reference
Silver Creek	Above Silver Mountain Site	38.6031	119.76973	1.76	1966	4	53.4681	0.74	0.176	Reference
Sagehen Creek	Below Highway 89	39.43274	120.20279	0.91	1867	2	38.2806	2.16	0.848	Test
Prosser Creek	Above Highway 89	39.39615	120.1885	0.97	1766	3	76.7232	1.70	0.465	Test
Silver King Creek	Lower Meadow	38.56785	119.62523	1.08	1959	3	112.863	0.00	0.000	Reference
Carson River (East Fk)	Above Silver King Creek	38.56603	119.62754	1.03	1955	3	123.231	0.00	0.000	Reference

Stream Name	Site Name	GPSLat	GPSLong	Slope (%)	Site Elev (m)	Stream Order	Area (km)	Roadedness (km/sqkm)	Road Xings	Reference / Test
Little Truckee River	Upper Perazzo Meadow	39.48692	120.36777	0.56	1987	3	67.5243	0.97	0.473	Test
Hot Springs Creek	Above Footbridge	38.69991	119.8474	0.80	1793	3	38.9871	0.66	0.183	Reference
Willow Creek	Above West Carson	38.77952	119.91801	0.70	2157	3	28.1574	0.47	0.224	Reference
Swauger Creek	Above Gauging Station	38.28077	119.29547	0.58	2022	3	139.846	1.52	0.252	Test
Little Walker River	Above Cow Camp Creek	38.32812	119.44958	1.55	2153	3	98.7399	0.28	0.153	Reference
Green Creek	Above Green Creek Road	38.13393	119.23542	0.42	2380	3	48.213	0.80	0.163	Reference
Minaret Creek	Below Falls	37.63777	119.08731	0.68	2317	3	25.2639	0.00	0.000	Reference
San Joaquin (Middle Fk)	Below Soda Springs CG	37.64286	119.0817	1.03	2322	3	85.4334	0.15	0.042	Reference
Consumnes River (Middle Fk)	Pipi CG	38.56523	120.44129	0.52	1174	3	118.944	1.80	0.559	Test
Consumnes River (North Fk)	Above Caps Crossing CG	38.64993	120.40831	0.52	1536	2	53.8569	1.77	0.481	Test
Jones Fork Silver Creek	Above Icehouse Road	38.84842	120.37637	0.17	1497	3	65.6541	1.26	0.496	Test
American River (Middle Fk)	Above Ahart Campground	39.15278	120.39999	0.99	1641	3	75.7224	1.46	0.684	Test
Lyons Creek	Below Wright Lake Road	38.81371	120.25589	1.09	2022	2	17.28	0.33	0.154	Reference
Meadow Valley Creek	Above Meadow Camp	39.92997	121.04464	0.53	1137	3	35.901	2.52	0.472	Test
Spanish Cr	Below Meadow Valley Cr	39.94902	121.01967	0.56	1075	4	166.006	2.22	0.550	Test
Nelson Cr	Above Feather River	39.80582	121.04208	1.06	941	3	50.3145	0.26	0.118	Reference
Onion Valley Creek	Above MF Feather River	39.85506	120.86166	0.82	1186	4	117.854	0.86	0.324	Reference
Sulfur Creek	Above White Hawk Ranch	39.71107	120.53414	0.97	1400	3	38.0439	2.98	0.933	Test
Jameson Creek	Above Plumas Eureka CG	39.7398	120.70709	0.36	1602	3	19.4706	1.50	0.641	Test
Feather River (North Fk)	Below Gun Club	40.3531	121.4127	0.51	1626	3	59.7528	1.00	0.295	Reference
Warner Creek	Above CG	40.36429	121.30659	0.58	1523	3	116.464	0.71	0.333	Reference
Butt Creek	Above Soldier Cr	40.19473	121.28523	1.16	1431	3	53.1396	1.83	0.309	Test
Willard Creek	Above 29N02	40.36709	120.80288	1.68	1469	3	55.1223	3.11	0.750	Test
Wolf Cr	At County CG	40.15651	120.95572	0.75	1098	3	91.1223	2.54	0.752	Test
Susan River	By Biz Johnson Trail	40.40592	120.82208	0.38	1458	3	304.06	1.95	0.724	Test
Goodrich Creek	Above Hwy 36 Bridge	40.32976	120.93088	0.33	1553	3	78.1938	1.52	0.499	Test
Susan River	Above Hobo Camp	40.42087	120.67546	0.21	1297	4	463.794	2.51	0.794	Test
Lassen Cr	Below Lassen Cr C.G.	41.25557	121.8793	0.62	1161	3	111.592	1.79	0.644	Test
Pit River (South Fk)	Below Jess Valley Bridge	41.83227	120.29946	0.59	1624	3	44.2368	3.36	0.581	Test
McCloud River	Above Algoma CG	41.23338	120.34153	0.15	1545	4	250.52	1.61	0.509	Test
Burney Creek	Above Jackrabbit Bridge	40.87187	121.68665	0.41	969	3	236.882	1.54	0.544	Test

Stream Name	Site Name	GPSLat	GPSLong	Slope (%)	Site Elev (m)	Stream Order	Area (km)	Roadedness (km/sqkm)	Rd Xings	Reference / Test-
Hatchet Creek	Above Moose Camp	40.8612	121.83743	0.77	1131	3	58.3047	0.53	0.348	Reference
Hat Creek	Below Twin Bridges CG	40.63047	121.46606	1.80	1428	3	273.113	1.65	0.430	Test
Big Meadow Cr	At Big Meadow Camp	36.72338	118.81498	1.16	2291	3	18.1341	1.29	0.434	Test
Little Boulder Cr	Little Boulder Sequoia Grove	36.7534	118.81726	1.94	1941	3	11.934	1.92	0.683	Test
Mugler Cr	Below Beasore Rd	37.45943	119.41564	0.75	2008	3	21.8007	2.18	1.000	Test
Oregon Cr	above Millers Crossing	39.47098	120.9246	1.16	1134	3	35.8425	2.19	0.724	Test
Poplar Cr	above gravel yard	39.85187	120.72567	1.11	1262	3	29.6496	2.11	0.704	Test
Fall Cr	above FS Road #24	39.64455	121.14382	0.80	1169	2	35.1819	2.18	0.613	Test
Cascade Cr	below FS Road #94	39.69833	121.20379	1.24	1154	3	13.2912	2.63	0.900	Test
Deer Cr	DFG fishing access	40.2634	121.43418	0.45	1490	3	135.791	2.31	0.647	Test
Butte Cr (Shasta)	above wooden bridge	41.62381	122.06375	0.72	1477	3	157.204	1.59	0.533	Test
Martin Cr	at Mineral	40.34849	121.59264	1.81	1504	3	17.7228	0.93	0.349	Reference
Mill Cr	below summer homes	40.32411	121.51771	1.32	1392	3	69.8148	1.66	0.802	Test

Note*: Freeman Creek at Pyles camp excluded from Reference data set because of local disturbances in the form of housing development and gravel quarry upstream from study reach, even though meeting road criteria for reference.

Table 2. Central Coast Range study sites and reach coordinates, slope, elevation, order, upstream catchment size, riparian road density, and percent human land use in the catchment. Some test designations marked * based on exclusions for specific local disturbances or because natural forest vegetation was <40% at all spatial scales (catchment, riparian, reach), precluding reference designation.

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

Note*: 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.

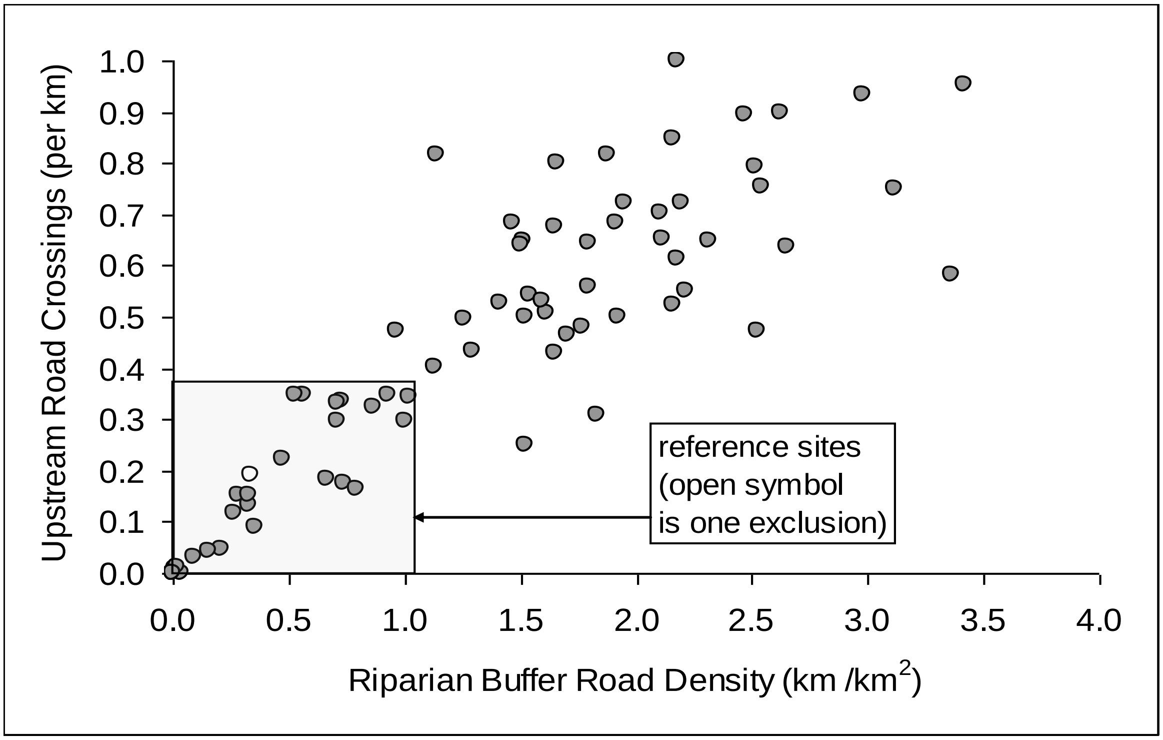


Figure 3. Partition of reference site data set for the Sierra Nevada based on lowest levels of road disturbance exposure (crossings or density within riparian buffer zone).

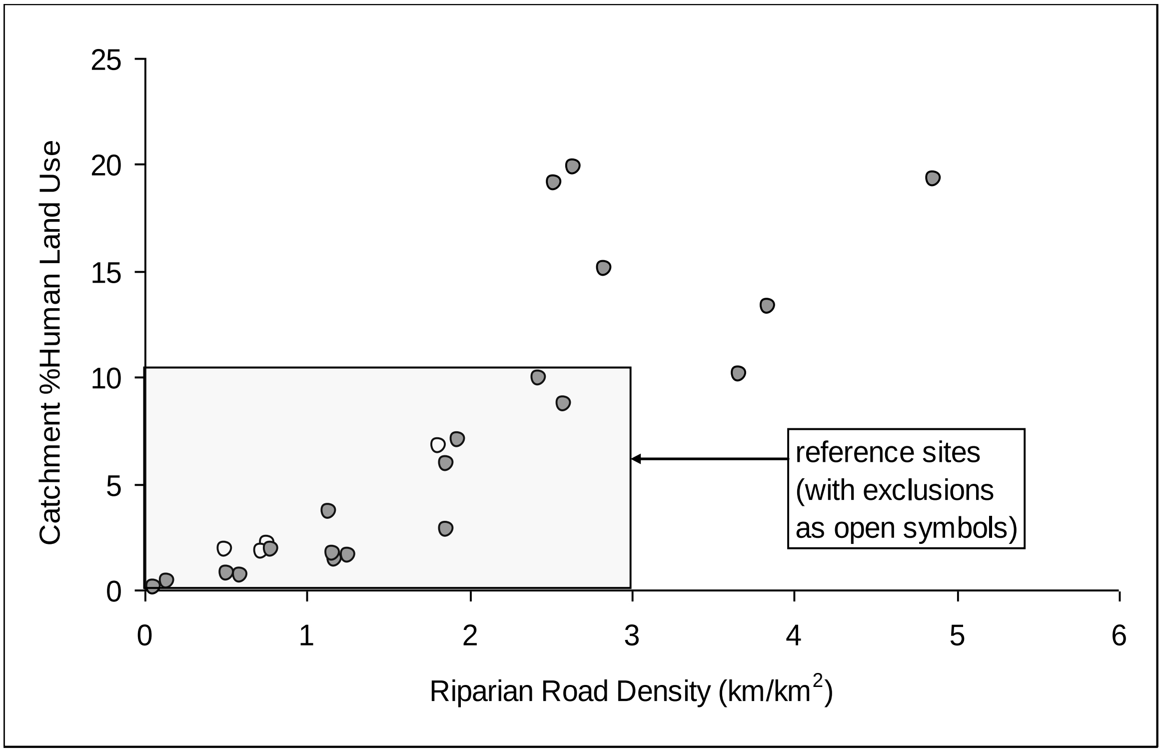


Figure 4. Partition of reference site data set for the Central Coast Range based on low levels of riparian road density and human land use <10% (Appendix A).[further specific exclusions (open symbols) based on local disturbances present; see note Table 2]

potential to generate increased levels of erosion. Because access for nearly all types of land use requires roads, riparian road densities and road crossings serve as proxies for the intensity of other types of development and disturbance. We defined reference sites in the Sierra as those with road density within a 100 m buffer each side of the stream of less than about 1.0 km/km^2 and upstream road crossings less than 0.4 crossings/km (Figure 3). In the coast range, limits were set using mixed criteria of riparian roads ≤3.0 km/km^2 and ≤10% combined human land uses within the catchment (Figure 4). Coast range criteria also correspond to the levels used for reference selection in sediment TMDL research on the San Lorenzo River (Herbst et al. 2011). In the Sierra these boundaries also correspond to the lower trisection of the range of road disturbance exposure, while in the coast range references sites were within the lower half of land use and road disturbance levels. Some reference exclusions were made in both regions based on local impacts not evident in GIS. Through this selection process, we identified references at 28 of 74 sites in the Sierra, and 14 of 24 coast sites. Test sites thus covered a range of potential inputs of sediment by virtue of having higher levels of road density and associated land uses.

Landscape Analyses

We conducted all landscape analyses at three spatial scales: (1) catchment, which included all area in a watershed upstream of a stream survey location; (2) riparian, which included the area within 100 meters of each side of all perennial stream channels upstream of a survey location; and (3) reach, which included the riparian area (100 meters on each side of stream channel) within 500 meters above the lower end of each reach location (Figure 5). For all landscape analyses, we used a Geographic Information System (ArcGIS 9.2, Environmental Systems Research Institute) and derived stream channel locations from the National Hydrography Dataset (NHD) (Bondelid et al. 2006).

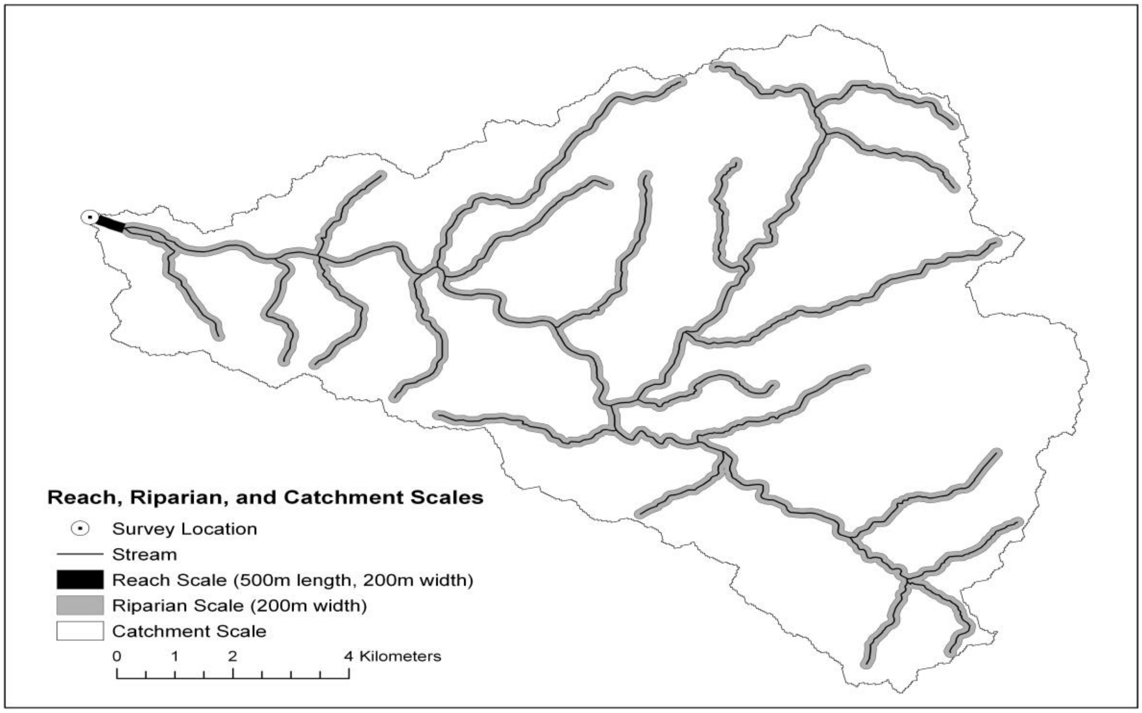


Figure 5. Landscape scales for analysis of land use effects.

Topography and Hydrology Landscape Measures

We derived averaged hillslope from a 30-meter resolution Digital Elevation Model (DEM) by calculating percent slope for each pixel and combining these as an averaged pixel slope for each site. We defined channel relief ratio as the elevation gain (relief) over the mainstem stream channel of each site divided by the length of the mainstem stream channel for each site. Mainstem stream channels for each site were determined using the NHD “VAA navigate upstream mainstem” tool to calculate mainstem length and the relief of the mainstem channel from a 30-meter resolution DEM.

Individual Landscape Disturbance Measures – Road Density & Development Intensity

In order to evaluate the magnitude of disturbance to watersheds from roads, we calculated road density and road crossings for each site. Road locations were obtained from the Topologically Integrated Geographic Encoding and Referencing (TIGER) dataset produced by the U.S. Census Bureau. Road density was calculated as the length of road within the area of each spatial scale divided by the area of that scale (km/km^2). Road crossings were defined as the number of road-stream intersections in a watershed divided by the total length of stream segments in a watershed (road crossings/km).

We used the Development Footprint, created by the California Department of Forestry and Fire Protection as a measure of the density of development on the landscape. The Development Footprint is based on both U.S. Census Bureau and NLCD (National Land Cover Dataset) data to estimate population density. In the Development Footprint dataset, pixels are assigned to 1 of 4 classes of population density, and from this the mean value of population class rankings was calculated for each site.

Individual Landscape Disturbance Measures – Land Cover

Imperviousness is a measure of the landscape’s inability to absorb water (typically paved surfaces), and was obtained from the Multi-Resolution Land Characteristics Consortium’s (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. This layer was used to calculate the percent area classified as impervious for the catchment of each site.

The Fire Perimeter dataset available from the California Department of Forestry and Fire Protection (FRAP) was used to account for disturbance to watersheds from fire. This dataset is a multi-agency comprehensive fire perimeter layer for wildfire and prescribed burns. We extracted fires that occurred within the last ten years prior to our field sampling (1995-2005) and calculated the percentage of area, at each scale, where recent fires have occurred.

We estimated the potential distribution of livestock grazing in our study sites by adapting cattle grazing distribution modeling methodologies (Wade and et al. 1998). Potential rangeland grazing was calculated as the percentage of area within one km of a stream designated as “Grassland / Herbaceous” in the 2001 NLCD. This measure was modified by adding a travel cost for cattle movement based on hillslope (cattle are less likely to graze on steep slopes). This coverage provides an estimate of the potential area where cattle movement and grazing are most likely to occur. Coverage of actual livestock allotments on US Forest Service lands were not used because they did not account for private land grazing.

We derived a measure of forest mortality from the United States Forest Service aerial detection survey geodatabase. This geodatabase provides spatial data for pest and fire mortality that was mapped during aerial detection surveys for USFS Region 5 from 1993 to 2007. One component of the geodatabase is an estimate of the number of damaged trees per acre. From this database, we calculated the percent area of the catchment of each site where mortality of at least ten trees per acre was observed.

Because land management data such as logging activity and forest mortality is not readily available for private land, we calculated the percentage of private land for the catchment of each site. Private land data was obtained from the California surface ownership geodatabase of the Bureau of Land Management, and was defined as any area not administered by a federal or state agency.

Coverage of natural vegetation, forest canopy density, and human land use were derived from the 2001 NLCD. This provided a classification of land surfaces from 2001 Landsat 7 satellite data (Appendix A). Natural vegetation cover consisted of NLCD classes that could potentially serve as protection from rainfall impact and/or in filtering sediment from reaching stream channels. These classes included 41 (deciduous forest), 42 (evergreen forest), 43 (mixed forest), 52 (shrub/scrub), 90 (woody wetlands), and 95 (emergent herbaceous wetlands). Forest canopy density quantifies the density of tree canopy in each pixel of classes 41, 42, 43 and 90 as a percent. Combined human land use cover was defined as all NLCD classes that are the result of human activities including 21 (developed, open space), 22 (developed, low intensity), 23 (developed medium intensity), 24 (developed high intensity), 81 (pasture/hay), and 82 (cultivated crops).

Cumulative Landscape Disturbance Measure - Equivalent Roaded Area

Equivalent Roaded Area (ERA) is an index that has been developed to evaluate the cumulative watershed effects from landscape disturbances such as roads, forest harvesting, wildfire, and grazing. ERA was adopted and implemented by the USFS in the Sierra Nevada and has been used to document post-logging landscape recovery and relationship to macroinvertebrate diversity (McGurk and Fong 1995).

To determine the cumulative ERA for a particular watershed, an ERA for each disturbance in that watershed is calculated individually and then summed. The ERA for each disturbance activity is calculated as the product of the area of the disturbance by an ERA coefficient that is specific to each disturbance type. ERA coefficients account for the potential impact of each disturbance activity on streams as well as the amount of time since the activity occurred. All coefficients were derived in relation to the impacts from a road, which has a coefficient of 1.0. For example, a two year old tractor clearcut has an ERA coefficient of 0.24 while a fifty year old tractor clearcut has an ERA coefficient of 0.08. The road coefficient of 1.0 remains static since the impacts from roads generally do not diminish over time.

We followed the ERA methodology described by Menning et al. (1997) and used ERA weighting coefficients for different land use types developed by Kuehn and Cobourn (1989), Carlson and Christiansen (1993), and modified by Menning et al. (1997). Data from roads, logging, fire, and grazing were included in our ERA calculations. Road data was derived again from the Topological Integrated Geographic Encoding and Reference system (TIGER) of the U.S. Census Bureau. When calculating the area of a road, we assumed a road width of eleven feet. Logging data came from the

USDA Forest Service Activity Tracking System (FACTS) and Accomplished Harvesting Activities geodatabase, and fire data came from the California Interagency Fire History geodatabase. Logging extent was calculated as the percentage of the catchment that had logging activity within the last 6 years (an assumed recovery time from logging effects on sedimentation). Grazing cover data came from the USDA Rangeland Management Units geodatabase, and used only rangeland grazing allotments that were classified as active.

Geographic information data for logging and grazing is not readily available for private lands. Most of the streams on the coast were located in areas that were predominantly privately owned. The ERA methodology was intended for use on forested public lands (the National Forests), so we applied this approach only in the Sierra and only in catchments where private land area was less than 20% (63 of 74 sites).

Watershed Erosion Potential –K factor

Soil erodibility, or K factor, represents the susceptibility of soil to erosion as well as the rate of runoff associated with a particular soil type. K factor is dependent upon the mineral content and texture of a soil type. For example, clay soils have a low K factor as they are more resistant to detachment while soils with high silt content have a higher K factor as they are more easily eroded and produce higher rates of runoff (Renard et al. 1997). K factor values were derived from the State Soil Geographic (STATSGO) database. In GIS we created 30-m grids of K factors of the top mineral horizon of all soil types in our study watersheds, and then calculated the average K-factor at different scales (catchment, riparian, reach).

Physical Habitat Surveys of Reach Geomorphology

Channel and Transect Descriptions

Each site location was identified by local feature or landmark name (e.g. road crossings, tributaries) and GPS coordinates. Prior biological and habitat surveys, the pH, conductivity, and stream temperature were measured using a calibrated Oakton pH Con/10 meter. Sample reach length was 150 m for streams with an average width of less than 10 m, and 200 or 250 m for streams wider than 10 m. Each reach was delineated by setting fiberglass surveyor tape on reels extending from the downstream start-point to the upstream end-point. Beginning and end-points of riffles and pools were recorded to describe the extent and position of these macrohabitat features and to guide slope measurements. Photos of the entire reach were also taken at 50 meter intervals, upstream and downstream at each point, and at depositional bar features.

Transects for physical measurements of channel morphology were located at 20 regularly placed cross-sections within each sample reach. At each transect the wetted stream width was measured. To provide an index of channel sinuosity, compass declination along the channel midline of each inter-transect segment was recorded by standing at stream center and reading the compass bearing directed toward the stream center of the previous transect. At five equally-spaced points across the submerged transect, depth and substrate size were measured. Substrate size was measured as the intermediate axis of all particles larger than 2 mm, or recorded as sand for particles estimated as 0.25 to 2 mm, or as fines if < 0.25 mm (surveyors were trained to recognize these classes by texture). In addition, substrate cover present in the form of macroalgae, detritus, leaf, root, wood, moss, and aquatic vegetation were recorded if present at the point-intercept. If cobble substrates (64 – 256 mm in diameter) were encountered at sample points, embeddedness was measured as the percentage (±5%) of the stone volume embedded/buried in sand and or fine substrate. Group training of observers was conducted prior to surveys to achieve consistent scoring of embeddedness. If 25 embeddedness measurements were not recorded on completion of transects, remaining counts were obtained from random locations throughout the reach. The stream bank zone between the wetted margin and bankfull marking (assessed visually using erosion marks, vegetation, and bank slope evidence) was described by recording categorical attributes of bank cover (armored, vegetated, or open), stability (stable, vulnerable, or eroding), and bank angle (shallow <30°, moderate 30-90°, or undercut >90°). The dominant vegetation within this zone was categorized as herbaceous, or woody bush, or tree (bush and tree morphotypes were separated by stature at < or > 3 m height). A forest canopy densitometer (grid-inscribed concave mirror) was used to measure riparian cover density from the water surface at stream center in upstream and downstream directions, and at both margins (after Platts et al. 1987).

Slope was measured using an auto-level (Topcon AT-G7) and stadia rod. Measurements were made for ten equally spaced sections along the reach, with additional measurements taken at the bottom and top of riffle sections (slope breaks). If vegetation, sinuosity, or other sightline disruptions prevented the section from being viewed in one sighting, shorter sections were measured and combined.

At ten of the 20 transects, cross-sectional width and depth measurements were taken to determine bankfull channel dimensions. Twenty evenly-spaced depth (height) measurements were recorded as the distance from the stream bed to a taught meter tape stretched between bankfull marks on both banks. A profile of depths and substrate type was also taken along the channel thalweg, defined as the deepest point along the primary longitudinal flow path of the stream. For this measure, depth and substrate composition were recorded at intervals of 2 meters (and at pool-tail crests), with substrates classified as fine (<0.25 mm, F), sand (0.25–2 mm, S), gravel (2–16 mm, G), pebble (16–64 mm, P), cobble (64–256 mm, C) or boulder (>256 mm, B). These data were used to compute the variability in cross-section and thalweg depths that have been used as indicators of the extent of depositional infilling as bed profile becomes more homogeneous with sedimentation (Bartley and Rutherford 2005) and may have more depositional cover.

Large wood debris (LWD) encountered within the inter-bankfull channel segments was counted and classified according to diameter and length dimensions (shown below). The volume per piece for each class was taken as the median volume of the smallest to largest pieces within a class (maximum length of 10 m in class L). The number in each class was summed over all segments to find total reach LWD. LWD provided a measure of geomorphic heterogeneity, habitat structure, allochthonous organic matter inputs, and debris flow remnants.

Diameter	**Length (m)**			**Class**	**Median volume m^3**
(cm)	**0.25-1.5**	**1.5-5**	**>5**	A	0.037
5-10	A	A	T	T	0.152
10-25	A	T	S	S	0.609
25-50	T	S	M	M	2.086
50-100	S	M	L	L	4.418

Bedrock along transect

Selected study reaches were not bedrock-controlled, but there were cases of bedrock outcrops on some substrate transects. In these cases, where diameter could not be measured, size was estimated as the value of the wetted width divided by two.

Depositional bar delineation, fine/sand grid counts, and mapping

Depositional bars form along stream channels as a function of the dynamics between import and export of bedload and suspended load of sediments in accord with the power and competence of stream flows. Surveys conducted during lower flows permits these features to be mapped. Bars may form at the inside of meander bends as point-bars, as alternating lateral bars along the margins of a stream, or as detached islands. Bar formations were recognized as areas where accumulated substrate particles formed emergent features that typically left stranded areas above the stream level. Bar features were delineated by measuring their downstream to upstream position, at channel left, center, or right (Figure 6). Size, shape, and substrate composition of bars were mapped on scaled grid paper according to length and width dimensions (3 equal-spaced width measures across each bar to bankfull). Based on observed particle facies patches over the bar, mapped grids were assigned to one of 4 clasts: sand + fine (<2 mm), gravel, cobble, or mixed sand (50% sand-fine + another clast). In addition, on submerged portions of bars, deposits of fines and sand were determined by randomly placing 20 quadrats in 10 cm water depth at bar positions selected from a random number table. At each sample location, a 20 x 20 cm square grid frame (holding 5 x 5 intersecting filament lines) was gently placed over the substrate, and counts made of the number of fine and sand particles at the 25 intersection points (using a 10 cm diameter PVC plastic cylinder with clear plexiglass glued at one end for underwater viewing).

Scales of sediment deposition measurement

The techniques described above allowed deposition within reaches to be characterized at three scales: point-counts along transects over the entire reach, patch-scale (deposition along bar formations measured using grid-frame counts), and facies-scale (maps of large depositional bar features along the channel). These represent fine-to-coarse levels of resolution of particle deposition, at increasing scales of spatial pattern.

Data Analysis of Reference-Test Groups and Environment-Sediment Relations

At the outset of the study, we hypothesized that measures of sediment deposition in the study reaches would change in predictable ways between reference and test streams, with hydraulic geometry, and with land use. Many variables exhibited non-normality in distribution, so we used nonparametric Mann-Whitney U-tests for contrasts (as one-tailed tests specified by the expectations). Bonferroni corrections to p-values for the multiple comparisons were not used as these were planned as *a priori* hypotheses of the study (Moran 2003). NMDS ordination of reach sediment features was conducted to depict similarities among streams and reference-test separation over environmental gradients (PC-Ord, v.5 MjM software, Gleneden Beach, Oregon). In addition, quantile regression (Blossom software) was used to describe road and land use influences on sediment, and multiple regression to determine environmental variables at different scales that contributed most to observed sedimentation (NCSS 2007 software, Kaysville, Utah).

Fine Sediment Pollution Indicators

Instream sediment data collected during stream sampling formed a heirarchy of scales of resolution. Primary measurements taken as points along transects included percent sands and fines, added percent gravel (less than 8 or 16 mm), D50 median grain size, and thalweg fine-sand-gravel. Grid sampling of the distribution of fines and sand on depositional bars was used to measure patch-scale clustering of fines and sand on bar formations, and the area and composition of the bars themselves provided the largest scale measure of deposition in a reach. In addition to these measures, independent estimates of the extent of sedimentation were also derived from calculation of relative bed stability and excess sand and fines (Kaufmann et al 2009). These parameters involved comparing the difference between expected particle size distribution (based on principles of stream flow forces operating on particles) and those observed.

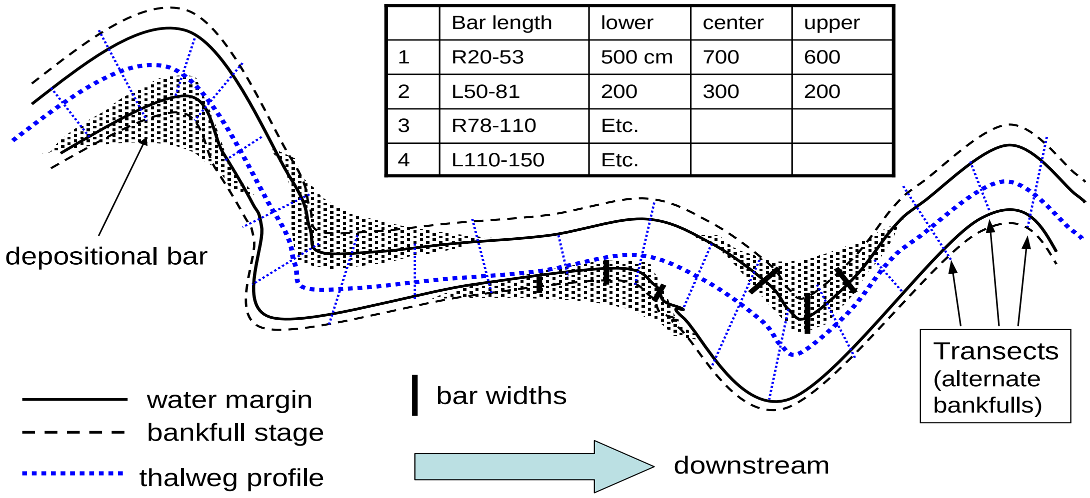
Relative Bed Stability (RBS) calculates the departure of substrate size distribution from the expected condition, based on reach slope and geometry(Kaufmann et al 1999):

> RBS = $[D_{50}] / [13.7 * [R_{bf} - R_w - R_p] * S]$, where D_{50} is the median grain size (mm), R_{bf} is the mean reach hydraulic radius (cm), R_w is the volume of large woody debris (m^3), R_p is ½ the mean residual depth (mm), and S is reach slope. Geometric mean grain size (mm) may be substituted for $[D_{50}]$.

The calculation of excess fines and sands (FS) was based on EPA methodology (Kaufmann et al. 2004). We regressed the percent of fines and sands found at reference sites against the log-10 transformation of expected median grain size (denominator of the RBS equation). 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:
$Y = m (\log10(13.7 * [R_{bf} - R_w - R_p] * S)) + b$, as calculated specific to each test site.

<u>Reach-Scale</u>: Deposition within active bankfull channel

- Measure dimensions of point bars, lateral bars and islands below bankfull
- Map particle clast facies over each bar (sand-fine, gravel, cobble, mixed)



	Bar length	lower	center	upper
1	R20-53	500 cm	700	600
2	L50-81	200	300	200
3	R78-110	Etc.		
4	L110-150	Etc.		

Figure 6. Physical habitat surveys of depositional bars and other features.

RESULTS

Reference and Test Group Differences

Previous definitions of sediment include a size range of silt-sand and smaller gravel fractions, their spatial pattern of distribution in channels, and how they alter streambed in terms of stability and embedding of larger rock substrata. We used a variety of such measures to describe sedimentation and found strong correlation among many, indicating that sediment measures are often interchangeable response variables (Table 3). Only embeddedness and bar area were not well-correlated with other sediment measures. Fines and sand (FS) on grid-frames and bar forms had higher correspondence with one another than to FS from point-transects, related to the fact that the random placement of grids was restricted to the depositional bar areas. We found significant differences between reference and test sites for most in-stream measures of deposition in the Sierra Nevada and in the Coast Range (Table 4). All differences were consistent with our expectations for the response of channel geomorphology and sediment storage to increased landscape disturbance. Some measures of sediments differed between regions, for example, the percent of fine particles were increased in test sites over reference sites in the Sierra, but not for sand substrate, while the reverse was true in the Coast Range (sand but not fines increased in test sites, see Figure 7). The proportion of sediment deposition measured at the reach-scale that was less than 8 or 16 mm (fine, sand, and gravel sizes) was significantly different or nearly so (p=0.05) in both regions, as were these same particles measured along the thalweg profile. Streambed profile variation, expressed as thalweg variability was higher in coastal reference sites, while cross-sectional variability was higher in Sierra reference sites. Although there were significant differences found for embeddedness in the Sierra Nevada, this was not the case in the Coast Range. On average, reference sites in both geographic regions had lower percentages of fines and sand, and equal or higher percentages of pebble, cobble and boulder than test sites (Figure 7). The combined particle size distributions for both regions showed test sites with much more accumulation of fine and sand substrates, resulting in a shift to smaller diameter-particles for the cumulative distribution profile of the population of test sites compared to references (Figure 8).

Fluvial Regime and Landscape Disturbance Relations to Sediment Deposition

Stream power exerts control over stream bed particle size, with small substrates dominating in low power channels, and substrate size increasing as power increases, and the competence and capacity of the channel to transport small particles increases (Mount 1995, Gordon et al. 2004). We observed this pattern across all streams surveyed but found that curves describing this relationship differed between reference and test sites (Figure 9). Contrasting streams over the range of the stream power index, we found that test sites of low power had higher levels of fines, sand, and gravel less than 8mm (FSG<8) than comparable reference sites, but the difference lessens with increasing stream power. This amounted to a range of 5-20% more FSG<8mm at test sites than reference levels over the range of a stream power index less than 4.

Rather than examining a large correlation matrix of univariate relationships between stream sediment and environmental features, we chose to use ordination and multiple regression statistical methods to explain the most important overall patterns (Van Sickle 2003). Non-metric multidimensional scaling (NMDS) ordination was performed to examine the dissimilarity among sites with regard to a group of descriptor variables of sedimentation, and relation of these differences (distances) between sites to environmental gradients. The group of measures used in NMDS to describe the sediment regime of each stream reach at mixed scales in the Sierra included %FS, %FSG<8, log D50, thalweg %FSG, RBS, bar-patch %FS grids, excess %FS and embeddedness. All analyses used the Sorensen distance measure. For Sierra Nevada sites we found separation of reference from test streams (Figure 10a; 2D solution, final stress = 11.3, 37 iterations), associated predominantly with the influence of stream power on sediment content of sites (Figure 10b, using FSG<8 to express sediment). The small sample size of coastal streams surveyed in this study (24) was supplemented with 60 additional stream surveys done in the San Lorenzo River region of the central coast in 2008 and 2009 (Herbst et al. 2011). Some sediment measures differed in these studies, so the group of sediment descriptors used for coast streams consisted of %FS, %FSG<8, %FSG<16, D50, log RBS, and embeddedness. Ordination of this expanded data set also showed separation of reference and test sites was again most clearly related to stream power and associated high FS at low stream power (Figure 11 a, b; both main and second matrix relativized, 2D solution, final stress = 7.6, 60 iterations).

Multiple regression analysis using the stepwise procedure was conducted to discriminate how sediment deposition was related to environmental factors that were grouped to contrast channel fluvial geomorphic features with land use disturbances that were compared at nested watershed spatial scales (catchment, riparian, and reach). Land use measures of fire, forest mortality, population density, private land, and natural vegetation (this last just for the Sierra) were removed as regression variables because of outliers, non-normality, or frequent coverage limits at zero or 100% values. The expanded coast data set used natural vegetation cover rather than canopy density, and could not use equivalent roaded area or grazing because these could not be estimated with confidence where private land cover was so common. San Lorenzo River region surveys also incorporated some different field measures of sediment aggregation (patch and facies). Regression models for most sediment measures across both regions showed greater R^2 coefficient of determination values for channel fluvial and geomorphic features than any scale or type of land use disturbance (Tables 5 and 6). Consistent with ordinations, models for both Sierra and Coast showed log of the stream power index having the highest percent of sediment variation explained. Land use influence on sediments in catchment and riparian models performed similarly, and better than at the reach scale. The land use factors most often accounting for model variability were road density and crossings, and equivalent roaded area. Human land use combined cover and natural vegetation within the riparian area at coastal streams also accounted for sediment variation. Combining the best variables from channel fluvial features and land use effects, sediment measured as fines, sand and gravel less than 8 mm (FSG<8) can be predicted with an adjusted R^2 of 49.6% in the Sierra, and 34.9% on the Coast (Table 7).

Sediment showed a wide range of variation in relation to road density or combined human land use coverages, not easily fit to the average for a conventional linear regression analysis, but lowest sediment levels observed became higher with added disturbance. A boundary at the edge of responses to such integrative and composite land use measures may best be represented by quantile regression, which examines relationships along such minimum or maximum limits imposed when many factors interact to influence response of a dependent variable (Cade and Noon 2003). To examine a broader range of road density and land use effects on sediments, the Sierra and Coast data collected in this study were supplemented with surveys conducted in the eastern Sierra region as part of the California Surface Water Ambient Monitoring Program (SWAMP). Streams in catchments with riparian road densities above 2.5 km/km^2 were added from the SWAMP surveys and quantile regression of the 10th percentile of the distribution showed a rising trend of about 5-6% minimum increase in FSG<16 mm of sediment per km of roadedness increase (Figure 12). The average linear regression suggests about 10% increase per km road. This same rising minimum sediment content imposed by roads was also observed in the expanded coastal data set (Herbst et al. 2011). Combined human land use coverage within the riparian zone of Sierra streams were mostly less than 5%, so to extend the range we added SWAMP data with 4-10% cover (this compared to over 40% in coastal streams, Herbst et al. 2011). Even over this lower range, Sierra sites exposed to increased land use also appeared to be constrained to rising limits on how low sediment levels could be, and showed minimum %FSG<16 increasing to a similar extent as that seen in coast streams (Figure 13).

The influence of road crossings in the Sierra, possibly more direct conduits for sedimentation, can also be seen as increased levels of cobble embeddedness and negative values of RBS indicative of smaller-than-expected particle sizes (Figures 14 and 15). Above about 0.5 crossings per km, embeddedness increases substantially in the Sierra (not on the coast, Table 4), as does the fraction of sites showing bed instability in both the Sierra and coast. The explicit modeling of road-related sediment loading provided predictions of sediment delivery with high correlations to the range of deposited sediments observed in all streams (see report 2 of this series). Road disturbance in the Sierra, measured as upstream road crossings typically had somewhat stronger correlations with sedimentation than road density, and density expressed at any spatial scale showed similar correlations with sediment, except that embeddedness and log RBS were poorly correlated at the reach scale (Table 8). Deposition measured at the transect point scale or along the thalweg were slightly more responsive to road disturbances than %FS at the patch-scale on bars. Larger-scale sedimentation expressed as area of bar formations or bar FS showed little correlation with road disturbances except at the reach scale, where sites with no local roads had less coverage of bar area or bar FS than sites with roads present (Table 8).

Soil detachability, the K-factor, contributes to the natural erosive character of differing geologic formations. Across all scales of K-factor, the coastal sites dominated by sedimentary geology had higher levels than found in the granitic Sierra Nevada (Figure 16, at riparian scale). This indicates coast sites may be more susceptible to erosion, and may partly account for the higher levels of sediment occurring in reference sites of the coast compared to the Sierra (though these also were more disturbed).

Excess Sediments and Relative Bed Stability

The amount of fine and sand present in excess of the reference background suggested that deposition increased on average by about 8-9% at Sierra test sites and 14-15% at coast test sites (Table 4), and could be attributed in part to accumulation in low power streams, where below an SPI of 4 streams are most vulnerable to deposition and among test sites from both regions below this level, the median level of excess FS is 9-

10% above the reference background (Figure 17). Negative Log RBS and elevated excess sediment levels show the extent to which test site disturbances produce instable bed conditions and higher levels of deposition (Figure 18). Taken together, these measures show sedimentation arises most often under conditions of watershed land disturbance where stream power is low.

Sediment Impairment Criteria

Selecting the indicators shown to have significant differences between reference and test groups in each region (Table 4), multiple measures of sediment deposition can be used to set criteria for impaired condition based on the highest sediment levels found in the distribution of reference streams. Values above the 90th percentile of the reference distribution define the criterion threshold (or below the 10th percentile for those indicators that decrease with sedimentation), and the number of exceedances of these levels can be tallied as a measure of the extent of sediment-impaired condition (Appendix B). These values were set separately for each region, using 9 indicator variables (6 shared and 3 differing between regions). This resulted in fifteen test and three reference sites in the Sierra with at least five of nine indicators exceeding the criterion levels, and five test and one reference in the central coast streams surveyed (Appendix B). Two of the sites on the coast were difficult to assess and might be excluded from the data set as special cases (the test sites at Scott Creek and lower Soquel Creek) as these were both low elevation (<10 m), within one km of the ocean, and harbored invertebrates indicative of a tidal influence. The impairment criteria identified through this process should be regarded as preliminary, to be integrated with biological indicators, and supplemented by additional reference data as this becomes available through further surveys. Big Sur River is also a possible outlier in the data set as this watershed, though less disturbed by development at the catchment scale, has a history of severe fires and subsequent catastrophic mudflows in highly erodible terrain, and local disturbance by roads and channel/land clearing in the adjacent riparian/upland zones below Highway 1.

To simplify application of these criteria, a reduced set of sediment indicators is recommended for the Sierra in Appendix C, and these criteria set at 75th or 90th percentiles (25th or 10th for indicators decreasing with sediment level) to identify a range of values that can be used to designate supporting, partially supporting, or not supporting of standards to incorporate a margin of safety. These designations may be useful for prioritizing regulatory and management decisions. Similarly, using an expanded reference stream data set, modified sediment criteria for central coast streams are presented in a separate report (Herbst et al. 2011).

	F	**S**	**FS**	**FSG 8mm**	**FSG 16mm**	**D50**	**Geomean**	**Emb**	**RBS**	**Thalweg FSG 16mm**	**Bar FS**	**Grid FS**	**Pct Bar Area**	**Excess FS**
F	1.00	0.19	**0.63**	**0.59**	**0.55**	-0.48	-0.48	0.25	-0.36	0.37	0.28	0.37	-0.06	**0.58**
S	0.19	1.00	**0.88**	**0.84**	**0.78**	**-0.51**	-0.45	0.37	-0.37	**0.64**	**0.62**	**0.53**	-0.09	**0.83**
FS	**0.63**	**0.88**	1.00	**0.95**	**0.88**	**-0.63**	**-0.59**	0.41	-0.46	**0.68**	**0.62**	**0.60**	-0.10	**0.94**
FSG 8mm	**0.59**	**0.84**	**0.95**	1.00	**0.96**	**-0.72**	**-0.64**	0.38	-0.49	**0.70**	**0.63**	**0.58**	-0.10	**0.89**
FSG 16mm	**0.55**	**0.78**	**0.88**	**0.96**	1.00	**-0.78**	**-0.67**	0.37	-0.45	**0.73**	**0.54**	**0.50**	-0.03	**0.79**
D50	-0.48	**-0.51**	**-0.63**	**-0.72**	**-0.78**	1.00	**0.89**	-0.23	**0.52**	**-0.52**	-0.28	-0.23	-0.15	**-0.54**
Geomean	-0.48	-0.45	**-0.59**	**-0.64**	**-0.67**	**0.89**	1.00	-0.20	**0.67**	-0.44	-0.29	-0.24	-0.15	**-0.53**
Embeddedness	0.25	0.37	0.41	0.38	0.37	-0.23	-0.20	1.00	-0.25	0.30	0.15	0.25	0.03	0.43
RBS	-0.36	-0.37	-0.46	-0.49	-0.45	**0.52**	**0.67**	-0.25	1.00	-0.22	-0.33	-0.34	0.06	**-0.58**
Thalweg FSG 16mm	0.37	**0.64**	**0.68**	**0.70**	**0.73**	**-0.52**	-0.44	0.30	-0.22	1.00	0.45	0.46	0.11	**0.53**
Bar FS	0.28	**0.62**	**0.62**	**0.63**	**0.54**	-0.28	-0.29	0.15	-0.33	0.45	1.00	**0.73**	-0.29	**0.62**
Grid FS	0.37	**0.53**	**0.60**	**0.58**	**0.50**	-0.23	-0.24	0.25	-0.34	0.46	**0.73**	1.00	-0.17	**0.60**
Pct Bar Area	-0.06	-0.09	-0.10	-0.10	-0.03	-0.15	-0.15	0.03	0.06	0.11	-0.29	-0.17	1.00	-0.25
Excess FS	**0.58**	**0.83**	**0.94**	**0.89**	**0.79**	**-0.54**	**-0.53**	0.43	**-0.58**	**0.53**	**0.62**	**0.60**	-0.25	1.00

Table 3: Pearson correlation coefficients (R) for sediment particle size measures. F (<0.25 mm); S (0.25 – 2 mm); FS (<2mm); FSG 8mm (<8mm); FSG 16mm (<16mm); D50 (median particle size); Geometric mean; Embeddedness (the volume cobble-size substrates buried by fines or sand); RBS (relative bed stability); Thalweg FSG 16mm (particles <16mm measured along the thalweg); Bar FS (particle sizes <2mm measured on depositional bars); Grid FS (particle sizes <2mm measured on patch-scale grids located on depositional bars); Pct Bar Area (percent of bankfull area with depositional bars). F=fines, S=sand, G=gravel.

Bold indicates correlations greater than 0.5

Table 4. Sediment deposition indicators for the Sierra Nevada (A) and the Central Coast Range (B) showing predicted responses to land use disturbance and erosion, observed response in test (dose) contrast to reference, and one-tailed P for Mann-Whitney U-Test.

A. Sierra Nevada Variable	**Predicted Response**	**Observed Response**	**Reference Mean**	**Test Mean**	**P**
F	+	+	0.025	0.089	<0.001
S	+	+	0.108	0.116	0.059
FS	+	+	0.133	0.246	<0.001
FSG <8mm	+	+	0.200	0.332	<0.001
FSG <16mm	+	+	0.274	0.402	0.002
Thalweg Variability	–	−	35.51	34.77	0.442
Xsect Variability	−	−	4.82	3.78	0.028
Geometric mean	−	−	33.85	22.49	0.004
Embeddedness	+	+	0.115	0.232	<0.001
RBS	−	−	1.194	0.825	0.003
D50	−	−	48.30	34.23	0.012
Excess FS	+	+	0.00*	0.094	<0.001
Excess FSG <8mm	+	+	0.00*	0.109	<0.001
Thalweg FS	+	+	0.168	0.218	0.130
Thalweg FSG<16mm	+	+	0.381	0.485	0.003
Patch-Scale Grid FS	+	+	0.365	0.460	0.010
Bar FS bankfull area	+	+	0.041	0.049	0.195

B. Central Coast Range Variable	**Predicted Response**	**Observed Response**	**Reference Mean**	**Test Mean**	**P**
F	+	+	0.049	0.088	0.229
S	+	+	0.156	0.287	0.022
FS	+	+	0.204	0.375	0.027
FSG <8mm	+	+	0.254	0.421	0.033
FSG <16mm	+	+	0.361	0.492	0.054
Thalweg Variability	–	–	33.739	20.391	0.027
Xsect Variability	–	–	4.653	3.425	0.190
Geometric mean	–	–	39.227	27.536	0.039
Embeddedness	+	+	0.178	0.263	0.146
RBS	–	–	1.372	1.265	0.099
D50	–	–	47.214	33.575	0.050
Excess FS	+	+	0.00*	0.153	0.027
Excess FSG 8mm	+	+	0.00*	0.142	0.045
Thalweg FS	+	+	0.292	0.452	0.018
Thalweg FSG<16mm	+	+	0.587	0.748	0.010
Patch-Scale Grid FS	+	+	0.420	0.484	0.232
Bar FS bankfull area	+	+	0.062	0.080	0.279

*excess sediment measure based on linear regression among reference sites and so will average zero (see text for explanation of calculation). Excess measures compare test to reference FSG content

Codes: F=fines, S=sand, G=gravel (less than 8mm, or 16 mm); Thalweg Variability is an index of longitudinal variability in depth profile (after Madej 1999), and Xsect Variability is cross-sectional variability across bankfull transects (see text); Geomean is geometric mean particle size and D50 is the median particle size from transect point-counts; (see text). Thalweg FSG is the percent of thalweg-depth counts of FSG, patch-scale grid.FS is the count of FS on quadrats placed on bars, and Bar FS bankfull area is the percent of bankfull area that is FS bar form. All decimal fractions are proportions (x100=%).

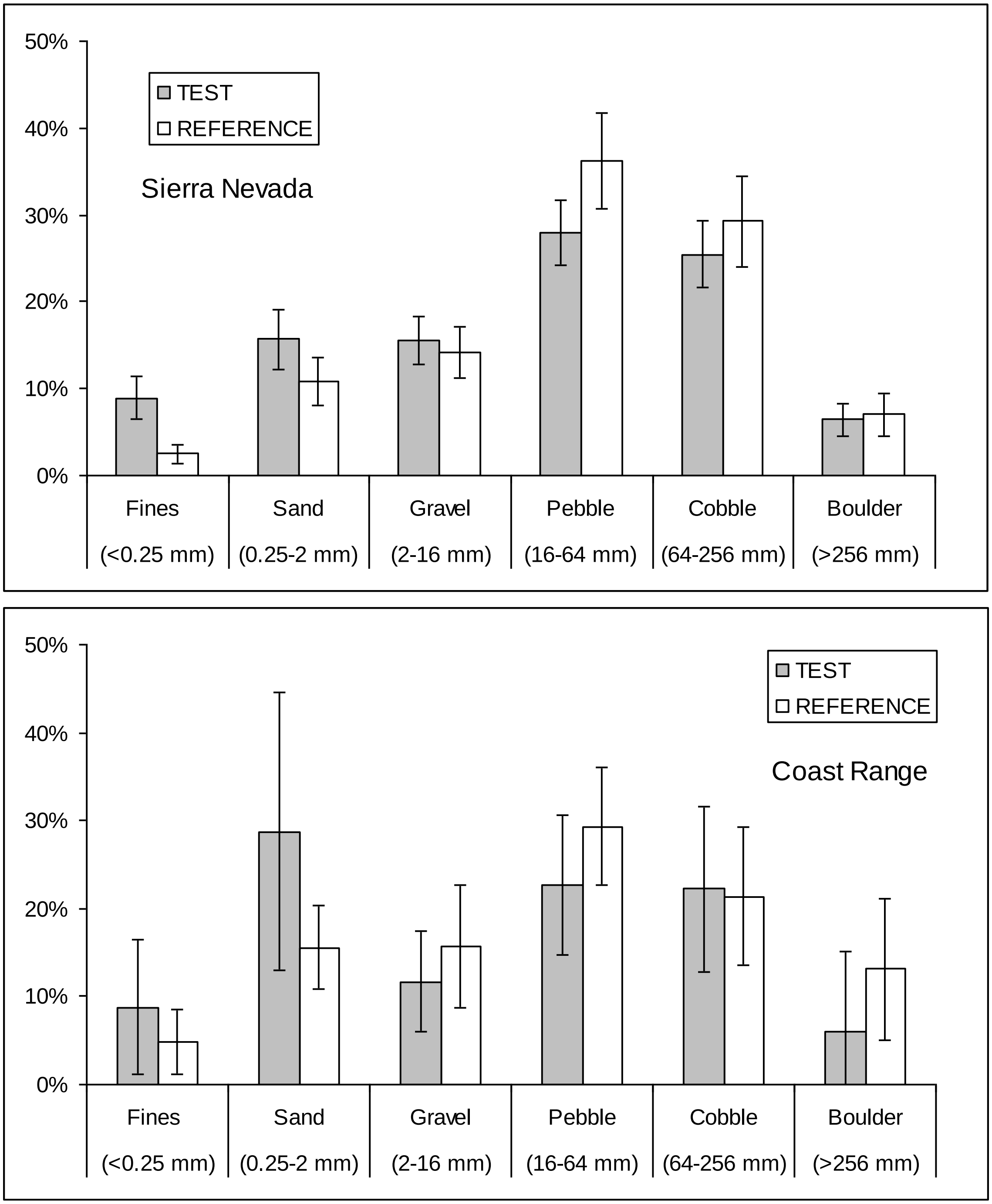


Figure 7: Average particle size distributions from transect point counts (n=100 for each reach survey) and 95% confidence intervals. Upper panel Sierra (n=28 reference, 46 test), and lower panel Coast (n=14 reference, 10 test).

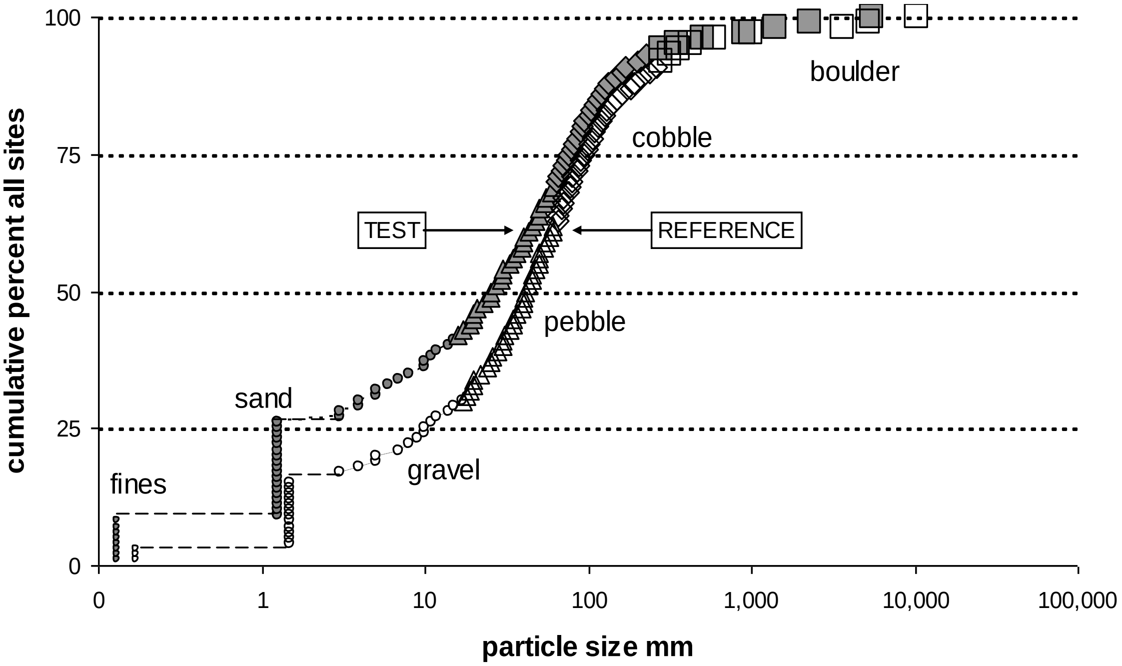


Figure 8. Cumulative particle size distributions for all test sites compared to all reference sites over both Sierra and Coast Streams.

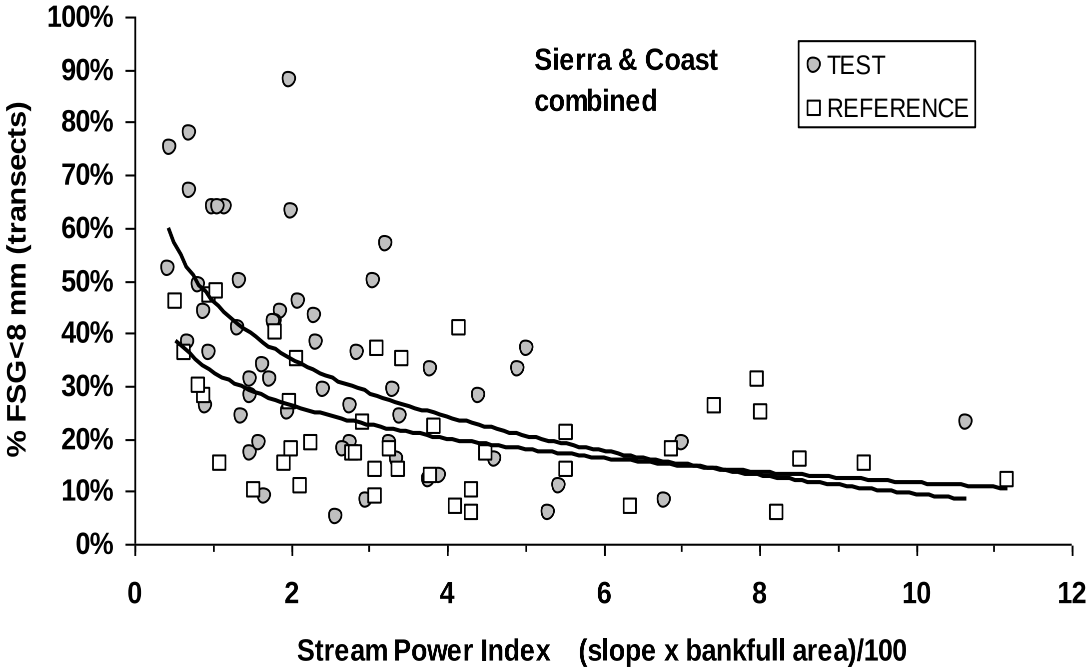


Figure 9. Relation of stream power index to sediment deposition contrasting reference and test sites (logarithmic regression lines) combined Sierra and Coast sites.

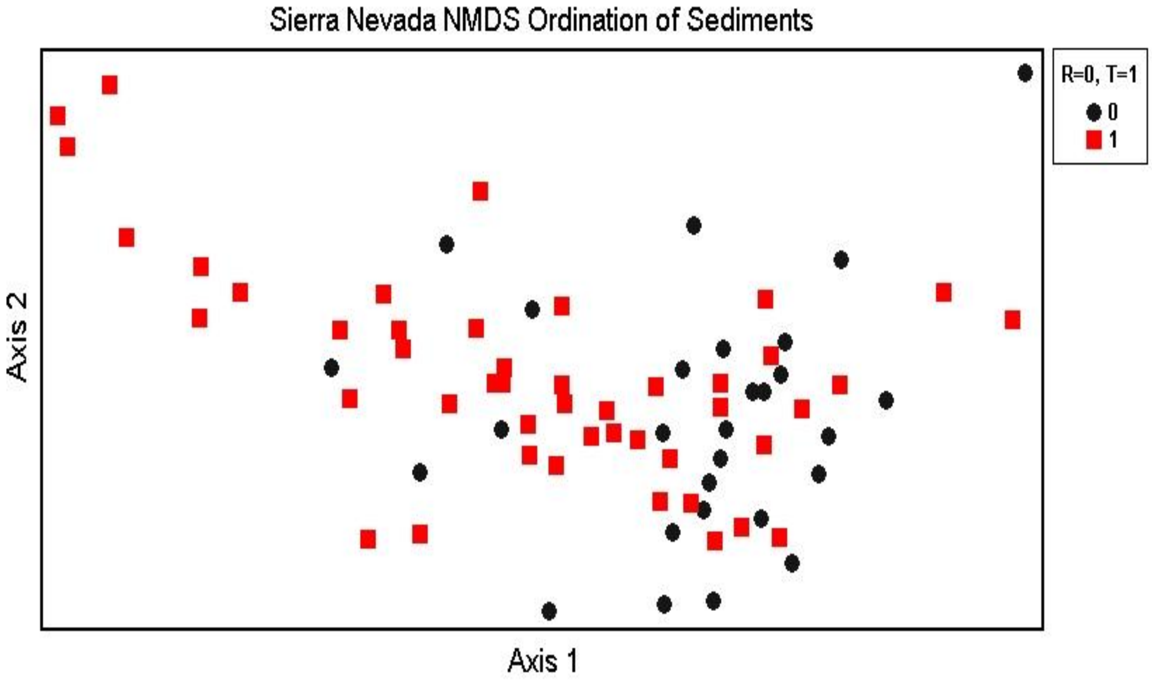


Figure 10a. NMDS ordination of similarities in stream sedimentation regime of sites in the Sierra Nevada. Test sites are red squares and reference sites are black circles.

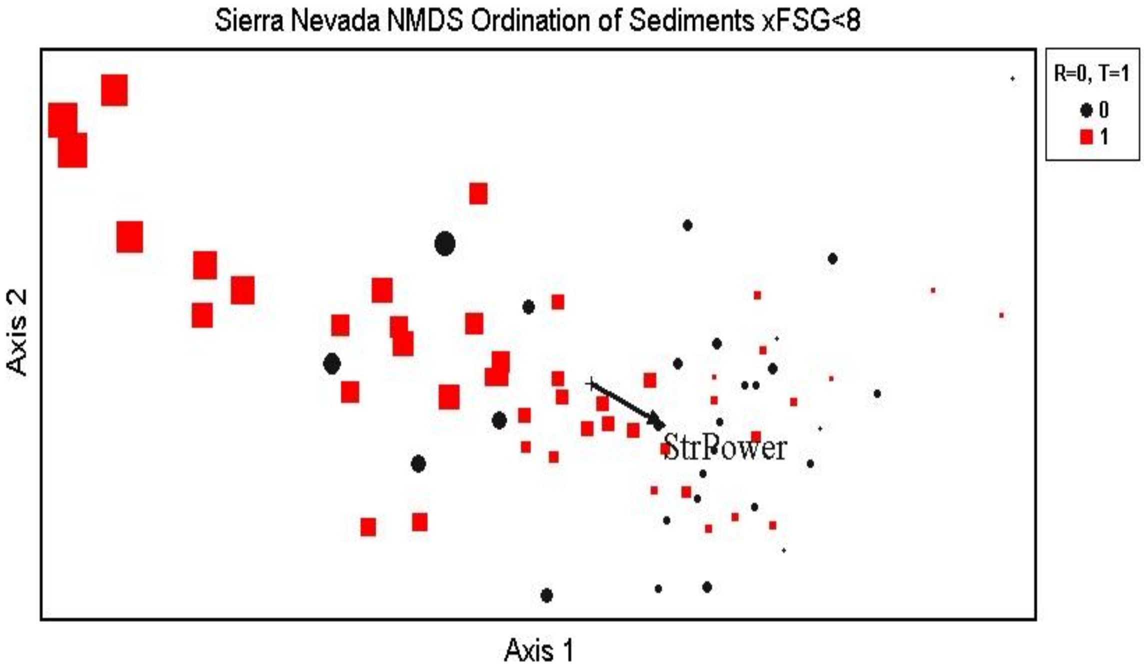


Figure 10b. Same plot as Figure 10a, but size of symbol is proportional to the percent cover of FSG<8 present at that stream site. Environmental vector best correlated with the separation of R and T and reduced sediment cover is log stream power (StrPower).

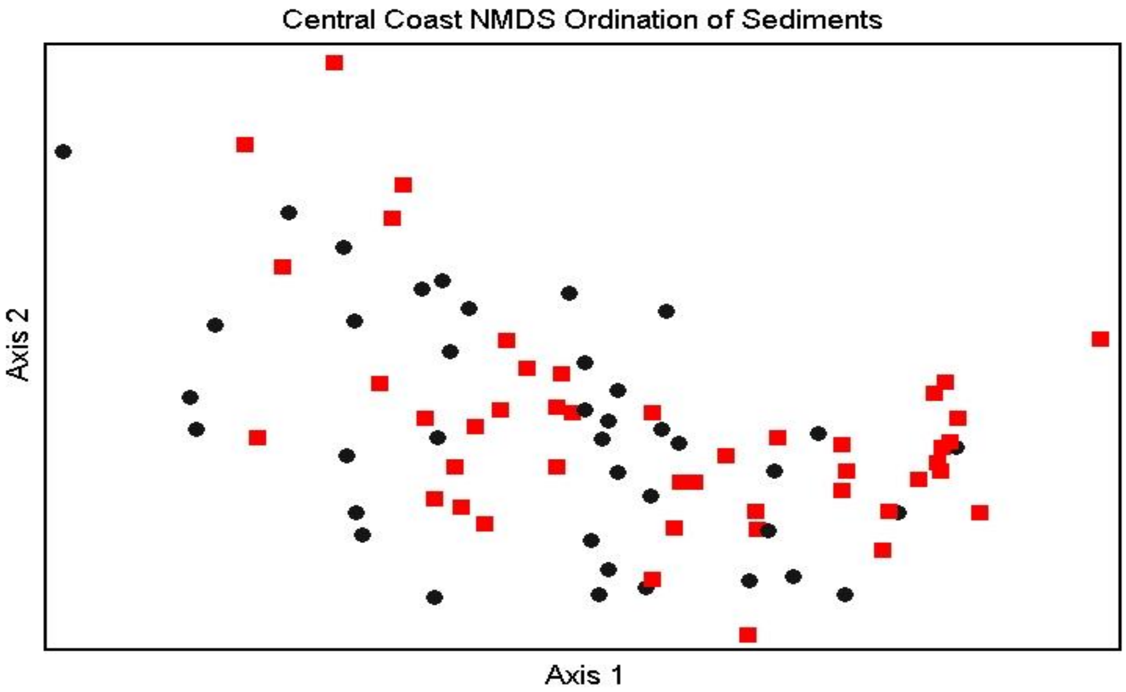


Figure 11a. NMDS ordination of stream sedimentation regime in the central coast region (60 surveys in the San Lorenzo River region in 2008-09 combined with 24 surveys here). Test = red squares, Reference = black circles.

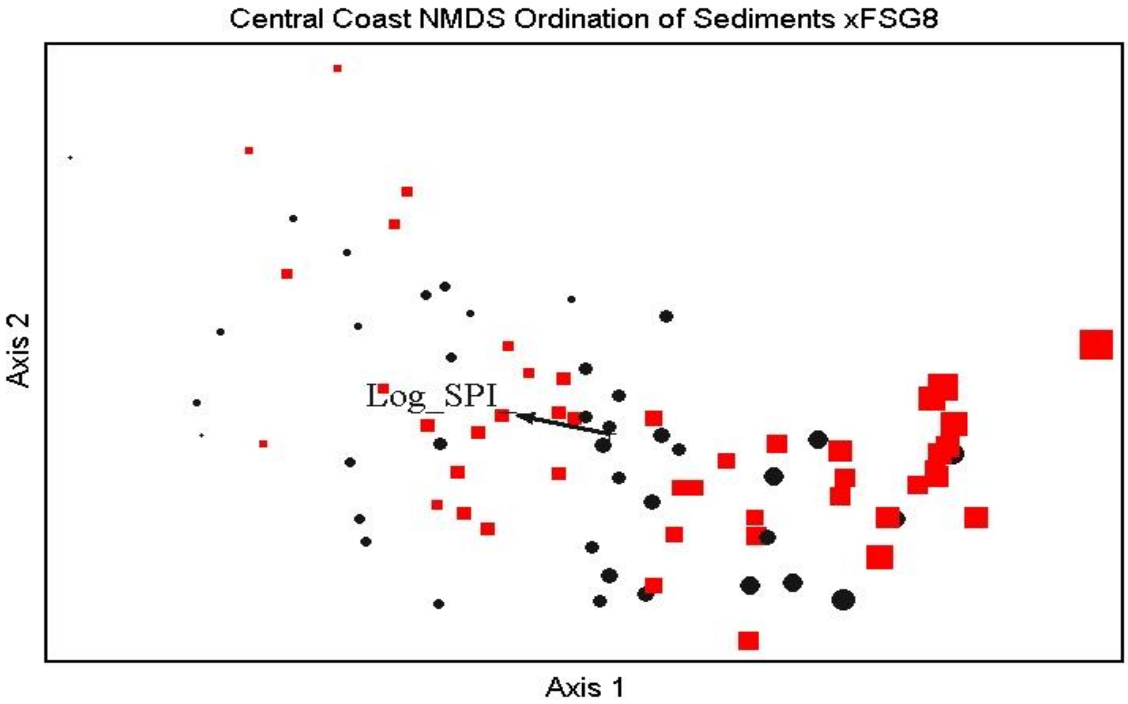


Figure 11b. Same plot as above but size of symbol is proportional to the percent cover of FSG<8 present at that stream site. Environmental vector best correlated with the separation of R and T and reduced sediment cover is stream power (Log SPI).

Table 5. Multiple Regression Models for **Sierra Nevada** Streams: Incremental R^2 (as %)

Independent Variables: Channel Features and Land Use at Nested Spatial Scales	%FS	%FSG<8	%FSG<16	D50 mm	Thalweg %FSG	Log_RBS	Bar patch.grid_%FS	Excess_FS	%Embeddedness
CHANNEL features of fluvial geomorphology									
Relief ratio	4.6	4.0				5.3	4.2	6.1	
Riparian cover	3.3	3.0						4.2	
Catchment area - km^2	5.1	3.6			3.1	4.5	6.6	5.3	
Log stream power index	29.4	38.2	45.1	50.3	31.8		9.8	22.4	
Wetted width						18.1	4.7		
Depth average									16.3
Hydraulic radius							4.3		
Sinuosity	4.9	5.4			4.7	5.0	5.6	5.3	
Percent pools									
Percent eroded banks									
Large Wood Debris				3.5	7.0				
FULL MODEL	**47.3**	**54.2**	**45.1**	**53.8**	**47.6**	**32.9**	**35.2**	**43.3**	**16.3**
CATCHMENT spatial scale land use disturbance features									
Road density - km/km^2				7.4					20.4
Equivalent roaded area	12.2	11.7	9.9		9.7		10.1	12.0	
Human combined cover									
Canopy density									
Impervious									
Grazed							5.8		
Soils K-factor									
FULL MODEL	**12.2**	**11.7**	**9.9**	**7.4**	**9.7**	**none**	**15.9**	**12.0**	**20.4**
RIPARIAN spatial scale land use disturbance features									
Road density - km/km^2									22.1
Road Xings /km	7.9	7.5		8.0		11.1		8.7	
Equivalent roaded area			7.4						
Human combined cover			7.0						
Canopy density						5.9			
Impervious									
Grazed									
Soils K-factor									
FULL MODEL	**7.9**	**7.5**	**14.4**	**8.0**	**none**	**17.0**	**none**	**8.7**	**22.1**
REACH spatial scale land use disturbance features									
Road density - km/km^2				6.3					
Equivalent roaded area	6.3	8.9	9.8		6.2				
Human combined cover									
Canopy density							6.2		
Impervious									
Grazed									
Soils K-factor									7.2
FULL MODEL	**6.3**	**8.9**	**9.8**	**6.3**	**6.2**	**none**	**6.2**	**none**	**7.2**

Stepwise procedure assumes probability to enter model ≤0.05 and for removal at each step of ≥0.20. Environmental and GIS cover variables as defined in text. Equivalent roaded area (ERA) calculated only where private land is less than 20% of total, so 11 of 74 sites eliminated in these regression models.

Table 6. Multiple Regression Models for **Central Coast** Streams: Incremental R^2 (as %)

Independent Variables: Channel Features and Land Use at Nested Spatial Scales	%FS	%FSG<8	%FSG<16	D50 mm	Log_RBS	Patch Grid_%FS	Facies %FS	%Embeddedness
CHANNEL features of fluvial geomorphology								
Catchment area - km^2								
Relief ratio		4.8			7.2			
Hydraulic radius	11.1	7.3	6.2					
Log stream power index	13.9	17.8	22.8	20.8		13.6		
Wetted width		3.8						
Depth average	4.8	5.8	6.7			22.9		
FULL MODEL	**29.8**	**39.5**	**35.7**	**20.0**	**7.2**	**36.5**	**none**	**none**
CATCHMENT spatial scale land use disturbance features								
Road density - km/km^2	12.7	10.0	6.4					
Human combined cover								
Impervious								
Natural vegetation						20.6		
Soils K-factor								
FULL MODEL	**12.7**	**10.0**	**6.4**	**none**	**none**	**20.6**	**none**	**none**
RIPARIAN spatial scale land use disturbance features								
Road density - km/km^2								
Riparian road Xings /km								
Human combined cover	15.2	12.5						
Impervious					5.2			
Natural vegetation			10.1	8.4	8.7	27.4		
Soils K-factor					4.8			
FULL MODEL	**15.2**	**12.5**	**10.1**	**8.4**	**18.7**	**27.4**	**none**	**none**
REACH spatial scale land use disturbance features								
Road density - km/km^2							10.4	
Human combined cover								
Impervious								
Natural vegetation								
Soils K-factor						10.9		
FULL MODEL	**none**	**none**	**none**	**none**	**none**	**10.9**	**10.4**	**none**

Stepwise procedure assumes probability to enter model ≤ 0.05 and for removal at each step of ≥ 0.20. Environmental and GIS cover variables as defined in text. Patch Grid_FS taken as counts of 25-point 20x20 cm grid frame at 20 intervals over the reach. Facies_FS is a map of the streambed area covered as aggregate zones of fines or sand (from the 60 surveys in the San Lorenzo River region in 2008 & 2009).

Table 7. Regression models for both regions best predict %FSG<8mm. Combining the most significant variables found above, these are the best overall models:

Sierra FSG8 = 0.55 + 1.35 x Channel Relief Ratio – 0.072 x Catchment Road Density* – 0.36 x Log Stream Power Index + 0.19 x Riparian Road crossings – 0.17 x Sinuosity

Adjusted $R^2 = 49.6\%$, F-ratio = 15.37, $p < 0.0001$, n=74 (*substituted for ERA)

Coast FSG8 = 0.22 + 0.0005 x Catchment Road Density – 0.005 x Depth + 0.0074 x Hydraulic Radius – 0.23 x Log Stream Power Index + 0.36 x Riparian Human land use cover

Adjusted $R^2 = 34.9\%$, F-ratio = 9.90, $p < 0.0001$, n=84

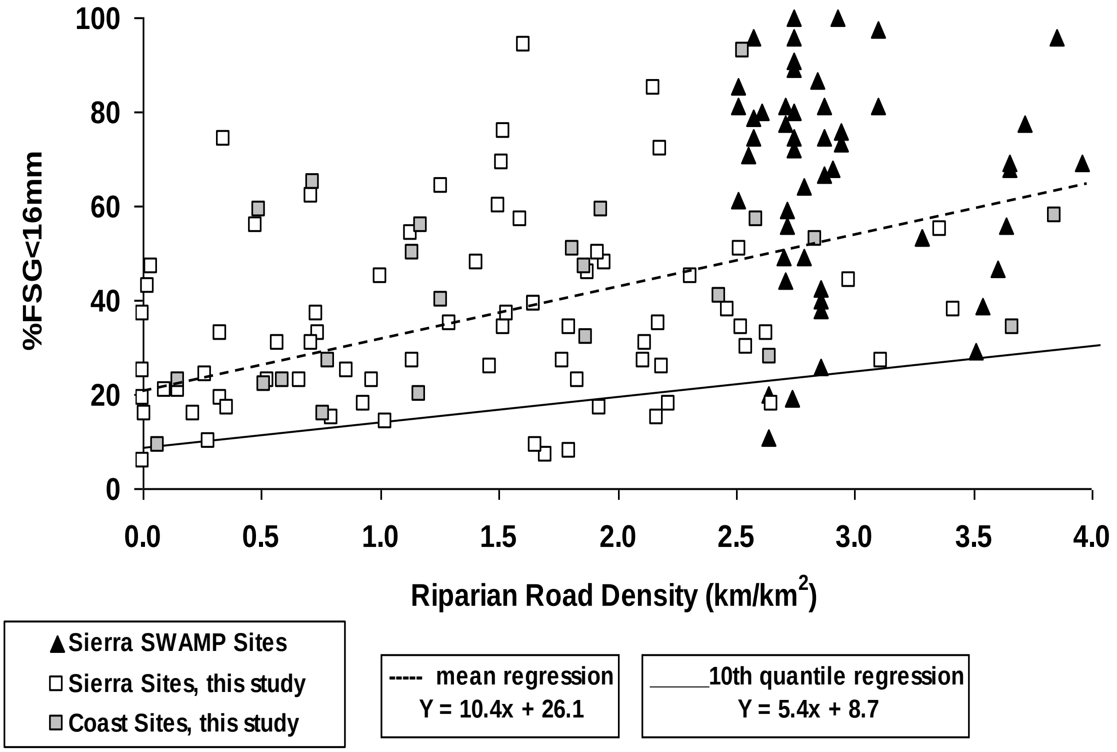


Figure 12. Quantile regression of riparian road density to deposited fine, sand and gravel.

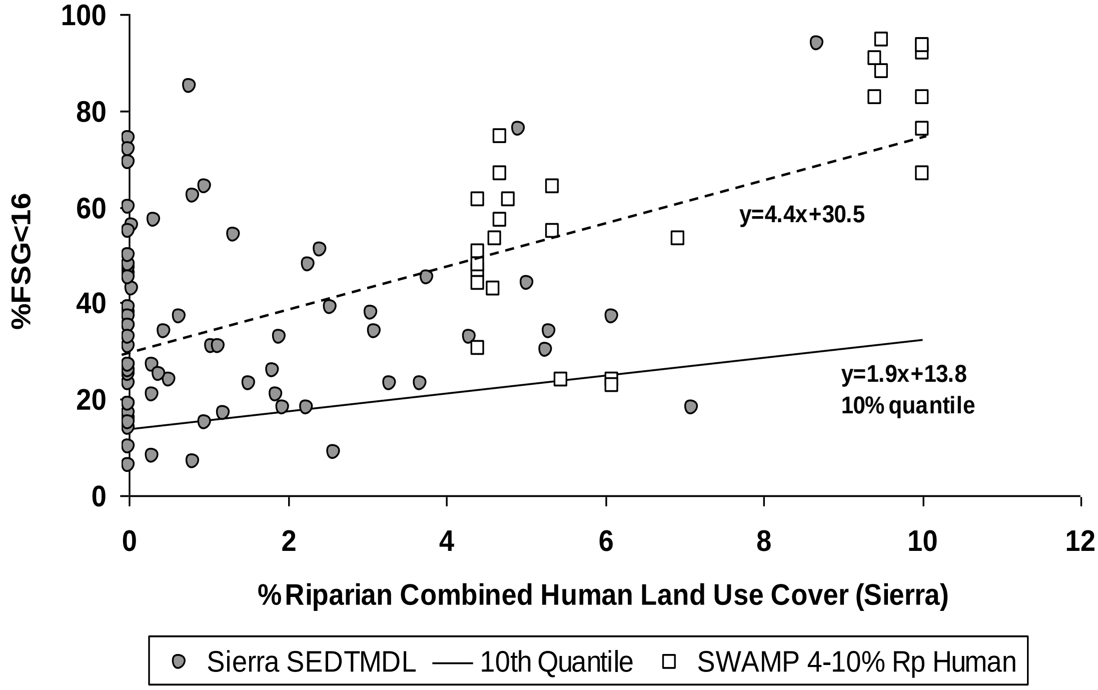


Figure 13. Quantile regression of combined human land use to deposited fine, sand and gravel (Sierra Nevada streams only).

Spearman Rank Correlations of Road Density at Different Spatial Scales of Sierra Watersheds

Sierra Nevada Streams	%FS	%FSG<8	%FSG<16	D50 median particle size	Thalweg %FSG<16	Patch-Grids %FS (bars)	%Bankfull Area as Bar	%Bankfull Area as Bar FS	%Embeddedness	Log Relative Bed Stability	Excess FS
	74	74	74	74	74	74	74	74	73	74	74
CATCHMENT											
Road Density											
R	0.192	0.234	0.247	-0.231	0.201	0.172	-0.033	0.074	0.391	-0.135	0.174
p-value	0.102	0.045	0.034	0.048	0.085	0.142	0.781	0.533	0.001	0.252	0.138
RIPARIAN											
Road Density											
R	0.212	0.227	0.228	-0.227	0.192	0.174	0.022	0.034	0.398	-0.231	0.206
p-value	0.070	0.052	0.051	0.052	0.101	0.138	0.854	0.772	0.0005	0.047	0.078
Road Crossings											
R	0.256	0.271	0.255	-0.216	0.228	0.224	-0.106	0.114	0.395	-0.264	0.258
p-value	0.028	0.019	0.028	0.065	0.051	0.055	0.367	0.332	0.0005	0.023	0.027
REACH											
Road Density											
R	0.185	0.223	0.210	-0.301	0.173	0.167	0.274*	0.198*	-0.112	-0.026	0.167
p-value	0.114	0.057	0.073	0.009	0.139	0.155	0.018	0.092	0.345	0.825	0.156

*These values due to many sites with no roads within the reach zone, so comparing sites grouped with or without reach roads, there is 22.4% vs. 16% bar area with and without roads, and 5.4% to 3.9% bar FS with and without roads. These differences are significant (t-test, p<0.05)

Table 8. Spearman rank correlations of roadedness at different spatial scales (catchment, riparian, reach) with measures of deposition at different reach scales (point, patch, bar).

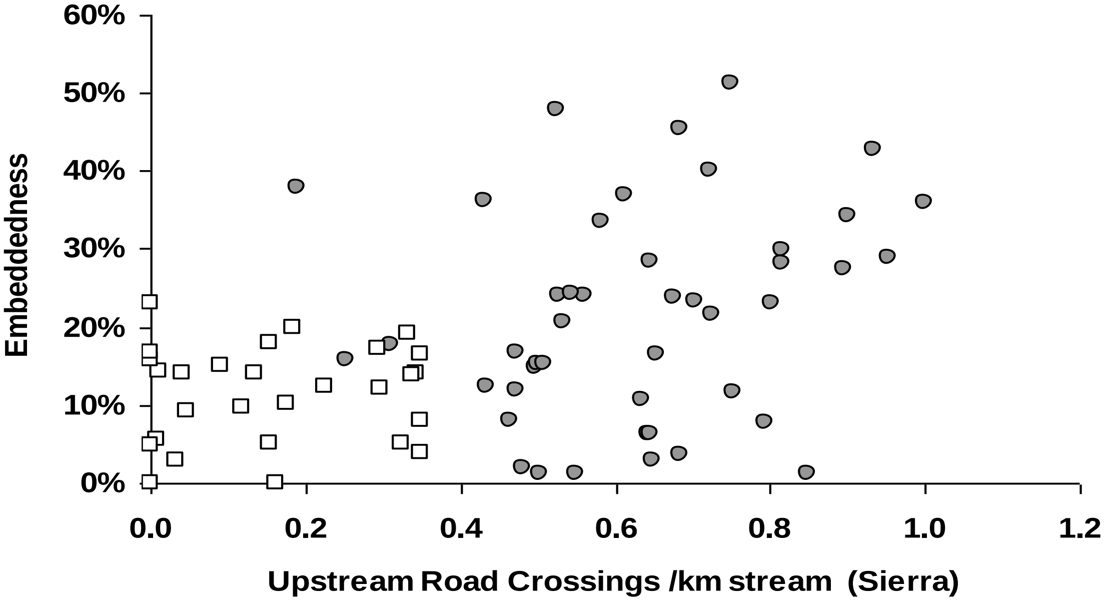


Figure 14. Increased cobble embeddedness associated with catchment road density exposure (Sierra). Open symbols =reference, filled symbols =test streams.

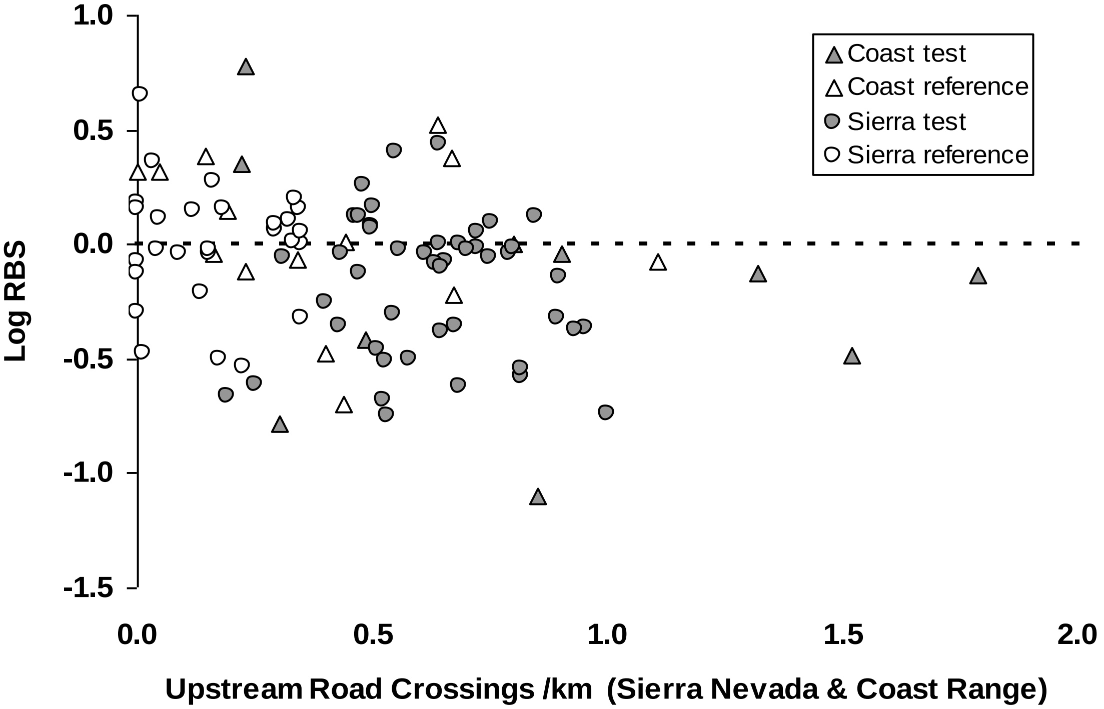


Figure 15. Influence of upstream road crossings on relative bed stability based on expected D50 size (negative log RBS indicates instability or excess in sediment levels).

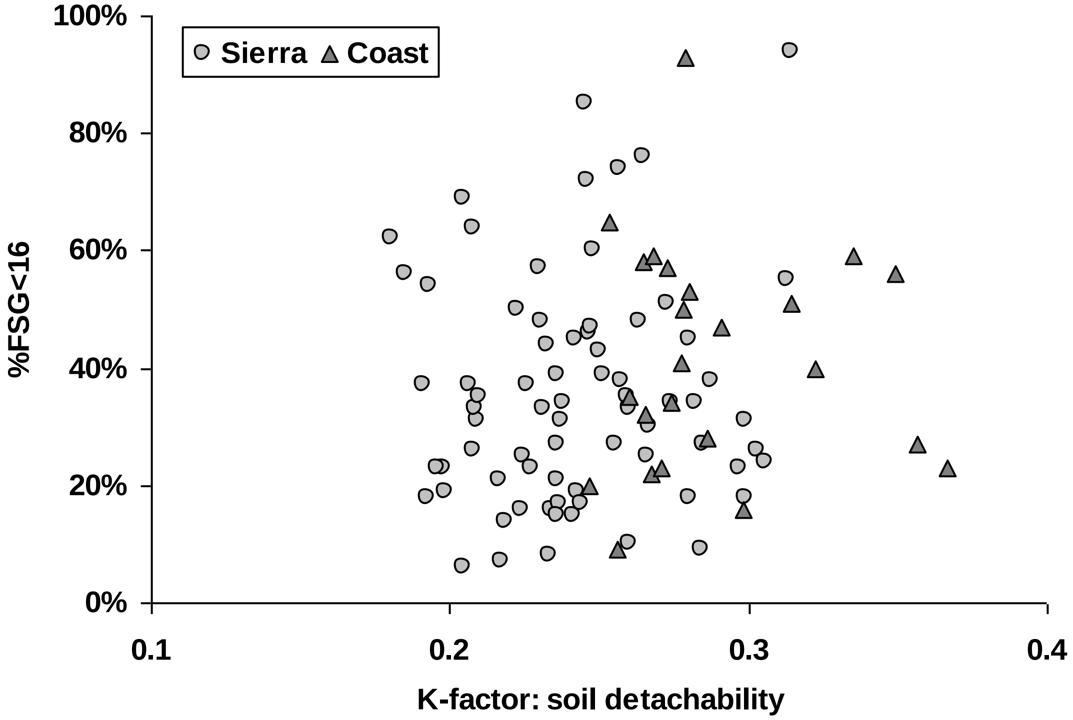


Figure 16. Relative erodibility of riparian soils and geology contrasting Sierra and Coast.

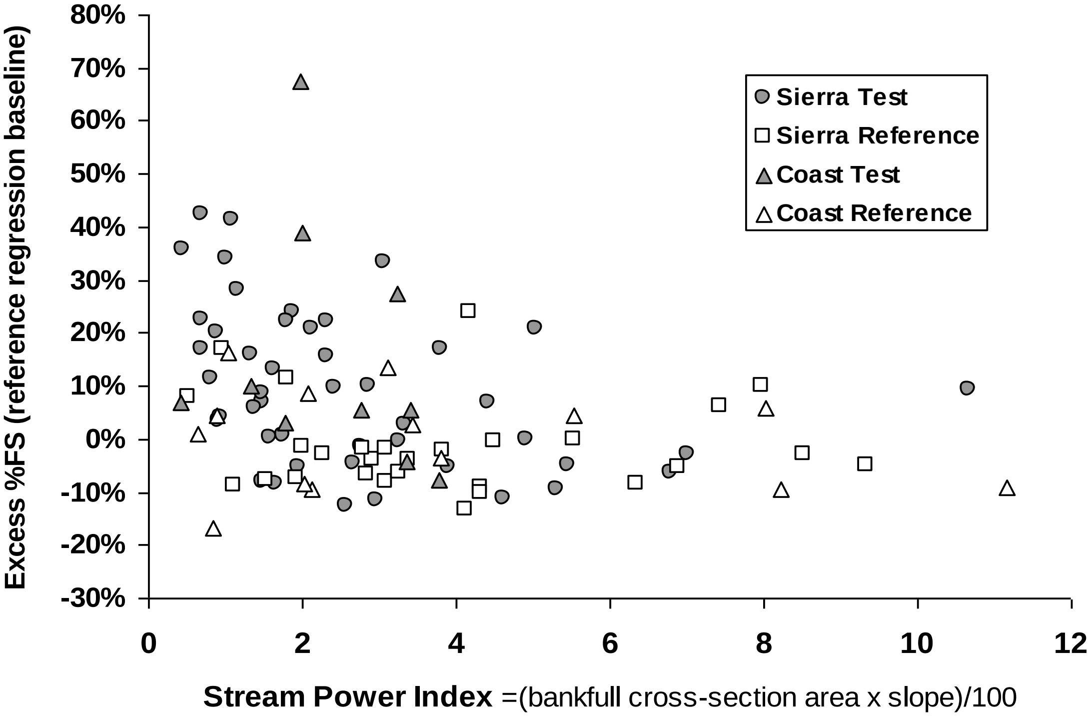


Figure 17. Excess FS above background increases among streams with SPI less than 4.

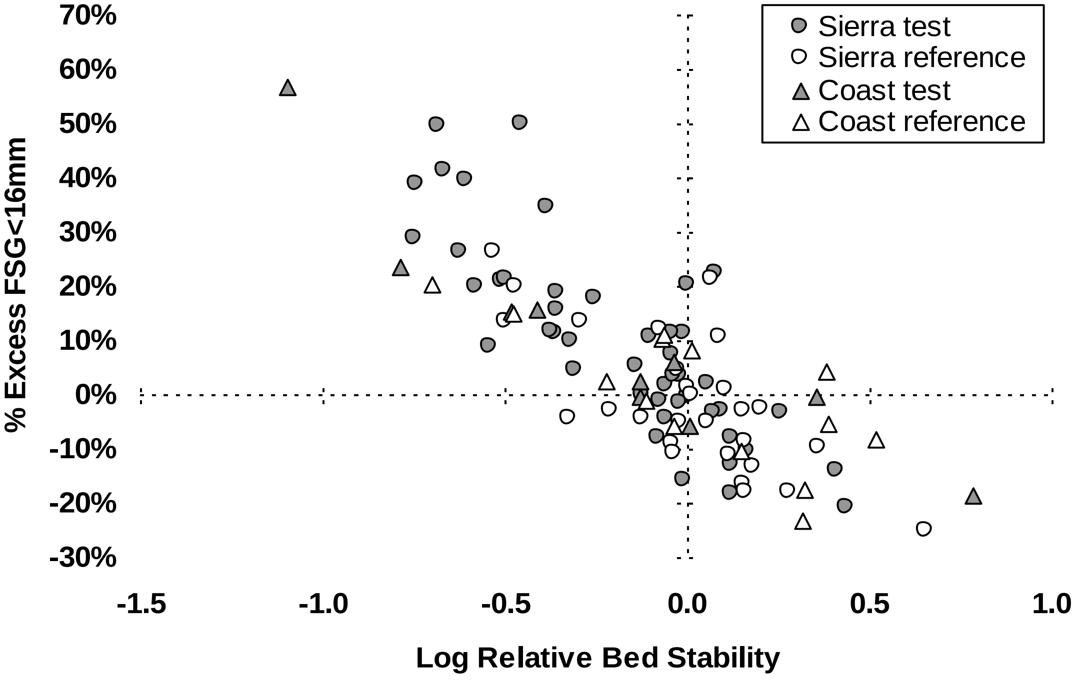


Figure 18. Relation of log relative bed stability to excess sediment at reference and test sites in both the Sierra Nevada and central coast streams.

DISCUSSION

Contrast of Reference and Test Streams

Least-disturbed reference streams, taken to represent the natural background condition, showed lower sediment levels compared to test streams under the influence of varied landscape disturbances. As predicted, greater exposures to potential erosion from upstream roads and land use resulted in significant increases of test over reference streams in most reach-scale measures of deposition in both the Sierra Nevada and central coast region (Table 4). Sediment levels were higher in coastal streams than in the Sierra, but the sand fraction comprised most of the difference between test and reference streams on the coast, while fines accounted for much of this difference in the Sierra (Figure 7). Though all measures changed as expected, some sediment increases at test sites were significant only in one region. For example, Sierra test streams had reduced cross-sectional variability in depth profile, and higher levels of embeddedness and patch-scale FS on bars. Coast test streams had decreased depth variability, and elevated FS along the thalweg, perhaps owing to the greater amount of sand carried by these streams. Physiographic features cannot account for differences between reference and test groups, which showed similar distributions for watershed area, elevation, channel slope, stream power, stream order, sinuosity, and reach-scale bank vegetation cover (Table 1). Geology and weathering processes between the Sierra and Coast differ in that the Sierra is primarily granitic and degrades slowly, commonly comprised of minerals such as biotite and plagioclase that weather to fine clay particles, while the Coast Range is mostly sedimentary rock that erodes more rapidly and would be expected to yield coarser grain sizes of hard quartz sand (also seen in the differences in K-factor erodibility, Figure 16). Precipitation in the Sierra is also dominated by snow, which has less erosive impact than the intense rainfall that can occur on the coast where this may often produce high volume landslide hillslope movements (Cover et al. 2008). These differences may account for road-disturbed streams of the Sierra having more fines, and overall higher sand content in coastal streams. This may be why coastal reference streams also have more sediment than in the Sierra, but reference criteria also permitted higher road and land use disturbance on the coast (Figure 4).

Establishing Sediment Indicator Criteria Based on the Reference Distribution

The conventional approach to developing sediment TMDL numeric targets has often emphasized fish habitat relations as endpoint indicators (USEPA 1999). The amount of fines in spawning gravels (Kondolf 2000), extent of infilling of pools, and substrate permeability to flow (Cover et al. 2008), and the growth, survival and invertebrate food availability to juvenile steelhead trout (Suttle et al. 2004) have been used in assessing the extent to which sedimentation impairs salmonid populations. TMDL case studies on the California coast (e.g. Garcia River, Eel River, Redwood Creek, San Lorenzo River) have set indicators and targets based mostly on fish habitat requirements, and assessed the contribution of different sediment sources to determine where load originates and how it can be controlled. Rather than attempting to develop load budgets for each watershed, another approach to setting expectations for unimpaired sediment levels is to use the reference distribution of sediments as a standard for defining criteria in all streams of a region. Extensive surveys such as the EPA Western Stream Assessment (Stoddard et al. 2005) have used the high-end of the reference distribution

(75th and 90th percentiles) to set limits on what levels may be considered impaired for different stressors or biological indicators. Sediment deposition criteria set in this way can be supplemented with aquatic invertebrate biological indicators that are also based on what is found in reference streams and how they respond over a sedimentation gradient. The relationships between differing measures of deposition, land use disturbance, and biological response may then be used to infer linkages between indicators and causes of impairment, and of the assimilative capacity of aquatic life to resist degradation.

Using 9 metrics of deposition that provided the most separation between reference and test sites, provisional sediment criteria can be set based on exceedances of the 90th percentile of the Sierra and coast region reference distributions for metrics that increase with deposition, and below the 10th percentile for those metrics expected to decline with sedimentation. This multi-parameter set of indicators provides a tool for assessment and management of stream habitat quality. Six indicators are shared between regions and three differ in each (Appendix B). These are:

Sites would be considered impaired by sediment if:

1. % Fines and Sand (FS) >26.6% (Sierra) and >34.1% (Coast)
2. % Fines, Sand and Gravel <8mm (FSG<8) >40.3% (Sierra), >36.7% (Coast)
3. % Fines, Sand and Gravel <16mm (FSG<16) >45.6% (Sierra), >56.7% (Coast)
4. D50 median particles size <19.3 mm (Sierra), <15.0 mm (Coast)
5. Relative Bed Stability of D50 particle size <0.433 (Sierra), and <0.411 (Coast)
6. % Excess Fines and Sand >10.4% (Sierra), >12.0% (Coast)

additional measures, differing between regions:

For Sierra streams:

7. % Fines and Sand for patch-scale grids >69.2%
8. % Embeddedness of > 18.4%
9. Cross-sectional depth variability index <2.80

For Coast streams:

7. % Sand >27.9%
8. % Fines, Sand and Gravel in the thalweg >78.1%
9. Thalweg depth variability index <15.5

As sediment conditions are improved at impaired sites, recovery may occur sooner for some indicators than others. This would permit the tracking of progressive recovery as erosion sources and delivery of sediment to streams becomes reduced, or as export of deposits is increased. Additional reference sites and between-year variation in these measures among references should be incorporated to strengthen the reliability and applicability of criteria, and account for variability. Within-site replicates could also be integrated to determine detectable differences relative to sampling error.

Where 5 or more of 9 measures exceeded limits, there were 15 (of 46) test and 3 reference sites identified as impaired in the Sierra, and 5 (of 10) test sites and 1 reference on the coast (Appendix B). Declaration of some references as impaired results from the procedure of eliminating extremes of the reference range as inaccurate indicators of the unimpaired state. Had we used only sediment levels outside the full reference range, the effect of outliers in the reference distribution could introduce increased chance of making statistical errors of interpretation. Type II errors, or false negatives, are 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). It should further be noted that in using larger numbers of reference sites that have some level of existing impact from land use and roads, the criteria are not as stringent had more pristine conditions been available, or had we selected lower disturbance limits for defining the reference state. Using the 90th percentile for assessment of impairment increases the certainty of correctly identifying test site impairment, but may fail to discriminate less severe impairment. To incorporate these lower levels of impact, add a margin of safety, and permit degrees of impairment to be assigned for regulatory priorities, an alternative set of criteria that use the 75th and 90th reference percentiles was also developed for this study (Appendix C). This approach was also used with an expanded set of reference sites for coastal streams, resulting in a refined set of criteria (Herbst et al. 2011). Below the 75th percentile of reference sediment levels, streams could be designated as supporting reference standards. Between 75-90th percentiles, streams could be considered partially supporting, and above 90 percent not supporting. The 28 reference sites in the Sierra were selected to conform to particular stream types (low gradient, no dams in catchment, etc), but this is a small sample size on which to base standards. Using less restrictive channel form definition, but applying the same criteria for reference selection (less than 1 km/km^2 riparian roads, less than 0.4 upstream road crossings per km, and low levels of land use and absence of local disturbance sources such as livestock grazing), this reference population was expanded to 154 site surveys from the eastern Sierra SWAMP data set. For this population we found that the 75th-90th limits on %FS for example, were increased from 15-27%, to 27-37%, showing that the reference population used has an important influence on the standards that would be derived. The expanded coast reference set changed from 27-34% to 36-42% FS.

Sediment Deposition is Related to Stream Power, Roads, and Land Use Disturbance

Using a reach-scale index of stream power confirmed that deposition levels were determined in large part by hydraulic forces acting through local geomorphology of slope and bankfull cross-section area (Figure 9). Below a stream power index of about 4, streams were most vulnerable to increased levels of deposition (Figure 17). Landscape disturbance shifts the relationship between stream power and streambed sediment deposition. The elevated levels of FSG<8 sediment observed among test sites relative to reference sites of equal stream power suggests that these road- and land use-disturbed streams are receiving excess sediment they do not have the capacity to transport. If sediment load inputs to channels exceed export capacity, then an imbalance resulting in accumulation will occur. The erosion and sediments produced by roads and landscape disturbance appear especially critical for streams of low power where, compared to less disturbed reference sites, deposition of small particles was increased. As stream power increases, the capacity of the streams to transport excess sediment is increased, and the disturbed streams we surveyed did not show elevated deposition. Small streams in forested areas also have greater proportional inputs of large woody debris that can create flow obstructions and sediment traps that are rearranged and flushed only under infrequent high discharge events (Hassan et al. 2005). Studies of streams in the pacific northwest also reported that stream power was important in the control of sedimentation levels (Kaufmann et al. 2009). The exposure of streams of low power to sediment accumulation may occur most often either where gradients are low, or where bankfull area and discharge are relatively low. This suggests there may be disproportionate sedimentation vulnerability for smaller streams within gently sloping valley segments of catchments.

Roads in forested mountain terrain increase the drainage density of stream networks, routing flows of water and sediment into streams and causing gully formation and extension (Megahan and Kidd 1972, Montgomery 1994, Wemple et al. 1996, Sheridan and Noske 2007). Roads with dirt surfaces that are regularly perturbed by traffic and grading may be a source of substantial fine sediment input to streams (Reid and Dunne 1984, MacDonald et al. 2004). Road crossings and the cut-and-fill slopes of unpaved roads alongside streams form direct routes for water and sediment delivery into channels. The density of roads and stream crossings were explicitly used in this study as a means for examining how such land surface disturbance and erosion routing could lead to disequilibrium in sediment accumulation in low gradient riffle-pool channels where deposition is favored. An increase in minimum sediment deposition levels was observed in both Sierra and coast streams as road density increased (Figure 12, Table 8). Above about 0.5 road crossings/km there was a substantial increase in cobble embeddedness in Sierra streams (Figure 14), and instable bed conditions of smaller D50 than hydraulic predictions (Figure 15).

The patch dynamics that maintain habitat complexity and biological diversity of streams in forested mountain landscapes may be disrupted by increased flood peaks and debris flows where road networks create drainage and erosion paths (Jones et al. 2000). The increased hazard of scouring debris flows from roaded terrain may cause substantial bedload transport of coarse substrate, and the removal and export of large wood debris (Swanson et al. 1998). The mobility and instability of sediments may be evaluated using the relative bed stability index (Kaufmann et al. 1999), where negative values of Log RBS indicate smaller substrate sizes than expected based on calculated bed shear stress. We found lower RBS for test compared to reference groups for both regions (Table 4), and that excess sediment levels in test streams of low power increased as Log RBS values became more negative (Figure 18). These observations are consistent with loss of habitat complexity that may accompany sediment delivery from roads and debris flow scouring. Indeed, sediment addition to experimental mesocosm streams resulted in the mobilization and loss of stored organic matter, depleting resources and reducing habitat complexity and ultimately invertebrate diversity (report 4 of this series).

Studies of land use impacts on stream habitat in urbanized or agricultural landscapes have often reported declining habitat quality and biological integrity as percent land disturbance increases (Allan 2004b). In the predominantly forested watersheds of the Sierra Nevada there was little or no land use cover, but minimum deposition of FSG<16 increased as combined land use cover in the riparian zone increased to 10 percent (Figure 13).. Land use disturbances in the central coast region covered greater proportions of land area (over 40% in some cases) and minimum deposition here also increased with land use (Herbst et al. 2011).

Imprecise or coarse resolution of land cover data (NLCD) that fails to account for mixed cover classes may explain in part for the wide variation in relating land use to instream habitat features. Assigning a single class of land cover to 30 meter DEM pixels results in an oversimplified view of interactions between natural and human-altered landscape elements, and may not appropriately represent the complexities of erosion sources and controls that may have disproportionate effects, such as landslides or different forms and density of riparian vegetation. Lumping land uses into a single combined cover without weighting of the influence of particular uses on erosion also ignores the qualitative differences between disparate sources of disturbance. Other than specifying absolute constraints of landscape features on habitat conditions (minimum deposition levels), it may not be possible for simple percent cover to make precise predictions of stream responses to human land uses. The poor resolution of vegetation coverage with existing GIS land cover data sources prevents a more refined analysis of the varied protection that may be afforded by different types of plant cover. Information on how vegetation type controls soil erosion, incorporating both forest canopy and understory plants, would further enable model calibrations to specific soils and slopes.

Spatial Scales of Landscape Disturbances and Reach-Scale Deposition

Catchment and riparian scales of land cover and use typically produced stronger correlations with deposition measures than at the reach scale (Tables 5, 6, and 8). Local bank erosion tallies taken at the margins of each transect was unrelated to sediment deposition, but fewer than 10% of sites had bank erosion in excess of 20% (none higher than 40%). While the dominance of road effects that we observed in the forested mountain landscapes of the Sierra may result from cumulative effects over riparian and catchment areas, the influence of localized disturbances are more evident in areas of rangelands, agricultural, and urban land use. Localized bank erosion where livestock grazing tramples banks and denudes riparian vegetation, can create direct inputs of sediment within reaches. Sediment yields have been shown to increase with the length of riparian exposure (Wohl and Carline 1996), localized exclosures have been shown in some cases to have larger substrate size than adjacent grazed reaches (Ranganath et al. 2009), and fine sediment deposition on streams within a grazing lands catchment in Wales were most closely correlated with the extent of bank erosion within 500 m upstream of study sites (Larsen et al. 2009). In some agricultural settings, the local stream buffer has been shown to be more closely tied to stream habitat sediments than whole-catchment land character (Richards et al. 1996), and urban streams often have direct local influences from stormwater runoff and culverts that act to concentrate inputs (Booth and Jackson 1997). Channel confinement also plays a significant role in the hillslope-channel connection of local sediment delivery to streams (Hassan et al. 2005). Within surveyed reaches we found that deposition measures taken at the point-transect scale and covering the entire extent of the reach, or at patch-area grid-frames, were more closely related to the effects of roads and land use disturbance than data collected from the area and composition of large bar formations(Tables 5 and 6). Substrate facies mapping of particle aggregates on the stream bed was also found to be a poor indicator in studies on the San Lorenzo River region (Herbst et al. 2011). Mebane (2001) speculated that bankfull particle counts outside the wetted instream channel may provide a better indication of upstream watershed erosion disturbances than just those present on the submerged stream bed. Our surveys of both the area and FS composition of depositional bar features found that this was not the case. Point-transects of instream particle counts were more consistently related to land use disturbances than bankfull bar area or FS content (Table 5 and 6). Bars are longer-term features of channels, forming under high flows while deposits of sediment dispersed over the reach are indicative of chronic partial bedload connectivity ("phase I") transport of fines and sand that occur over stable beds under lower flows (MacDonald and Coe 2007). While FS from point counts seems to be the best integrative sediment indicator, we also found that adding the gravel classes of smaller size (<8 mm), or all gravel (<16 mm), improved resolution of the minimum levels of deposition occurring with land use and road density. This may be because these particle sizes are less transportable under higher flow and power and so tend to persist while FS may be exported more frequently (follows from the basic Hjulstrom curves of particle transport, Gordon et al. 2004). FSG often show a minimum deposition that represents a basement that is less often moved, while looking at FS shows more of a ceiling where FS can always be depleted even under rising landscape disturbance because of resuspended transport, but when not removed, it may become elevated to higher and higher upper limits with land use and road exposure.

Applications:

Utility of the data set for continued monitoring of degradation under land use activities, or improvement where erosion control plans are underway, will provide for an adaptive management approach to erosion control and management in the watershed. The numeric targets identifying potential thresholds of sediment impairment at levels beyond the capacity of the channel (in the sediment transport sense), establish standards for determining when and where attainment of standards has been achieved, or if further remediation is required. Water Board staff can use these numeric targets to evaluate impairment and TMDL attainment (listing and de-listing of 303(d) stream segments). Use of reference sites permits determination of the natural range of deposition, and identification of some of the potential causes of erosion and accumulation e.g. road density and crossings, land uses, impervious cover). Maps of sediment levels along stream courses, and below tributaries or erosions sources might 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, sediment control, and further studies:

- Adopt multi-parameter standards based on reference distributions for attainment of natural sediment levels, and couple these to biological standards
- Re-sample reference sites to establish between-year variability and include additional reference streams to enhance accuracy of criteria and represent a greater variety of stream types and geographic coverage
- Implement erosion controls for roads where sediments exceed reference limits
- Modify standards as appropriate using biological data, and identify responses over sediment deposition gradients at differing spatial scales (sediment indicator taxa)
- Improve roads-related GIS data with details on surface type and use levels to provide more accurate predictions of disturbance and erosion from these sources

Summary Conclusions and Project Findings:

- Reach stream power is of primary importance in determining the local distribution of deposited sediment, and streams with a power index less than 4 are most susceptible to sedimentation, and in this range Test streams exceed References in the amount of sediment deposition
- Minimum deposition levels rise with increasing roadedness & land use
- A mosaic of disturbance patterns across streams determine cumulative local deposition, and this is related most to roads and land uses within the riparian zone or entire catchment, and less so to local reach influences
- Finer-scale stream-bed deposition patterns measured at point-, and patch-scales are more effective in detecting land use impacts on sedimentation than large-scale depositional bar formations
- Reference distributions may be used as a foundation for setting criteria and regulatory classification for prioritizing management within the Sierra Nevada and central coast region of California
- Applications include numeric criteria for sediment TMDL guidance, ambient and restoration monitoring, 303(d) listing and de-listing, and management targets

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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

Pooled 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, 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. Listing of sites with 5 or more of 9 criteria exceeding the 90th/10th percentile reference limits for sediment impairment.

			%FS	**%FSG<8**	**%FSG<16**	**D50**	**RBS**	**Excess.%FS**	**%Grid.FS**	**Embeddedness**	**X-Sect. Variability**	**Impairment Criteria Met**
Sierra Nevada	**Threshold Value =**		26.6%	40.3%	45.6%	19.3	0.433	10.4%	69.2%	18.4%	2.80	≥5 of 9
Stream	**Site**											
South Creek	Below Johnsondale	Test	**0.59**	**0.78**	**0.85**	**1.25**	**0.21**	**0.423**	**0.73**	**0.478**	**2.32**	9
Freeman Creek	Pyles Camp	Test	**0.57**	**0.64**	**0.74**	**1.25**	**0.22**	**0.412**	**0.906**	**0.38**	4.63	8
Pit River (South Fork)	Below Jess Valley Bridge	Test	**0.55**	**0.75**	**0.94**	**1.25**	**0.35**	**0.358**	**0.914**	0.152	**2.22**	8
Little Boulder Cr	Little Boulder Sequoia Grove	Test	**0.34**	**0.46**	**0.5**	**15.5**	**0.24**	**0.208**	**0.702**	**0.454**	3.93	8
Nobe Young Creek	Camp Whitsett	Test	**0.38**	**0.44**	**0.48**	22.5	**0.31**	**0.238**	**0.896**	**0.24**	3.40	7
Swauger Creek	Above Gauging Station	Test	**0.45**	**0.64**	**0.76**	**4**	**0.25**	**0.281**	0.484	0.158	**2.07**	7
Mugler Cr	Below Beasore Rd	Test	**0.5**	**0.64**	**0.72**	**2.125**	**0.18**	**0.340**	0.54	**0.36**	5.04	7
Butte Cr (Shasta)	above wooden bridge	Test	**0.48**	**0.5**	**0.57**	**6**	**0.18**	**0.335**	0.582	**0.206**	3.89	7
Nelder Cr	Below California Cr	Test	**0.36**	**0.43**	**0.46**	25.5	**0.26**	**0.221**	0.542	**0.3**	6.36	6
Tenmile Creek	Below Tenmile CG	Test	**0.39**	**0.67**	**0.69**	**3.5**	**0.41**	**0.227**	0.664	0.028	7.25	6
Willow Creek	Above West Carson	Reference	**0.32**	**0.47**	**0.56**	**9.5**	**0.29**	**0.171**	0.602	0.124	15.53	6
Sulfur Creek	Above White Hawk Ranch	Test	**0.38**	**0.42**	0.44	21	**0.42**	**0.223**	0.492	**0.428**	**2.15**	6
Jameson Creek	Above Plumas Eureka CG	Test	**0.34**	**0.5**	**0.6**	**7.5**	1.00	**0.161**	0.352	0.064	**2.32**	6
Lassen Cr	Below Lassen Cr C.G.	Test	**0.33**	0.38	**0.55**	**10**	**0.32**	**0.169**	0.366	**0.336**	3.12	6
Home Camp Cr	Inside Wilderness	Reference	**0.28**	0.4	**0.47**	**16.5**	0.84	**0.115**	0.38	**0.23**	3.29	5
Kern River (South Fork)	Above Campground	Reference	**0.37**	**0.41**	0.43	80	**0.33**	**0.240**	**0.87**	0.144	5.86	5
Jones Fork Silver Creek	Above Icehouse Road	Test	**0.3**	**0.49**	**0.64**	**8**	1.19	**0.116**	0.4	0.1484	3.67	5
Susan River	Above Hobo Camp	Test	**0.38**	**0.44**	**0.51**	**13.5**	0.91	**0.201**	0.522	0.078	4.10	5

			%FS	**%FSG<8**	**%FSG<16**	**D50**	**RBS**	**Excess.%FS**	**%S**	**Thalweg %FSG**	**Thalweg Variability**	**Impairment Criteria Met**
Central Coast	**Threshold Value =**		34.1%	36.7%	56.7%	15.0	0.411	12.0%	27.9%	78.1%	15.54	≥5 of 9
Stream	**Site**											
Big Sur River	Coyote Flat	Test	**0.62**	**0.63**	**0.65**	**1.25**	**0.16**	**0.389**	**0.28**	**0.85**	**11.7**	9
Aptos Cr	Below Valencia Confluence	Test	**0.88**	**0.88**	**0.93**	**1.25**	**0.08**	**0.676**	**0.88**	**0.97**	**3.3**	9
San Lorenzo R	Cowell Park - below RR bridge	Test	**0.51**	**0.57**	**0.58**	**1.25**	**0.33**	**0.273**	**0.34**	**0.80**	18.8	8
San Lorenzo R	Upper Camp Campbell	Reference	**0.42**	**0.48**	**0.57**	**8**	0.85	**0.163**	0.19	**0.79**	60.9	6
Scott Cr	Swanton Ranch - CalPoly	Test	**0.39**	**0.52**	**0.59**	**5**	2.25	0.069	0.25	**0.84**	**4.3**	6
Soquel Cr	Lower	Test	**0.36**	**0.41**	0.53	**15**	0.91	0.101	**0.28**	**0.81**	**15.3**	6

Appendix C. Reduced set of sediment criteria based on >75/90 and <25/10 percentiles of the reference distribution for Sierra streams, and setting of expectations for supporting, partially supporting, and not supporting standards. The upper panel corresponds to a reference distribution exceeding the 75th and 90th percentiles, above which the percentages of sediment shown partially supporting, or not supporting of numeric criteria derived by this approach. Below panels show the 10th and 25th percentiles for indicators that decrease with sediment level. Based on the 28 Sierra reference sites in this study. For comparable criteria for the coast, see Herbst et al. 2011.