Stormwater Pollutant Removal in Roadside Vegetated Buffer Strips

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Abstract: The Roadside Vegetated Treatment Sites Study was a two-year water quality monitoring project undertaken to evaluate the removal of storm water contaminants by existing vegetated slopes adjacent to freeways. The objectives of this study were to determine if standard roadway design requirements result in biofilter strips with treatment equivalent to those specifically engineered for water quality performance, and to generate design criteria. Variables such as width, slope, vegetation density, and hydraulic loading were evaluated by studying the runoff through existing vegetated slopes at four locations in northern California and four locations in southern California. At each location, concrete channels, approximately 30 m long, were constructed to capture freeway runoff after it passes through existing vegetated strips of varying widths. The quantity and quality of the runoff discharged from the buffer strip was compared to freeway runoff collected at the edge of pavement. The study found that buffer strips consistently reduced the concentration of suspended solids and total metals in stormwater runoff. The strips were generally less effective at removing dissolved metals and essentially no change in concentration was observed for nitrogen and phosphorus. Concentrations of organic carbon, dissolved solids, and hardness were observed to increase. For the constituents exhibiting a decrease in concentration, steady state levels were generally achieved within 5 meters of the pavement edge for slopes commonly found on highway shoulders and when the vegetation coverage exceeded 80%. Slope, vegetation type and height, highway width, and hydraulic residence time had little or no impact on the final concentrations.

INTRODUCTION

The Clean Water Act, which was enacted in 1972 and amended in 1987 to include storm water discharges, requires that states assess the condition of surface waters within their jurisdiction to determine whether they support their designated beneficial uses. A total maximum daily load (TMDL) must be developed for each of the segments designated as impaired for the constituents that are contributing to the impairment. The TMDL is the maximum pollutant load that can be assimilated by the waterbody without impairing its beneficial uses. When TMDLs are developed each of the dischargers to these impaired segments, including transportation agencies, may have to implement Best Management Practices (BMPs) to reduce the discharge of pollutants.

BMPs include vegetative stormwater controls such as grassed swales and vegetated filter strips. Vegetated filter strips, also known as buffer strips are relatively smooth vegetated areas with moderate slopes that accept stormwater runoff as overland sheet flow. The mechanisms of pollutant removal are filtration by grass blades or other vegetation, sedimentation, adsorption, infiltration into the soil, and biological and chemical activity in the grass/soil media. Although not designed specifically for water quality treatment and often not recognized by regulatory agencies, vegetated areas, such as medians and shoulders may provide substantial pollutant reduction; consequently, evaluation of the degree to which these areas reduce the adverse impacts that might be caused by discharging untreated runoff directly to receiving waters is important. Vegetated areas may mitigate the impact of highway runoff in two major ways, reduction of the concentrations of pollutant and reduction of the amount stormwater discharged to surface waters as a result of infiltration into the soil.

LITERATURE REVIEW

Vegetated swales and filter strips have not always been accepted as primary controls for the treatment of stormwater runoff. This is mainly the result of the wide range of pollutant removals reported for vegetative controls in various studies (Schueler et al, 1992; Young et al, 1996). Consequently, a lack of confidence emerged among regulatory agencies that vegetative controls could provide reliable and consistent removal of pollutants in stormwater. Some design manuals recommend vegetative controls only for pretreatment to reduce sediment loading to filtration systems or other structural stormwater controls. Unfortunately, many of the studies in which lower removal efficiencies were observed were not well designed and significant removal of the pollutants occurred before the runoff entered the test sections that were monitored.

One example is the evaluation of a grassy swale in Austin, Texas, by Welborn and Veenhuis (1988). The authors reported low or negative removals for many stormwater constituents; however, the runoff had traveled through a grassy swale for more than 200 feet *before* reaching the influent to the site that was monitored. The median influent total suspended solids concentration (TSS) was less than 20 mg/L, even though the drainage was derived from an area of medium density townhouses. Unpublished data collected by the City of Austin indicate that TSS concentrations in stormwater runoff from this type of land use are typically above 100 mg/L. The low influent concentration indicates that most of the removal occurred before entering the test section; therefore, the removals reported understate the potential improvement in water quality resulting from use of vegetative controls.

Kaighn and Yu (1996) recognized that the quality of highway runoff entering two test swales was considerably better than that observed at an edge of pavement site located nearby. For example, average TSS concentrations in runoff entering the swale were 38.7 and 32.8 mg/L, while runoff sampled from the pavement nearby had a TSS concentration of 112.9 mg/L. Additional monitoring indicated that much of the removal occurred in the vegetated filter strip crossed by the runoff before entering the swale test section.

Dorman et al (1996) analyzed the performance of three vegetated channels for treating highway runoff and reported TSS removal efficiencies ranging from 98% to negative 7 %. Operational problems and erosion of the channel were reported at the Virginia site. The influent TSS concentrations were as low as 8 mg/L at the Maryland site, and the average was less than 30 mg/L. The third site in Florida was extremely effective in removing suspended solids. The wide range of reported removal efficiencies reinforces the belief that small changes in channel characteristics cause large changes in pollutant removal effectiveness; however, only the data from the Florida site is indicative of the pollutant removal that might be expected in grassy channels.

The stormwater discharged from the vegetated controls in many of these studies contained 20 mg/L or less of TSS, which is well below the concentrations that would be expected based on the land use in the watershed. However, the impression conveyed by these published reports is that the vegetative controls are unreliable or worse, do nothing at all. In the studies described above, the monitored vegetative controls generally operated to polish the quality of the discharge rather than as the primary treatment device. A more efficient and consistent performance would be expected when the concentrations in the influent to the controls are similar to what might be encountered in untreated urban or highway runoff. The TSS concentrations might range from 100-200 mg/L, which is almost an order of magnitude higher than the influent concentrations reported in the cited studies.

There was a relatively recent study of the performance of vegetated areas adjacent to highways funded by the Texas Department of Transportation (TxDOT) that tried to resolve some of the misconception produced by earlier studies. This study was conducted in Austin, Texas by Barrett et al. (1998). The study determined the efficiency of a grassy median for mitigating highway runoff by measuring concentrations of pollutants in samples of stormwater runoff that were collected directly off the road surface and in samples of stormwater discharged from the median. The sites were selected to investigate the potential for variation in performance between vegetated areas with different characteristics compared the differences in quality and volume of runoff between the edge of pavement and after flowing down a grassy median.

Barrett et al. reported that vegetated channels designed solely for stormwater conveyance can be as effective as sedimentation/filtration systems for reducing the concentrations and loads of constituents in highway runoff. The percent reduction in pollutant mass transported to receiving waters was greater than the concentration reduction because of runoff lost to infiltration. These data indicate that filter strips are effective for treating runoff from 3-lane (each direction) highways at average daily traffic counts greater than 50,000.

There remain a number of important site-specific questions regarding the pollutant removal that can be expected. Because of differences in rainfall patterns, soils, typical road cross-sections and other factors, additional data needs to be collected to ensure that the full benefit of vegetated shoulders and channels is recognized by regulatory agencies. In addition, there is little documentation on maximum slopes and minimum widths for effective stormwater treatment.

METHODOLOGY

Eight study locations were selected across California that represented the range of slopes, climate, vegetation coverage, soil characteristics, and other regional factors that might impact pollutant removal in roadside vegetated buffer strips. Concrete collection channels were constructed at various distances from the edge of pavement so that the effect of buffer width on pollutant removal could be quantified. The locations of the study sites are shown in Figure 1 and the characteristics of each site are show in Table 1. A photograph of a typical system is presented in Figure 2.

The monitoring occurred over two wet seasons, generally from October to April 2001-2002 and 2002-2003. Monitoring of the RVTS sites began shortly after the completion of construction of the collection systems and installation of the monitoring equipment. The number of sampled storm events ranged from nine at Yorba Linda in southern California to 23 events at the San Rafael site in northern California. Flow weighted composite samples were collected at all locations in accordance with Caltrans guidelines (Caltrans, 2000). Precipitation during each storm event was characterized by total rainfall, duration of rainfall, rainfall intensity, days since last rainfall and antecedent rainfall depth. Most sampled storm events were preceded by at least 24 hr without rainfall, meeting the minimum required antecedent dry period.

Flow monitoring was conducted during each monitored storm event and continually throughout the storm season at each of the RVTS biofilter strips. Flow was measured using bubbler flow meters in conjunction with trapezoidal flumes. During several events, particularly in southern California, flow did not discharge through the biofilter strips due to infiltration.

Vegetation plays an important role in the concentration reduction in buffer strips by slowing the velocity of runoff, stabilizing the slope, and stabilizing accumulated sediment in the root zone of the plants. A vegetation assessment was conducted at all the test sites on a quarterly basis throughout the study duration to characterize the vegetation condition of the test sites. The vegetation was characterized by percent vegetation cover/density, height, plant species composition, and indication of maintenance activity.

Analysis of variance (ANOVA) was used to determine whether concentrations measured at each buffer width differed significantly. The purpose of this was to determine whether statistically significant differences exist between constituent concentrations at different buffer strip widths, and whether steady-state concentrations were achieved at any distance away from the edge of pavement. The constituent data were log-transformed prior to applying ANOVA. Initially, ANOVA was applied to the edge of pavement and all buffer widths at each site simultaneously. If there was no statistically significant difference in the means, then it was concluded that the vegetated area had no effect on runoff concentrations. If there was a difference, ANOVA was applied to the concentrations measured at adjacent collection channels to determine the minimum distance from the edge of pavement the greatest change was observed.

Equilibrium concentrations were determined to exist when the following conditions were met: 1) the mean concentration at a given length was significantly different (alpha = 0.05) than the edge of pavement mean concentration. 2) all mean concentrations at greater distances were not significantly different (alpha = 0.05) from the mean at the aforementioned length. When these conditions are satisfied, it can be inferred that the pollutant concentration has stabilized, and will not significantly change regardless of length away from the pavement. For some constituents the greatest change was observed to occur at the farthest distance monitored from the edge of pavement. In these cases, no judgment about whether these represent equilibrium concentrations can be made.

RESULTS

Water Quality Performance

There are a number of possible measures of performance of storm water BMPs. The two most common report performance as a removal efficiency (i.e., a percentage change between the influent and effluent quality) or focus on the effluent quality achieved. A boxplot of observed TSS data at Sacramento is presented in Figure 3 and suggests that an irreducible minimum concentration occurs that is relatively insensitive to concentrations at the edge of pavement. Consequently, the primary measure of performance among the sites in this report is the minimum concentration for each constituent at each site and the distance at which it first becomes manifest.

Summary statistics for each of the monitored sites are presented in Tables 2 through 9. The tables contain the summary statistics (arithmetic mean, range, and standard deviation) of the monitoring data collected. The rows have been color coded to indicate whether the observed concentrations at various distances from the edge of pavement exhibit statistically significant increases (shown in red) or decreases (shown in green) in concentration at the 95% confidence level. If the colored cell is located at the far right then the lowest/highest concentration occurs at the greatest distances from the edge of pavement. If multiple cells are colored, such as for TSS in Table 2, then the lowest concentration occurs at the distance of the first colored cell (4.2 m) and no further statistically significant change occurs at greater distances. Constituents in rows with no colored cells did not exhibit any statistically significant change in concentration at the test site. For the constituents exhibiting a statistically significant decrease in concentration, the lowest concentration for all is achieved within 4.6 meters of the edge of pavement and those that increase achieve their highest concentration farthest from the edge of pavement.

A summary of the shortest length observed to produce a constant (best) discharge quality for all constituents that decrease in concentration is presented in Table 10. For the sites with relatively few samples (Irvine and San Onofre) the distance presented is where the lowest concentrations are observed rather than where no statistical difference was demonstrated. The only site not to produce significant reductions was Moreno Valley, which is located in an arid region and only had an average of about 25% vegetation coverage. Table 11 presents the TSS edge of pavement and average discharge concentrations for each of the sites. In general a substantial reduction is observed, except for the sites with abundant gophers and Moreno Valley.

Infiltration

Each length of the buffer strips was evaluated for the amount of infiltration that occurred at each distance based on all events during the study period (not just those monitored for water quality). The load reduction for each of the sites for selected constituents is shown in Table 12. This is the load reduction calculated from the edge of pavement concentration at each site, the discharge concentration, and the runoff coefficient at the buffer widths shown in Table 10. In general, infiltration is responsible for a greater portion of the load reduction than the change in concentration. Only Moreno Valley which was ineffective at reducing concentrations and which had a relatively high runoff coefficient (about 50%) did not have substantial load reductions for all constituents.

Vegetation

Vegetation type and relative quantity is similar at all the California sites except for Moreno Valley, which had less than 25% vegetation coverage for most of the study period. Non-native grasses (Italian rye and brome grasses primarily) dominate and comprise between 65% and 100% of the vegetative cover type. Consequently, there is little basis for relating type of ground cover to performance. Average vegetation height varied between 11 and 22 cm, and was not correlated with performance. The vegetation at Redding, which produced runoff with the lowest constituent concentrations, consisted of 73% grasses with an average height of about 15 cm. This height is near the conventional recommendation for vegetated storm water controls.

Redding and Sacramento have average vegetation coverage exceeding 80% and with moderate slopes achieve irreducible minimum concentrations within 5 meters of the edge of pavement. Sites in southern California such as Irvine, Yorba Linda, and San Onofre have coverages of about 75% or less and with similar slopes require about 10 meters to achieve minimum concentrations. This suggests that performance falls off rapidly as the vegetation coverage declines below 80%.

Performance of existing vegetated areas adjacent to highways was also reported by Barrett et al. (1998). They monitored two sites in the Austin, Texas area, which had substantially different types of vegetation. Despite the differences, average TSS concentrations discharged from the two sites were very similar, 21 mg/L and 29 mg/L. These concentrations are similar to those observed in this study, again suggesting that vegetation type is not an important factor in performance. This conclusion is reinforced by the results of an earlier unpublished study conducted by the California Department of Transportation (Caltrans) of buffer strips engineered and operated specifically for stormwater treatment. The average minimum concentration of TSS observed at these sites, which had a monoculture of salt grass was about 27 mg/L.

Regression Analysis

Multiple (stepwise) regression was performed with the monitoring data from the biofilter strips except for Moreno Valley, which was eliminated because little pollutant removal occurred. Initially five predictors were used strip width, slope, grass coverage, peak discharge and influent concentration. These five predictors gave physically unreasonable results, indicating that the steeper slopes resulted in lower discharge concentrations and that wider buffer strips increased concentrations compared to narrow ones. Slope and width were also combined using design storm rainfall rates and roadway width to determine resulting runoff velocity and buffer residence time. It was hoped that residence time would be a better predictor of discharge quality than the individual factors. Unfortunately, the southern California sites tended to have the longest residence times, but the worst discharge quality.

There were several factors that lead to the disappointing results of the regression analysis. The two steepest sites (San Rafael and Cottonwood) outperformed sites at some locations with much flatter slopes (San Onofre and Yorba Linda). Additionally sites with lower average vegetation density (Irvine) performed much better than sites with higher coverage (San Onofre) even though both suffered about the same gopher damage. Finally, high effluent concentrations at San Onofre tended to skew the results of all the regression analysis since the site characteristics were similar to others, but all effluent concentrations were far higher.

Soil Chemistry

There is a common concern that constituents removed from highway runoff in vegetated buffer strips will accumulate in the soil and vegetation to the extent that the material could eventually be classified as a hazardous waste and require special handling. Consequently, the soils at each of the sites were evaluated at the end of the study period using the Toxicity Characteristic Leaching Procedure (TCLP). The results of this test for metals that have concentration limits are summarized in Table 13. Soil samples were collected from each of the buffer widths at each of the test sites. The average concentration is the mean for all the sites combined and the maximum is the highest concentration observed. Even the highest concentrations observed at the study sites were two to three orders of magnitude below the level where these soils would be classified as hazardous waste. Consequently, no special handling of roadside soils is required. And accumulation rates of leachable metals must be very low since many of these sites have been subject to high traffic conditions for many years.

CONCLUSIONS

Based on evaluation of the data collected during the 2-year monitoring study, a summary of findings of the water quality performance of vegetated highway shoulders are listed below:

- Concentration reductions consistently occur for TSS and total metals and frequently for dissolved metals.
- Nutrient concentrations were generally unchanged by the buffer strips.
- Water quality performance declines rapidly when the vegetative cover falls below about 80%.
- Vegetation species and height was similar at most sites and no effect on performance was observed.
- A substantial load reduction is evident for almost all constituents even those that exhibit no change in concentration because of the large amount of infiltration that occurred at most of the sites.
- At sites with greater than 80% vegetation coverage, the following buffer widths result in irreducible minimum concentrations for those constituents whose concentrations decrease:
    - 4.2 meters for slopes less than 10%
    - 4.6 meters for slopes greater than 10% and less than 35%
    - 9.2 meters for slopes between 35% and 50%
- At sites with less than 80% coverage, the following buffer widths result in irreducible minimum concentrations:
    - No data for slopes less than 10%
    - 10 meters for slopes greater than 10%
- The minimum concentration produced varied among the sites, but could not be shown to be a function of buffer width, highway width, vegetation coverage, hydraulic residence time, vegetation type, or slope.
- For selected constituents whose concentrations were lowered by the buffer strips the median of the average values for all of the sites except Moreno Valley were:
    - TSS – 25 mg/L
    - Copper – 8.6 µg/L
    - Lead – 3.0 µg/L
    - Zinc – 25 µg/L
    - Dissolved Copper – 5.2 µg/L
    - Dissolved Lead – 1.3 µg/L
    - Dissolved Zinc – 12 µg/L

- Study sites with sufficient vegetation produced an effluent quality that was equal to or better than that observed from vegetated buffer strips that were engineered and operated specifically for water quality improvement.
- Toxicity Characteristic Leaching Procedure (TCLP) testing of soils at the study sites indicated that metals concentrations were far below levels that would require classification as hazardous waste, so removal or disposal of roadside soils would not be subject to any special requirements even after years of runoff treatment.
- Existing routine maintenance activities for vegetated shoulders were sufficient to establish conditions favorable for substantial pollutant removal.

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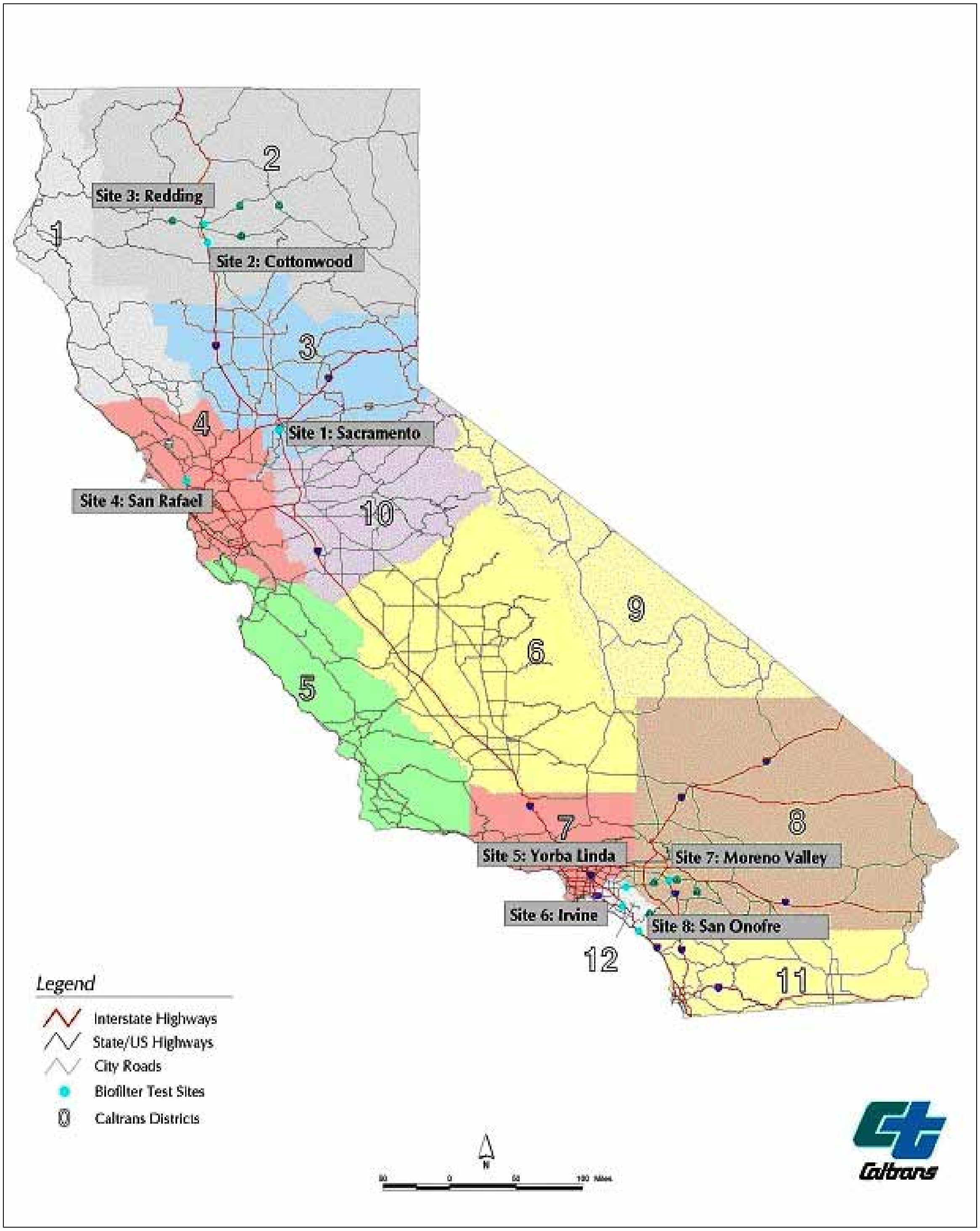

FIGURE 1. RVTS Buffer Strip Test Site Map

FIGURE 2. Redding, California Test Site

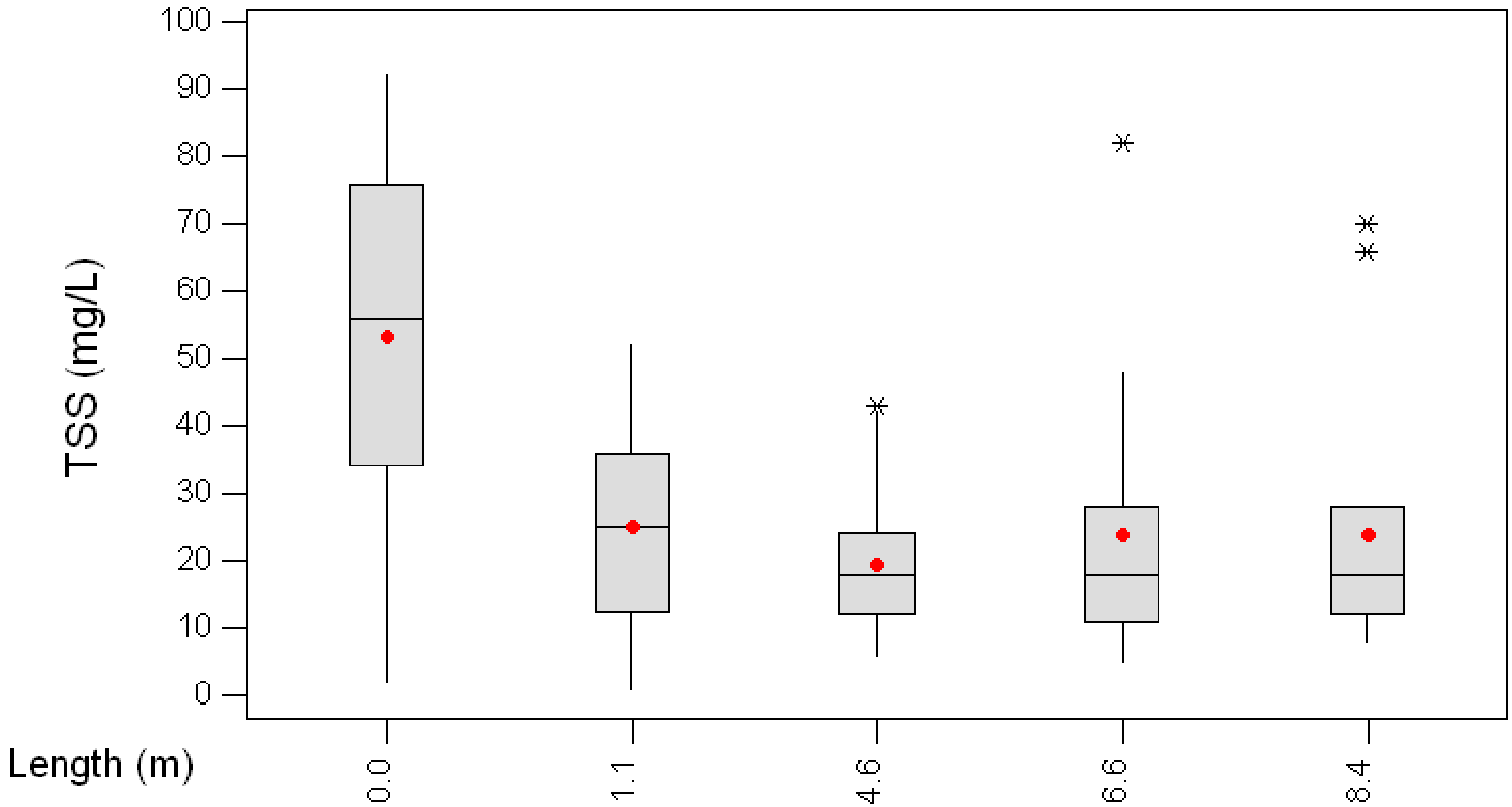

FIGURE 3. Boxplot of TSS EMCs at Sacramento

TABLE 1. Characteristics of the Test Sites

Site	System	Slope	Drainage Area [b] (m^2)	Strip Width (m)	Hydrologic Soil Type [c]
Sacramento					D
	System 1	EP	332	0.0	
	System 2	5%	376	1.1	
	System 3	33%	453	4.6	
	System 4	33%	498	6.6	
	System 5	33%	538	8.4	
Cottonwood					C
	System 1	EP	210	0.0	
	System 2	52%	546	9.3	
Redding					C
	System 1	EP	295	0.0	
	System 2	10%	372	2.2	
	System 3	10%	425	4.2	
	System 4	10%	478	6.2	
San Rafael					C/D
	System 1	EP	590	0.0	
	System 2	50%	890	8.3	
Yorba Linda					B
	System 1	EP	910	0.0	
	System 2	14%	1080	2.3/1.4 [d]	
	System 3	14%	1160	5.4/4.4 [d]	
	System 4	14%	1090	7.6	
	System 5	14%	1840	13.0	
Irvine					B
	System 1	EP	630	0.0	
	System 2	11%	710	3.0	
	System 3	11%	780	6.0	
	System 4	11%	1040	13.0	
Moreno Valley					C
	System 1	EP	368	0.0	
	System 2	13%	460	2.6	
	System 3	13%	518	4.9	
	System 4	13%	610	8.0	
	System 5	13%	672	9.9	
San Onofre					B/C
	System 1	EP	530	0.0	
	System 2	8%	558	1.3	
	System 3	10%	700	5.3	
	System 4	16%	840	9.9	

TABLE 2 Summary Statistics of EMCs at Sacramento Test Site

Constituent	**EOP** Mean Range Std. Dev.	**1.1 m** Mean Range Std. Dev.	**4.6 m** Mean Range Std. Dev.	**6.6 m** Mean Range Std. Dev.	**8.4 m** Mean Range Std. Dev.
TSS (mg/L)	53 2 - 92 24	25 1 - 52 14	19 6 - 43 11	24 5 - 82 21	24 8 - 70 19
TDS (mg/L)	64 32 - 170 33	57 1 - 120 31	99 49 - 150 33	135 82 - 250 45	153 58 - 300 92
TOC (mg/L)	8.7 2 - 21 5.4	11 3 -23 6.2	13 5 - 25 5.9	13 3 - 30 7.9	16 2 - 32 9.1
Total Cu (µg/L)	12 3 - 26 6.4	8.5 2 - 16 4.2	6.3 2 - 19 3.9	6.0 2 - 13 3.1	6.0 3 - 10 2.5
Total Pb (µg/L)	4.0 0.5 - 8.8 2.7	2.2 1.0 - 4.6 1.3	1.6 1.0 - 6.0 1.4	1.5 1.0 - 3.9 0.88	1.3 1.0 - 3.9 0.77
Total Zn (µg/L)	65 5 - 170 41	34 8 - 65 17	26 10 - 100 22	30 7 - 63 18	21 5 - 67 17
Dissolved Cu (µg/L)	4.0 1.4 - 11 2.4	4.3 1.0 - 10 2.5	3.5 1.0 - 9.3 2.1	3.4 1.0 - 11 2.7	4.2 1.0 - 9.8 2.7
Dissolved Pb (µg/L)	1.0 none 0.0	1.0 1.0 - 1.4 0.09	1.0 1.0 - 1.4 0.10	1.0 none 0.0	1.0 none 0.0
Dissolved Zn (µg/L)	14 5 - 40 11	17 5 - 41 13	12 5 - 29 8.3	8.5 5 - 28 6.9	7.9 5 - 23 6.1
NO_3-N (mg/L)	0.44 0.1 - 1.2 0.35	0.35 0.07 - 0.72 0.21	0.25 0.02 - 0.72 0.23	0.45 0.08 - 0.87 0.26	0.46 0.1 - 1.6 0.44
TKN (mg/L)	1.7 0.7 - 4.3 1.1	1.5 0.5 - 2.9 0.61	1.5 0.8 - 3.3 0.68	1.8 1.1 - 3.6 0.74	1.5 0.7 - 2.7 0.57
Total P (mg/L)	0.40 0.03 - 1.7 0.37	0.27 0.03 - 0.62 0.14	0.35 0.09 - 0.60 0.15	0.34 0.08 - 1.1 0.28	0.26 0.08 - 0.55 0.15
Dissolved P (mg/L)	0.17 0.03 - 0.41 0.11	0.21 0.08 - 0.45 0.12	0.25 0.05 - 0.43 0.12	0.17 0.03 - 0.37 0.12	0.17 0.03 - 0.44 0.14

TABLE 3 Summary Statistics of EMCs at Redding

Constituent	**EOP** Mean Range Std. Dev.	**2.2 m** Mean Range Std. Dev.	**4.2 m** Mean Range Std. Dev.	**6.2 m** Mean Range Std. Dev.
TSS (mg/L)	49 8 - 260 55	26 1 - 220 50	5.0 1 - 22 5.2	10 1 - 54 15
TDS (mg/L)	27 1-150 35	47 6 - 96 28	42 6 - 90 25	79 6 - 190 53
TOC (mg/L)	7.3 1 - 23 6.2	12 2 - 29 8.9	11 3 - 20 5.6	19 8 - 33 8.7
Total Cu (µg/L)	5.8 1.5 - 18 4.1	4.6 1.5 - 18 3.9	2.4 1 - 4.9 1.2	4.5 1.2 - 16 3.5
Total Pb (µg/L)	3.5 1 - 13 2.9	4.0 1 - 13 3.8	1.4 1 - 5.5 1.2	1.8 1 - 6.1 1.6
Total Zn (µg/L)	39 7 - 130 30	12 6 - 25 6.2	10 5 - 32 7.1	20 5 - 110 28
Dissolved Cu (µg/L)	2.8 1 - 12 2.8	1.9 1 - 4.1 1.0	1.8 1 - 4.1 1.0	2.6 1 - 6.7 1.7
Dissolved Pb (µg/L)	1.0 1 - 1.4 0.09	1.0 1 - 1.3 0.07	1.0 none 0.0	1.0 none 0.0
Dissolved Zn (µg/L)	16 6 - 50 11	13 5 - 43 13	8.2 5 - 26 5.4	12 2 - 51 13
NO_3-N (mg/L)	0.45 0.10 - 1.2 0.37	0.30 0.08 - 0.9 0.25	0.22 0.03 - 0.8 0.22	0.20 0.04 - 0.56 0.17
TKN (mg/L)	1.32 0.38 - 5.2 1.1	0.87 0.26 -2.0 0.50	0.84 0.27 - 1.9 0.40	1.2 0.49 - 3.6 0.80
Total P (mg/L)	0.14 0.03 - 0.67 0.18	0.09 0.03 - 0.26 0.07	0.10 0.03 - 0.31 0.07	0.17 0.03 - 0.61 0.17
Dissolved P (mg/L)	0.04 0.003 - 0.24 0.06	0.06 0.011 - 0.25 0.07	0.05 0.02 - 0.12 0.03	0.07 0.03 - 0.24 0.05

TABLE 4 Summary Statistics of EMCs at San Rafael

Constituent	**EOP** Mean Range Std. Dev.	**8.3 m** Mean Range Std. Dev.
TSS (mg/L)	70 5 - 210 50	19 1 - 38 11
TDS (mg/L)	71 10 - 290 60	142 80 - 230 47
TOC (mg/L)	16 5 - 41 10	13.5 3 - 33 9.4
Total Cu (µg/L)	38 7 - 82 19	6.6 1 - 16 3.4
Total Pb (µg/L)	14.5 1 - 45 11	2.7 1 - 11 2.7
Total Zn (µg/L)	123 33 - 330 69	25 6 - 110 26
Dissolved Cu (µg/L)	16 5 - 34 6.7	3.8 1.0 - 7.8 1.9
Dissolved Pb (µg/L)	1.2 1.0 - 2.7 0.45	1.0 1.0 - 1.3 0.07
Dissolved Zn (µg/L)	43 8 - 79 18	10 5 - 36 7.4
NO_3-N (mg/L)	1.9 0.1 - 4.6 1.2	0.61 0.08 - 2.2 0.48
TKN (mg/L)	2.3 0.6 - 4.7 1.1	1.2 0.6 - 4.8 0.94
Total P (mg/L)	0.21 0.04 - 0.81 0.17	0.13 0.03 - 0.31 0.08
Dissolved P (mg/L)	0.07 0.01 - 0.49 0.10	0.06 0.02 - 0.19 0.04

TABLE 5 Summary Statistics of EMCs at Cottonwood

Constituent	**EOP** Mean Range Std. Dev.	**9.2 m** Mean Range Std. Dev.
TSS (mg/L)	88 26 - 260 69	19 4 - 50 14
TDS (mg/L)	34 1 - 88 25	85 32 - 180 44
TOC (mg/L)	12 3 - 51 10	12 2 - 25 5.2
Total Cu (µg/L)	33 8 - 85 19	8.6 3 - 33 7.7
Total Pb (µg/L)	11 0.5 - 54 12	3.0 1.0 - 9.5 2.6
Total Zn (µg/L)	127 17 - 310 72	22 5 - 120 32
Dissolved Cu (µg/L)	12 4 - 33 7.6	5.2 2 -16 3.8
Dissolved Fe (µg/L)	172 22 - 949 229	476 50 - 1100 367
Dissolved Pb (µg/L)	1.4 1.0 - 5.8 1.1	1.3 1.0 - 3.6 0.78
Dissolved Zn (µg/L)	40 6 - 84 21	12 5 - 52 14
NO_3-N (mg/L)	0.81 0.1 - 3.4 0.78	1.4 0.1 - 5.2 1.3
TKN (mg/L)	1.9 0.8 - 4.6 0.98	1.9 0.7 - 7.4 1.7
Total P (mg/L)	0.19 0.03 - 0.85 0.23	0.15 0.03 - 0.67 0.19
Dissolved P (mg/L)	0.05 0.01 - 0.28 0.06	0.05 0.01 - 0.29 0.07

TABLE 6 Summary Statistics of EMCs at San Onofre

Constituent	**EOP** Mean Range Std. Dev.	**1.3 m** Mean Range Std. Dev.	**5.3 m** Mean Range Std. Dev.	**9.9 m** Mean Range Std. Dev.
TSS (mg/L)	104 12 - 206 58	66 7 - 150 51	50 11 - 140 40	90 18 - 216 83
TDS (mg/L)	118 16 - 360 95	131 10 - 360 124	112 40 - 278 66	90 14 - 278 39
TOC (mg/L)	31 8 - 84 24	25 9 - 73 18	30 11 - 86 22	29 11 - 86 17
Total Cu (µg/L)	58 13 - 110 28	31 9 - 75 19	26 10 - 46 13	18 8 - 46 7.3
Total Pb (µg/L)	68 15 - 190 46	34 8 - 100 26	41 11 - 110 33	41 3 - 110 28
Total Zn (µg/L)	265 46 - 510 142	81 20 - 160 47	78 21 - 250 73	57 20 - 250 30
Dissolved Cu (µg/L)	26 9 - 54 13	19 7 - 58 14	17 8 - 39 8.6	12 6 - 39 4.5
Dissolved Pb (µg/L)	16 3 - 75 20	8.5 1 - 21 6.2	11 3 - 24 6.8	14 1 - 32 11
Dissolved Zn (µg/L)	77 27 - 170 41	33 5 - 85 22	32 16 - 58 13	34 15 - 64 17
NO_3-N (mg/L)	1.5 0.2 - 4.6 1.4	1.6 0.2 - 5.7 1.8	0.72 0.1 - 1.9 0.61	0.60 0.1 - 10 0.68
TKN (mg/L)	1.8 0.4 - 4.2 1.2	2.0 0.1 - 5.2 1.6	1.6 0.6 - 2.7 0.94	1.7 1 - 10 0.52
Total P (mg/L)	0.35 0.03 -1.2 0.27	0.57 0.2 - 1.5 0.37	0.83 0.3 - 1.8 0.46	0.78 0.6 - 10 0.17
Dissolved P (mg/L)	0.11 0.03 - 0.36 0.10	0.37 0.06 - 1.4 0.35	0.67 0.3 - 1.6 0.39	0.59 0.4 - 10 0.17

TABLE 7 Summary Statistics of EMCs at Irvine

Constituent	**EOP** Mean Range Std. Dev.	**3.0 m** Mean Range Std. Dev.	**6.0 m*** Mean Range Std. Dev.	**13.0 m** Mean Range Std. Dev.
TSS (mg/L)	127 40 - 320 86	52 8 - 110 36	NA	25 14 - 38 11
TDS (mg/L)	164 1 - 350 96	135 44 - 292 85	NA	104 65 - 166 45
TOC (mg/L)	39 13 - 94 27	31 10 - 92 31	NA	21 14 - 34 8.9
Total Cu (µg/L)	84 37 - 130 27	41 11 - 74 25	NA	12 8 - 17 4.0
Total Pb (µg/L)	85 27 - 210 51	23 5 - 45 14	NA	4.8 2.7 - 6.3 1.5
Total Zn (µg/L)	286 110 - 480 113	99 40 - 200 57	NA	25 15 - 34 8.3
Dissolved Cu (µg/L)	35 15 - 75 18	19 5 - 50 17	NA	9.6 7 - 13 2.6
Dissolved Pb (µg/L)	11 2 - 38 12	3.8 1.0 - 7.4 2.6	NA	2.0 1.3 - 2.6 0.62
Dissolved Zn (µg/L)	80 40 - 170 36	36 13 - 94 31	NA	20 13 - 26 6.0
NO_3-N (mg/L)	2.6 0.7 - 5.2 1.6	1.5 0.2 - 4.4 1.6	NA	0.21 0.10 - 0.27 0.08
TKN (mg/L)	3.6 0.9 - 8.0 2.0	2.8 0.5 - 9.0 3.2	NA	1.0 0.7 - 1.7 0.45
Total P (mg/L)	0.48 0.2 - 1.0 0.26	0.70 0.4 - 1.3 0.40	NA	0.65 0.4 - 1.1 0.34
Dissolved P (mg/L)	0.22 0.03 - 0.49 0.15	0.37 0.04 - 1.1 0.38	NA	0.35 0.03 - 0.75 0.30

*Only a single sample collected at this distance

TABLE 8 Summary Statistics of EMCs at Yorba Linda

Constituent	**EOP** Mean Range Std. Dev.	**1.8 m** Mean Range Std. Dev.	**4.9 m** Mean Range Std. Dev.	**7.6 m** Mean Range Std. Dev.	**13.0 m** Mean Range Std. Dev.
TSS (mg/L)	114 24 - 221 73	222 47 - 670 189	119 28 - 400 115	124 19 - 330 116	42 15 - 108 45
TDS (mg/L)	68 19 - 149 44	87 8 - 190 58	67 1 - 182 49	91 20 - 150 49	80 44 - 124 34
TOC (mg/L)	20 9 - 48 13	21 3 - 44 13	24 8 - 57 16	24 9 - 50 16	21 11 - 32 8.8
Total Cu (µg/L)	43 16 - 100 22	44 25 - 85 19	31 9 - 77 20	16 7 - 26 7.2	10 7 - 14 3.7
Total Pb (µg/L)	23 4 - 45 11	29 17 - 47 11	24 8 - 55 16	19 7 - 42 15	7.3 3 - 17 6.5
Total Zn (µg/L)	321 94 - 640 208	224 95 - 550 154	105 31 - 250 69	54 21 - 96 29	33 20 - 58 17
Dissolved Cu (µg/L)	17 6 - 38 11	15 6 - 31 7.8	17 6 - 47 13	9.3 6 - 14 3.1	6.9 5.2 - 8.3 1.5
Dissolved Pb (µg/L)	5.2 1 - 12 4.0	4.3 1.0 - 9.0 2.6	4.5 1 - 11 3.0	2.9 1.0 - 7.4 2.4	2.2 1.0 - 4.3 1.5
Dissolved Zn (µg/L)	139 31 - 490 135	39 5 - 83 26	40 11 - 140 39	17 11 - 24 4.6	21 11 - 31 8.4
NO_3-N (mg/L)	0.83 0.1 - 2.2 0.67	1.8 0.4 - 6.0 1.7	1.3 0.3 - 3.9 1.2	0.84 0.2 - 2.0 0.70	0.26 0.14 - 0.41 0.11
TKN (mg/L)	2.2 0.9 - 4.9 1.4	2.4 0.8 - 5.0 1.2	1.9 0.7 - 3.8 1.1	1.7 0.4 - 3.7 1.3	1.3 0.8 - 2.3 0.70
Total P (mg/L)	0.26 0.18 - 0.46 0.09	0.40 0.24 - 0.99 0.23	0.40 0.19 - 0.65 0.16	0.54 0.2 - 1.2 0.38	0.67 0.5 - 1.2 0.34
Dissolved P (mg/L)	0.06 0.03 - 0.16 0.04	0.06 0.03 - 0.13 0.03	0.19 0.03 - 0.43 0.13	0.31 0.03 - 0.67 0.25	0.51 0.38 - 0.81 0.21

TABLE 9 Summary Statistics of EMCs at Moreno Valley

Constituent	**EOP** Mean Range Std. Dev.	**2.6 m** Mean Range Std. Dev.	**4.9 m** Mean Range Std. Dev.	**8.0 m** Mean Range Std. Dev.	**9.9 m** Mean Range Std. Dev.
TSS (mg/L)	71 11 - 257 81	161 34 - 680 213	330 56 - 1300 419	280 77 - 538 167	626 50 - 2600 812
TDS (mg/L)	66 26 - 110 34	100 16 - 230 74	81 14 - 172 52	81 12 - 163 54	59 8 - 100 38
TOC (mg/L)	31 9 - 96 30	33 9 - 83 26	30 9 - 90 27	31 9 - 85 27	26 9 - 73 22
Total Cu (µg/L)	38 16 - 100 27	36 20 - 72 18	37 14 - 71 19	32 18 - 53 12	40 21 - 67 15
Total Pb (µg/L)	8.4 4 - 13 3.2	12 4 - 32 8.8	16 5 - 42 13	16 6 - 31 9.0	27 6 - 52 17
Total Zn (µg/L)	349 150 - 800 237	184 62 - 640 188	196 44 - 630 190	191 79 - 510 139	404 120 - 1800 570
Dissolved Cu (µg/L)	26 11 - 87 25	24 12 - 61 16	23 14 - 62 16	19 10 - 40 9.3	18 10 - 39 9.5
Dissolved Pb (µg/L)	2.6 1.0 - 5.5 1.4	2.0 1.0 - 3.4 0.79	3.0 1.0 - 3.9 0.89	3.4 1.0 - 5.8 1.3	3.0 1.0 - 6.3 1.7
Dissolved Zn (µg/L)	261 99 - 700 206	55 29 - 140 36	49 18 - 120 31	53 25 - 94 21	56 21 - 110 28
NO_3-N (mg/L)	0.94 0.3 -3.6 1.1	1.1 0.4 - 2.5 0.77	1.1 0.5 - 2.7 0.72	0.88 0.3 - 1.9 0.59	0.65 0.2 - 1.6 0.48
TKN (mg/L)	3.7 1 - 13 4.0	3.5 1.4 - 8.0 2.3	3.8 1.2 - 9.1 2.9	4.8 2 - 13 4.0	4.6 2 - 14 4.3
Total P (mg/L)	0.57 0.1 - 2.3 0.72	0.52 0.2 - 1.1 0.30	0.69 0.2 - 1.8 0.58	0.48 0.09 - 0.84 0.25	0.80 0.5 - 1.1 0.26
Dissolved P (mg/L)	0.18 0.03 - 0.54 0.20	0.26 0.03 - 0.69 0.24	0.27 0.03 - 0.86 0.30	0.27 0.04 - 0.72 0.25	0.28 0.05 - 0.81 0.30

TABLE 10 Shortest Effective Length for each RVTS

Site	Distance (m)
Redding	4.2
Sacramento	4.6
San Rafael	8.3*
Cottonwood	9.2*
San Onofre	9.9
Irvine	13
Yorba Linda	13
Moreno Valley	Not Effective

*shortest distance monitored

TABLE 11 TSS Equilibrium Concentration for Each Test Site

Site	Edge of Pavement (mg/L)	Discharge Concentration (mg/L)
Redding	49	5
Sacramento	53	24
San Rafael	70	19
Cottonwood	88	19
San Onofre*	104	90
Irvine*	127	25
Yorba Linda*	114	42
Moreno Valley	71	626

*Gophers present in test strip

TABLE 12 Total Load Reduction (%) at Minimum Effective Width

Site	TSS	Copper	Lead	Zinc
Redding	97	76	84	90
Sacramento	85	83	87	87
Camp Pendleton	77	88	83	92
San Rafael	96	98	98	97
Cottonwood	96	95	95	97
Irvine	97	98	99	99
Yorba Linda	94	96	95	98
Moreno Valley	-450	46	-63	68

TABLE 13 Summary of TCLP Tests of Roadside Soils

Constituent	Average Concentration (μg/L)	Maximum Concentration (μg/L)	Hazardous Waste Threshold (μg/L)
As	2.2	4.7	5,000
Cd	0.5	0.5	1,000
Cr	8.2	19	5,000
Cu	24.5	210	25,000
Ni	8.4	31	20,000
Pb	45.6	240	5,000
Zn	44.5	120	250,000