Performance and Design of Vegetated BMPs in the Highway Environment

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Abstract

The objectives of this paper are to document the pollutant removal of existing vegetated areas adjacent to highways and to identify the minimum design requirements needed to obtain substantial pollutant reduction.

The pollutant removal performance of highway shoulders (buffer strips) is based primarily on eight test sites located on highway rights-of-way in California that were not designed for stormwater treatment. At each location, multiple stormwater collection systems (over 30 systems total) were installed and equipped with automated samplers to collect highway runoff after passing through vegetated buffer strips of varying widths. The vegetated buffers at each of the eight sites differed in characteristics such as slope (up to 50 percent), width, vegetation type and coverage, soil, and hydraulic loading. The data collected between 2001 and 2003 indicate that concentration reductions consistently occur for TSS and total metals and frequently for dissolved metals. Conversely, concentration increases were observed for dissolved solids and occasionally for organic carbon. Nutrient concentrations were generally unchanged by the buffer strips.

The pollutant removal and design of roadside swales is based primarily on the performance of two sites located in Austin, Texas, and which were constructed solely for stormwater conveyance. The data collected between 1994 and 1997 indicate that the majority of the pollutant removal occurs on the side slopes of the swales rather than along the length. Minimum discharge concentrations observed at these sites were similar to those observed from buffer strips in California. The greatest pollutant removal occurs when the geometry of the swale maximizes the length of the side slope; consequently, the optimum cross-section geometry for highway medians is V-shaped rather than the trapezoidal geometry normally illustrated in guidance manuals. In addition, the relatively constant side slopes facilitates mowing and is safer for the traveling public than channels with abrupt changes in side slopes. Swales along highways are normally sized to convey large, infrequent events, which when combined with the low side slopes implemented for safety reasons results in a broad bottom that reduces the concentration of runoff constituents. Consequently, a flat bottom is not required for effective operation.

Introduction

Many types of Best Management Practices (BMPs) are available for reducing the concentrations and loading of pollutants in stormwater runoff. These structural BMPs are often costly to construct, require substantial ongoing maintenance, and may be objectionable on an aesthetic basis. Consequently there is a need to develop and document the performance of sustainable treatment systems such as vegetated BMPs.

Vegetated BMPs include grassed swales and vegetated buffer strips that may mitigate the impact of storm water runoff in two major ways, reduction of the concentrations of pollutants and reduction of the volume of stormwater discharged to surface waters as a result of infiltration into the soil.

Vegetated buffer strips, also known as filter strips, are relatively smooth vegetated areas with moderate slopes that accept stormwater runoff as overland sheet flow. Buffer strips are often present along highways, especially in rural areas. Although not designed specifically for water quality treatment, vegetated areas such as highway medians and shoulders may provide substantial pollutant load reduction compared to discharging untreated runoff directly to receiving waters.

Methods

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. A photograph of a typical system is presented in Figure 1. A critical requirement in this study was the collection of runoff samples directly from the edge of pavement. This was done to avoid problems associated with previous studies where the runoff had crossed at least some vegetated area before the first sample was collected (Welborn and Veenhuis, 1988; Kaighn and Yu, 1996; Dorman et al., 1996).

Figure 1. Typical Monitoring Configuration of California Sites

Slopes at the individual sites ranged from 5 to 52 percent, which is much higher at the upper end than normally recommended in design guidelines for vegetated buffer strips. Widths varied between 1.1 and 13 meters. Vegetation coverage at the sites was generally between 60 and 100 percent; however, at one site in an arid location in southern California, the coverage dipped to as low as one percent at times. Sites in southern California differed from those in the north in that they receive less rainfall and gophers were present at all but the most arid site. Barrett et al. (2004) provided a summary of the sampling methodology and results and a detailed description of all study aspects were provided by Caltrans (2003).

Water quality performance of roadside swales was documented by Barrett et al (1998) at two sites along freeways in Austin, Texas. The pollutant removal performance was determined by comparing concentrations of pollutants in samples of stormwater runoff that were collected directly off the road surface and in samples of stormwater discharged from the swale located in the highway median.

The median swales were designed to convey stormwater and not as a runoff treatment device. A picture of one of the sites is presented in Figure 2. The median cross-section is V-shaped with a rounded bottom. Runoff from the highway flows as sheet flow down the sides of the grassy slope and then along the center of the median. The sides of the swale varied in slope between 9 and 12 percent, while the longitudinal slopes were 0.7 to 1.7 percent.

Figure 2. Median Swale Monitored in Austin, TX

Results

<u>Buffer Strip Performance</u>

There are a number of possible measures of performance of stormwater 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 total suspended solids (TSS) data at the Sacramento, California site is presented in Figure 2 and suggests that an irreducible minimum concentration occurs that is relatively insensitive to concentrations at the edge of pavement. Consequently, the primary measurements included in this report are the minimum concentration observed for each constituent and the distance at which it stabilizes. An analysis of variance indicates that the TSS concentrations at this site are not significantly different at distances of 4.6 meters and greater from the edge of pavement.

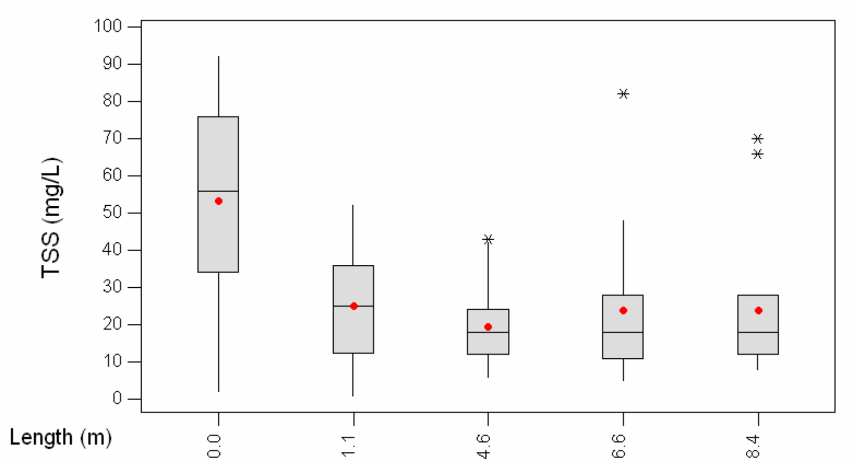

Figure 2 Relationship between Concentration and Width of Buffer Strip

Monitoring of the eight sites indicated that concentration reductions occur consistently for TSS and total metals and frequently for dissolved metals, and that nutrient concentrations were generally unchanged by the buffer strips. Concentrations of dissolved solids and total and dissolved organic carbon tended to increase as the runoff crossed the vegetated areas.

For the constituents whose concentrations were lowered by the buffer strips the median of the average values at each of the sites except Moreno Valley, which had no reduction in concentration because of the extremely low levels of vegetation coverage, is shown in Table 1.

Table 1 Comparison of Median Edge of Pavement and Discharge Concentrations

Constituent	Median Edge of Pavement Concentration	Median Discharge Concentration
TSS (mg/L)	88	25
Total Copper (µg/L)	43	8.6
Total Lead (µg/L)	23	3.0
Total Zinc (µg/L)	127	25
Dissolved Copper (µg/L)	16	5.2
Dissolved Lead (µg/L)	1.4	1.3
Dissolved Zinc (µg/L)	43	12

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 2. 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 the arid region and had a very low level of vegetation coverage.

Table 2 Buffer Width at which Concentrations Stabilized

Site	**Slope (%)**	**Vegetation Coverage (%)**	**Distance (m)**
Redding	10	88	4.2
Sacramento	33	93	4.6
San Rafael	50	87	8.3 (shortest measured)
Cottonwood	52	78	9.2 (shortest measured)
San Onofre	11	78	5.3
Irvine	11	74	13
Yorba Linda	14	80	13
Moreno Valley	13	19	No concentration reduction

Figure 3 presents a comparison of TSS effluent concentrations at the four northern California sites, which are generally similar except for slope. These slopes ranged from 10 percent at the "299" site near Redding, California to approximately 50 percent at Cottonwood and San Rafael. Based on an ANOVA these concentrations are not statistically different at the 95 percent confidence level despite the differences in slope among the sites. Consequently, vegetated buffers appear to be effective at much greater slopes than previously recommended by Young et al. (1996) and others.

Although concentration reductions were observed on slopes of up to 50 percent, any concentrated flow down these slopes resulted in severe erosion. Consequently, runoff should be diverted away from slopes that exceed about 30 percent.

The results of this study were compared to those obtained in the recently completed California BMP Retrofit Pilot Study in southern California that included an assessment of the performance of vegetated buffer strips (Caltrans, 2004). The buffer strips in the pilot study were engineered and operated specifically for water quality improvement. These sites also had a very rigorous operation and maintenance protocol that kept grass height and coverage within strict requirements. However, the improvement in water quality was no better than that observed in this study of standard roadside shoulders.

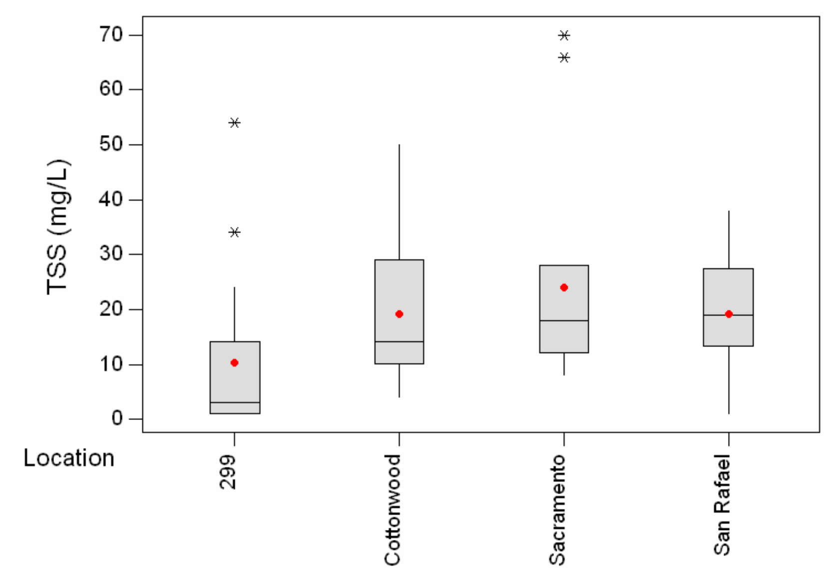

Figure 3 of TSS Effluent Concentration from Northern California Sites

Vegetated Swale Performance

The concentrations of selected constituents at the edge of pavement and at the discharge point of the swale are shown in Table 3. Note that the discharge concentration for TSS is the same in this study as in the California assessment of vegetated buffer strips. In contrast to the California study, reduction of nutrient concentrations was observed in the swale system.

Table 3. Concentrations Observed at Swale Sites (Barrett et al., 1998)

Constituent	Edge of Pavement Concentration	Discharge Concentration
TSS (mg/L)	174	25
Total Lead (µg/L)	115	80
Total Zinc (µg/L)	238	32
Nitrate (mg/L)	1.09	0.71
Total Phosphorus (mg/L)	0.39	.24
TKN (mg/L)	2.39	1.46

Figure 3 presents the concentration measured along the length of the swale for several events. Given that the average edge of pavement TSS concentration is 174 mg/L, it is apparent that substantial reduction in concentration occurs on the sideslopes of the swale before the runoff reaches the centerline. For many events the change in concentration along the length of the swale is small, which suggests that an irreducible concentration is often achieved on the sideslope.

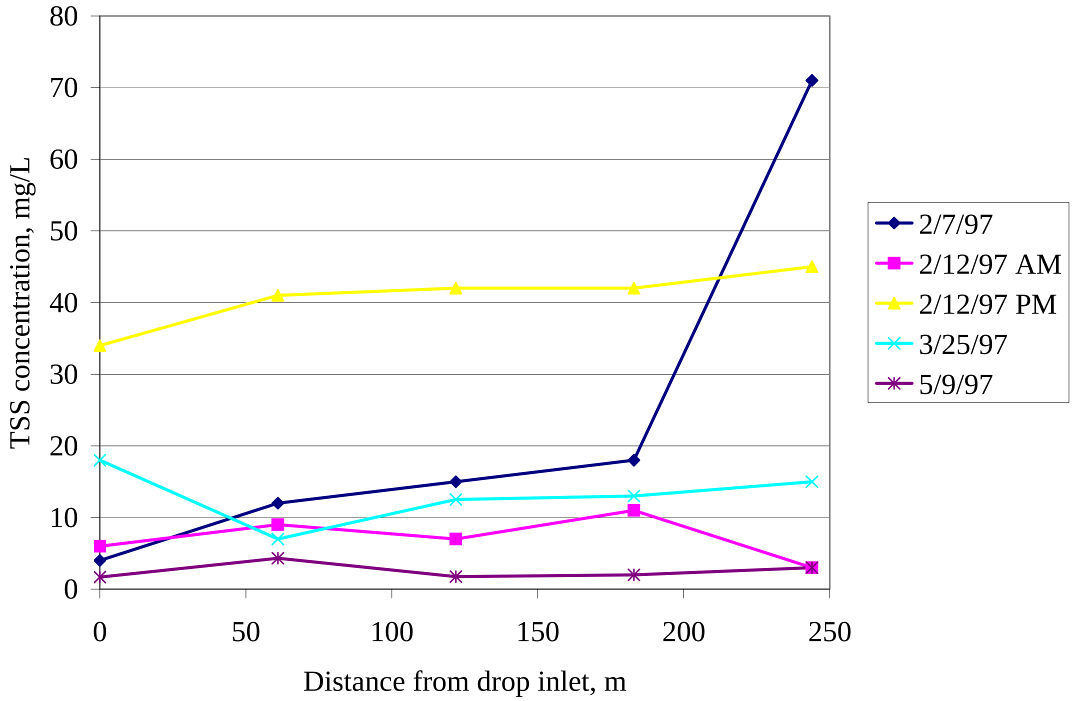

Figure 3. TSS Concentration along Center of Median (Barrett et al., 1998)

The amount of infiltration that occurred in both the California and Texas studies was substantial. No runoff from the longer buffer strips was observed during many events, especially in southern California where the antecedent moisture conditions were generally lower. In general, infiltration is responsible for an equal or greater portion of the load reduction than the change in concentration. The infiltration losses resulted in load reductions even for those constituents that did not exhibit a concentration reduction.

<u>Vegetation Type</u>

Vegetation type and relative quantity was 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. 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 less than 80% 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 about 75 or 80 percent.

The two swale sites monitored in the Austin had substantially different types of vegetation, with one consisting primarily of Prairie buffalo grass and the other a more diverse assemblage of Bermuda grass and various native wildflowers. Vegetation coverage was between 86 and 98 percent. 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 the California study, suggesting that vegetation type is not an important factor in performance. This conclusion is reinforced by the results of the earlier BMP pilot study conducted by the California Department of Transportation of buffer strips. The average minimum concentration of TSS observed at these sites, which had a monoculture of salt grass was about 27 mg/L (Caltrans, 2004).

In summary, these results indicate that substantial pollutant concentration and load reduction occurs in vegetated areas adjacent to highways, even when these areas were not designed as treatment systems. These reductions are comparable to those that would be expected in engineered systems for treating highway runoff. Consequently, maintaining vegetated areas adjacent to highways and eliminating curb and gutter conveyance systems where possible is a cost-effective, sustainable, stormwater treatment system for highways, especially those located in rural areas.

Design and Maintenance Recommendations

<u>Vegetated Buffer Strips</u>

- Vegetated shoulders exhibit substantial pollution removal at slopes up to 30 percent.
- A minimum vegetative cover of about 70 percent is required for concentration reduction to occur, although a rapid decline in performance occurs below about 80 percent.
- Vegetated shoulders with at least 80 percent coverage reduce pollutant concentrations to irreducible levels within 5 meters on slopes of less than 30 percent.
- At vegetation coverages of between 70 percent and 80 percent irreducible concentrations occur at about 10 meters.
- Runoff should be diverted away from slopes greater than 30 percent to prevent erosion.
- Vegetation type and height, highway width, and hydraulic residence time have little or no impact on discharge concentrations.

Vegetated Swales

- The greatest pollutant removal occurs when the geometry of the swale maximizes the length of the side slope, which is where most of the pollutant reduction occurs.

- The optimum cross-section geometry for highway medians is a broad V-shape or parabolic rather than the trapezoidal geometry normally illustrated in guidance manuals. The relatively constant side slopes facilitates mowing and is safer for the traveling public than channels with abrupt changes in side slope.

- The sides of swales along highways are often constructed at slopes of approximately 6:1 (H:V) for safety reasons and this is well within the range at which pollutant reduction occurs.

- Longitudinal slopes of the swales should not exceed 2 percent to prevent channelization or resuspension of previously accumulated material.

- A perfectly flat bottom is not required for effective operation of swales along highways, which are normally sized to convey large, infrequent events, which when combined with the low side slopes results in a broad bottom that reduces the concentration of runoff constituents.

Maintenance Requirements

The sites monitored in both the California and Texas studies were not subject to any special maintenance related to water quality. Primary activities included periodic removal of litter and mowing approximately twice per year. No particular effort was made to keep the vegetation height at some arbitrary level. Consequently, one can conclude that in areas with sufficient rainfall to maintain an adequate vegetation coverage no special maintenance is required to achieve water quality benefits. Occasional mowing for traffic safety reasons (i.e., to preserve visibility) or for fire suppression will produce roadside vegetation with characteristics that promote the removal of many stormwater contaminants.

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