STORMWATER
PROGRAM

California State University, Sacramento
University of California, Davis (UCD)
California Department of Transportation (Caltrans)

Effectiveness of Vegetated Biostrips in the Treatment of Highway Storm Water Runoff

Presented at:

American Water Resources Association, 2003 Annual Water Resources Conference, Nov. 2-5, 2003, San Diego

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EFFECTIVENESS OF VEGETATED BIOSTRIPS IN THE TREATMENT OF HIGHWAY STORM WATER RUNOFF

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BIOGRAPHICAL SKETCHES

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Misty Scharff has been involved with California State University, Sacramento, performing research on erosion and sediment control for the California Department of Transportation since 2000. She received her bachelor's and master's degrees in soil science from the California Polytechnic State University, San Luis Obispo, were she assisted in numerous erosion control research studies. She has been a member of IECA since 1996.

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ABSTRACT

To assess the effectiveness of water quality treatment of vegetated biofilter strips adjacent to highways, the California Department of Transportation (the Department) conducted a 2-year field study. Vegetation established adjacent to highways provides: erosion control, aesthetics, safety, environmental mitigation, and conveyance of runoff and storm water treatment. Vegetated strips, also called biofilter strips, receive sheet flow from the roadway before reaching the point of discharge. Benefits of biofilters include infiltration, adsorption, filtration, reducing storm water flow, and erosion. Objectives of this study included identifying the pollutant removal capabilities of various biofilters and the design parameters effecting removal.

Eight areas were equipped with two to five 30 m collection systems and automated samplers designed to capture highway runoff as it passed through various lengths of vegetated areas at the edge of pavement (EOP). Test strip lengths between EOP and collection channels were 1.1 to 13.0 m. Slopes were 5 to 52%. Vegetation was unmodified and included grasses, forbs and legumes.

Selected constituents concentrations were reduced by vegetated strips but varied among the sites. The average total suspended solids (TSS) concentration was reduced to 25 mg/L, total zinc was reduced to 25 ug/L, and dissolved zinc was reduced to 12 ug/L. Other metals concentrations were reduced to less than 10 ug/L.

Quarterly vegetation characterization was performed, which included mean percent absolute cover, mean height, mean absolute cover of broadleaf species, and mean absolute cover of grass species. Regardless of species, coverage of at least 65% was needed for pollutant removal, while removal was dramatically reduced when vegetation coverage fell below 80%.

Soil analysis was also performed at each monitoring location to assess soil type, soil chemistry, soil compaction, infiltration rate, density, and porosity. Soil properties and site characteristics were important because they control many of the hydrologic and sediment aspects of storm water. The purpose of these evaluations was to derive relationships between soil characteristics (mainly hydraulic residence times) and the runoff coefficient.

Substantial reduction in pollutant concentrations and load reduction occurred in vegetated areas adjacent to highways, even in areas not originally designed for treatment. Thus, vegetated areas adjacent to highways could be cost-effective, sustainable, storm water treatment systems for highways.

Key Words: biofiltration strips; water quality; BMPs; vegetated strips; storm water

INTRODUCTION

To assess the effectiveness of water quality treatment of vegetated biofilter strips adjacent to highways, the California Department of Transportation (the Department) conducted a 2-year field study titled the Roadside Vegetated Treatment Site (RVTS) study. Vegetation established adjacent to highways provides: erosion control, aesthetics, safety, environmental mitigation, and conveyance of runoff and storm water treatment. Vegetated strips, also called biofilter strips, receive sheet flow from the roadway before reaching the point of discharge. Benefits of biofilters include infiltration, adsorption, filtration, reducing storm water flow, and erosion. Objectives of this study included identifying the pollutant removal capabilities of various biofilters and the design parameters affecting removal.

Eight sites in California were evaluated. The sites were monitored over the 2001–2002 and 2002–2003 wet seasons. Storm water runoff was measured at the edge of pavement (EOP) and at various intervals from the highway to assess the treatment effectiveness of increased widths of vegetation. Runoff was monitored and analyzed for nutrients, metals, and other conventional pollutants.

SITE SELECTION AND LOCATION

Site selection was designed to include sites diverse in characteristics that represent California's varied conditions. Four sites each were chosen in northern and southern California. Sites were chosen in both urban and rural areas of the state. Each site contained vegetation that had been established for a number of years. Existing vegetation was utilized as biofilter strips. No additional seeding was applied to the slopes. Installing the concrete collection systems modified sites slightly, but did not change original site design. Routine department maintenance was performed including periodic mowing on some sites.

The northern California sites were established in Cottonwood, Redding, Sacramento, and San Rafael. Southern California sites were located in Moreno Valley, Yorba Linda, Irvine, and San Onofre. Sites ranged from 5 to 52% slope (refer to Table 1). Average Annual Daily Trips (AADT) ranged from 38,500 to 237,000. Average annual rainfall ranged from 10.3 to 39.4 in. Vegetation type, vegetation coverage, slope width, slope length, climate, and aspect varied from site to site.

METHODS

Storm Water Monitoring

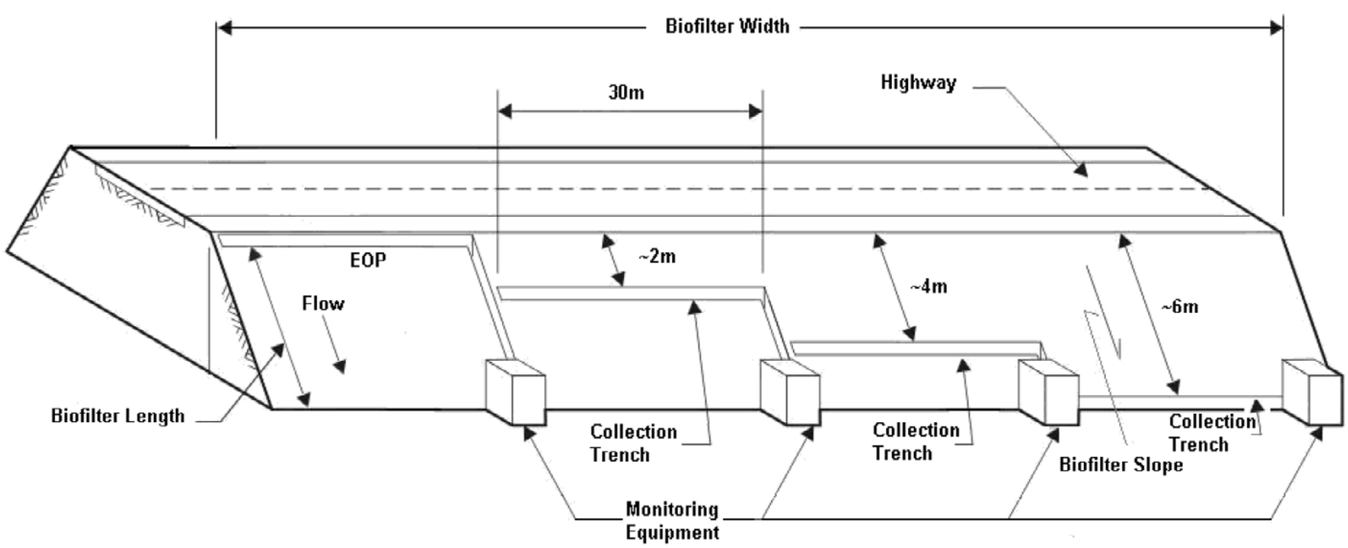
A 30 m long concrete collection system was designed and installed at the EOP of each site to collect storm water runoff. Additionally, one to four collection systems were installed at various distances from the EOP. Runoff traveled as sheet flow from the highway through the vegetated strip and into the collection system. Site size and slope constraints determined the number of additional systems installed. Systems were placed between 1.1 and 13.0 m from the EOP. A general site design is shown in Figure 1.

Rain covers were installed over each concrete collection system to avoid direct rainfall into the monitoring system (refer to Figure 2). Only runoff from the vegetated area was sampled. Rain covers consisted of fiberglass sheets connected with PVC pipe and fasteners. Covers were installed prior to each rainy season (approximately from October to April) and removed when monitoring was completed.

Storm water was monitored using automated samplers (ISCO Model 6712) to collect flow-weighted composite samples at each location. Each monitoring system was composed of an automated sampler, flow meter, cellular modem, data logger, and tipping bucket rain gauge. Stations were controlled remotely to download sampling data. The end of each collection system contained a 2 in, 60 degree trapezoidal flume used in combination with a bubbler to measure flow depth and rate. Flumes were made of either plastic or fiberglass and were

Table 1. RVTS Locations and Descriptions.

Site No.	Location	Freeway	Kilo-post (Post Mile)	District	Avg Annual Rainfall * mm (in)	Avg Annual Daily Trips (AADT)
1	Sacramento	I-5	21.7 (13.5)	3	437 (17.2)	75,000
2	Cottonwood	I-5	2.4 (1.5)	2	1001 (39.4)	38,500
3	Redding	SR-299	42.0 (26.0)	2	1001 (39.4)	11,800
4	San Rafael	I-101	24.0 (15.0)	4	912 (35.9)	151,000
5	Yorba Linda	SR-91	24.0 (15.0)	12	358 (14.1)	226,000
6	Irvine	I-405	4.0 (2.5)	12	325 (12.8)	237,000
7	Moreno Valley	SR-60	22.0 (14.0)	8	262 (10.3)	106,000
8	San Onofre	I-5	113.3 (70.4)	11	262 (10.3)	124,000



EOP= Edge of Pavement

Figure 1. Schematic of RVTS design.

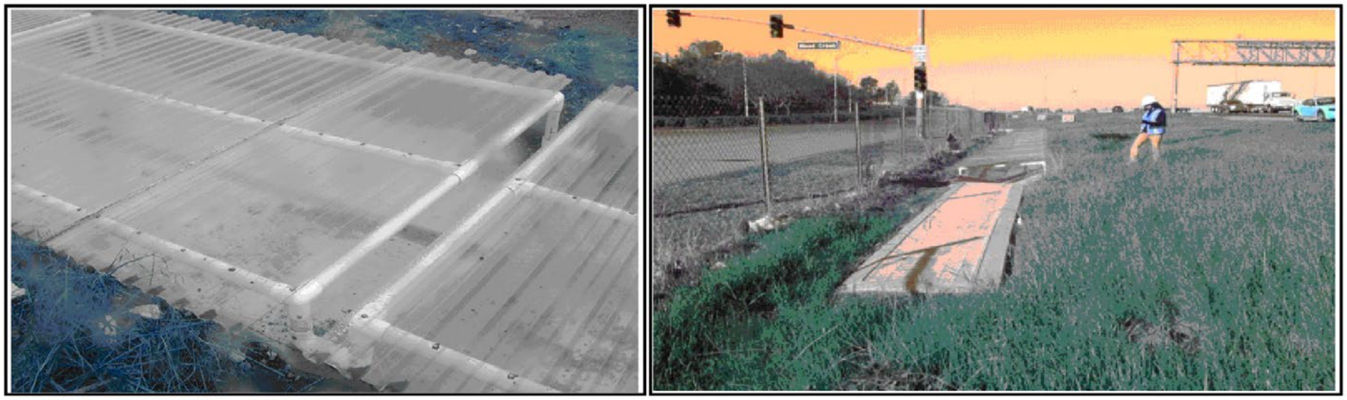


Figure 2. Rain covers.

preceded by a 10 ft approach section of concrete. Empirical observations were also made regarding site condition, erosion, gopher disturbance, sediment accumulation, and site damage.

Flow-weighted composite samples were taken during each storm event. Representative sample criteria were met by minimum acceptable storm capture parameters including percent capture and minimum number of aliquots. Percent capture was the percentage of total storm water flow passing the sampling station during a particular event that was sampled. The minimum numbers of sample aliquots depended on the amount of total precipitation for an event (Caltrans, 2002).

Automated samplers were run in pre-storm, storm and post-storm stages. Pre-storm activities included preparing general equipment inspections, setting data loggers to sampling mode, pre-icing sampling containers, entering the sample volume in the automated samplers, and documenting any notable observations (e.g., erosion, gopher activities, damage, etc.). Storm activities included changing sampling containers when full, labeling containers appropriately, collecting quality control samples, documenting observations, and preparing the samples for laboratory analysis. Post-storm activities included final preparation of samples for laboratory analysis, meeting holding times and volume requirements, sample labeling, and sample delivery to a certified laboratory.

Storm water quality was analyzed using the Department's storm water monitoring protocols (Caltrans, 2000). Constituent reporting limits and analysis methods followed standard Department protocol. Constituents analyzed included metals (total and dissolved), nutrients and conventionals.

Vegetation Monitoring

Quarterly vegetation assessments were made by a qualified biologist. The vegetation characterization included mean percent absolute cover, mean height, mean absolute cover of broadleaf species, and mean absolute cover of grass species. Five assessments occurred during Winter 2001, Spring 2002, Summer 2002, Fall/ Winter 2003, and Spring 2003.

Vegetation was assessed using an adopted stratified random sampling method. Quadrants were created using transect tapes placed along the lengths and widths of the biostrips. Quadrant size was 0.5 m by 0.5 m. Total vegetation cover was estimated visually within each quadrant. The percent cover from broadleaves and grasses was then identified. Taxonomic plant species names and heights were also recorded.

Soil Analysis

Soil analysis was also performed at each monitoring location to assess soil type, soil chemistry, soil compaction, infiltration rate, density, and porosity. Soil properties and site characteristics are important because they control many of the hydrologic and sediment aspects of storm water. This section focuses on the effects that soil properties and site characteristics have on infiltration, which are directly associated with storm water runoff volume.

Described below are the soil evaluations performed. The purpose of these evaluations was to derive relationships between soil characteristics (mainly hydraulic residence times) and the runoff coefficient (refer to Table 2).

Storm Water Runoff Coefficient

The runoff coefficient "C" is the factor directly associated with infiltration. Runoff coefficient can be defined as the ratio of storm water runoff volume to rainfall total over a given time period. The average runoff coefficient was calculated for each of the biofiltration strips.

Hydraulic Residence Time

Sheet flow occurs for some distance after rainwater falls on the ground. The flow depth is approximately uniform and is usually less than 50 mm. Sheet flow normally takes place for a distance less than 25 m although in some instances it could travel 100 m. The Kinematic Wave Equation was used to estimate the hydraulic residence time (i.e., travel time of sheet flow).

Infiltration

Infiltration rate measurements were performed at three locations (near the EOP, at the strip's centroid and near the concrete collection channel) within each of the 23 biofiltration strips using a Turf-Tec Infiltrometer. The infiltration rate measurements for each of the three locations were plotted on the same graph for each biofiltration strip. A logarithmic regression curve was drawn through the data, and the one-hour infiltration rate was calculated using the logarithmic equation that best fit the three data sets.

The vegetated strips were evaluated for the amount of infiltration that occurred at each distance based on all events during the study period (including non-monitored events). In general, infiltration is responsible for the majority of the load reduction rather than the change in concentration. The only site that did not have substantial load reductions for all constituents analyzed was Moreno Valley, which was ineffective at reducing concentrations and which had a relatively high runoff coefficient (about 50%).

Soil Texture Measurement

Near surface (top 2 in) soil texture was determined for each of the biofilter strips by collecting a representative soil sample and performing a sieve analysis using ASTM D 422-63—Standard Test Method for Particle Size Analysis of Soils. Results were used to classify the soil using the Unified Soil Classification System. More importantly, the results were used to determine the percentage of gravel, sand and fines (silt and clay) that exist in each biofiltration strip. These results were used to evaluate the relationship of these different-sized soils and rock materials with the runoff coefficient.

Soil Compaction Measurement and Soil Classification

Soil compaction was determined in situ at each of the biofiltration strips using ASTM D 2922-91—Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth). ASTM D 1557-91—Test method for Laboratory Compaction Characteristics of Soil using Modified Effort

Table 2. Average Runoff Coefficient and Relevant Soil and Site Characteristics for RVTS.

Site/System	Average Runoff Coefficient	Average Strip Width (m)	Slope (%)	Average Vegetative Cover (%)	Estimated Hydraulic Residence Time (min)	Relative Compaction (%)	Dry Density (lb/ft^3)	Infiltration Rate (in/hr)	Porosity (%)	Gravel (%)	Sand (%)	Silt/Clay (%)
Sacramento 2	0.31	1.1	2	93	5	93.5	121.6	2.96	29.2	51.8	36.9	11.3
Sacramento 3	0.32	4.6	33	84	5	81.2	105.6	2.68	38.5	31.9	36.5	31.6
Sacramento 4	0.28	6.6	33	92	6	79.7	103.6	2.35	39.6	32.5	36.5	31.0
Sacramento 5	0.15	8.4	33	90	8	78.4	101.9	3.14	40.6	39.2	35.8	25.0
Cottonwood 2	0.19	9.3	52	73	7	85.8	111.5	3.50	33.3	44.0	41.6	14.4
Redding 2	0.57	2.2	10	80	5	93.9	129.3	1.89	27.1	39.6	48.8	11.6
Redding 3	0.31	4.2	10	85	7	93	128.9	3.34	27.3	47.2	42.5	10.3
Redding 4	0.45	6.2	10	87	8	88.6	122.6	4.15	30.8	34.7	52.8	12.5
San Rafael 2	0.13	8.3	50	84	7	78.8	107.1	9.29	35.9	40.6	38.6	20.8
Irvine 2	0.39	3.3	11	70	5	88.4	108.7	1.54	34.0	24.9	59.9	15.2
Irvine 3	0.05	6.0	11	63	8	84.7	104.9	1.65	36.3	16.7	59.5	23.8
Irvine 4	0.16	13.0	11	62	12	87.6	107.8	0.92	34.6	20.1	46.5	33.4
Yorba Linda 2	0.37	1.9	14	61	4	89.2	114.7	1.26	33.4	28.1	53.4	18.5
Yorba Linda 3	0.51	4.9	14	82	6	82.5	106.0	0.87	38.5	25.3	53.5	21.2
Yorba Linda 4	0.58	7.6	14	74	8	87.7	112.7	1.57	34.6	17.2	60.6	22.2
Yorba Linda 5	0.17	13.0	14	76	12	86.8	111.6	1.81	35.2	34.2	49.6	16.2
Moreno Valley 2	0.95	2.6	13	3	1	90.7	123.4	0.72	28.9	20.3	61.5	18.2
Moreno Valley 3	0.95	4.9	13	16	2	93.3	126.6	0.57	27.0	29.7	53.0	17.3
Moreno Valley 4	0.48	8.0	13	22	2	92.9	125.8	0.94	27.5	16.5	59.1	24.4
Moreno Valley 5	0.51	9.9	13	18	3	93.9	127.3	1.04	26.6	13.7	70.2	16.1
San Onofre 2	0.45	1.3	8	81	3	95.9	122.7	2.25	27.4	19.0	63.8	17.2
San Onofre 3	0.27	5.3	10	74	7	88.5	114.7	1.25	32.2	27.1	56.8	16.1
San Onofre 4	0.07	9.9	16	69	9	85.3	108.3	0.75	36.0	21.7	55.7	22.6

Notes:
Bold results indicate runoff coefficient was adjusted from greater than 1.0 to reflect site condition.

[56,000 ft-lbf/ft³ (2,700 kN-m/m³)] was then used to determine the percent relative compaction of each density test.

Porosity

Average percentage of porosity was determined for the soils at each of the biofiltration strips. To calculate porosity, the soil's void ratio was first determined using soil compaction data.

RESULTS

Storm Water Quality Findings

The minimum concentrations produced varied among the sites. Water quality performance declined rapidly when vegetative cover fell below approximately 80%. Vegetation species and height were not observed to be significant factors that affected the performance of the biofilters. Selected constituents concentrations were reduced by vegetated strips. The medians of the average values for all of the sites (except Moreno Valley) are shown in Table 3. More detailed water quality results are presented in the RVTS report (Caltrans, 2003).

Table 3. elected Constituents and Average Concentration Reduction.

Selected Constituent	Median of Average Concentration Reduction
Total Suspended Solids	25 mg/L
Total Copper	8.6 ug/L
Total Lead	3.0 ug/L
Total Zinc	25 ug/L
Dissolved Copper	5.2 ug/L
Dissolved Lead	1.3 ug/L
Dissolved Zinc 12 ug/L	12 ug/L

Vegetation Results

Vegetation coverage was shown to be the most influential factor. Regardless of species, coverage of at least 65% was needed for pollutant removal, while pollutant removal was dramatically reduced when vegetation coverage was below 80%.

The vegetation types and amounts of cover were similar at each of the California sites except Moreno Valley, which had less than 25% vegetation coverage for most of the study period. Non-native grasses (Italian rye and brome grasses primarily) dominated and comprised between 65% and 100% of the vegetative cover type. Consequently, there was little basis for relating type of ground cover to performance. Average vegetation height varied between 7 and 59 cm. 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.

The Redding and Sacramento sites had average vegetation coverage exceeding 80% and with moderate slopes, achieved most of the concentration reductions within 5 m of the edge of pavement. Sites in southern California such as Irvine, Yorba Linda, and San Onofre had coverage of 75% or less, with similar slopes, requiring about 10 m to achieve minimum concentrations. This suggests that performance declines as the vegetation coverage declines below 80%.

Exploratory data analysis (EDA) was used to understand the correlation between y (TSS concentration) and each x (i.e., vegetative coverage, height and hydraulic residence time), and also the shape of the relationship (linear versus nonlinear) between the two variables. TSS concentration was selected because it is a reasonable indicator of biofiltration. The results of EDA showed a strong correlation (i.e., -0.76) between TSS concentration and vegetative coverage, and moderate to weak correlations with the other variables. A regression analysis was then used to derive a statistically significant relationship between TSS concentration and vegetative coverage. The following regression equation was identified based on the results of the regression analysis:

TSS concentration = -4.21 × (% vegetative coverage) + 385.91

The statistical significance level of the regression model (p value) is less than 0.0001, indicating a highly significant model. The square of the regression coefficient (r^2) for the regression equation is 0.58, which means that about 58% of the site-to-site variability in the estimated TSS concentration is explained by the regression model. The root mean square error is 96, which means that the TSS concentration estimated from the regression equation has accuracy of plus or minus 96 mg/L. Considering the accuracy and degree of unexplained variability of the model, it is not suggested for use. However, the data indicated substantial reduction in concentrations with coverage just exceeding 65%. Additionally, northern California sites had higher average vegetative coverage (> 80%) and better pollutant removal performance than southern California sites, which had an average vegetative coverage of approximately 71%. Accordingly, based on the data a minimum of 65% coverage is suggested.

Soil Analysis Results

Multiple regression analysis (MRA) was used to derive a statistically significant relationship between runoff coefficient and soil and site characteristics (refer to Table 2). MRA is commonly used to predict a dependent variable, y, as a function of relevant explanatory variables, x_1, x_2, …, x_n. Results of MRA provide an understanding of the percentage of the variability in y that is explained by the selected set of x variables.

A stepwise regression analysis was performed to identify the most efficient set of x variables that would explain most of the variability in y and also to assess whether the relationship between y and the selected set of x variables is statistically significant.

The correlation coefficient (r) between the runoff coefficient and each explanatory variable and also between natural logarithm of runoff coefficient and each explanatory variable was calculated. Additionally, the correlation coefficient was calculated for each transformed (natural logarithm) explanatory variable. The highest simple correlation was between the runoff coefficient and natural logarithm of hydraulic residence time (r = 0.79). Because the log-transformed explanatory variables generally show higher correlations with runoff coefficient than raw variables, stepwise MRA was performed between runoff coefficient and log-transformed explanatory variables. If a group of explanatory variables showed high correlations among each other, only one of the variables was retained for further analysis. For example, log of porosity was highly correlated with log of dry density and log of relative percent compaction. Also, log of relative percent compaction was highly correlated with log of dry density. Among these three variables, log of dry density showed the highest correlation with runoff coefficient. Therefore, only log of dry density from these three variables was retained for the stepwise MRA.

A stepwise MRA was then performed with the retained explanatory variables using a significance criterion of 0.2 for entering or removing an explanatory variable. The following regression equation was identified based on the results of the stepwise MRA:

Runoff coefficient = -3.06 + 0.809 × *ln* (dry density) – 0.071 × *ln* (infiltration rate) – 0.218 × *ln* (hydraulic residence time)

The statistical significance level of the regression model (p value) was less than 0.0001, indicating a highly significant model. The square of the multiple regression coefficient (r^2) for the regression equation was 0.70, which means that about 70% of the site-to-site variability in the estimated runoff coefficient is explained by the regression model. The root mean square error is 0.14, which means that the runoff coefficient estimated from the regression equation has (a one standard deviation) accuracy of plus or minus 0.14.

The use of the equation above requires the estimation of hydraulic residence time, which requires using other variables such as strip width, slope inclination, and vegetative cover in a computational procedure. Additionally, the infiltration rate would need to be known. If the estimation of hydraulic residence time and measurement of infiltration is considered to be more complicated and hence less practical than using other direct physical measurements, an alternative regression equation excluding hydraulic residence time and infiltration rate, but including physical site characteristics may be considered. With this objective, a stepwise MRA was performed without hydraulic residence time and infiltration rate. For this regression, explanatory variables in their raw scales were used because they would be simpler to use and interpret, and they showed a regression fit similar to using log-transformed variables.

The alternative regression equation based on this analysis is as follows:

Runoff coefficient = 0.186 – 0.028 × average strip width – 0.005 × average % vegetative cover + 0.006 × dry density

The p-value is 0.0001, the square of correlation coefficient, r^2, is 0.66, and the root mean square error is 0.15. Thus, the latter equation is somewhat less accurate in estimating runoff coefficient than the first, but still is highly significant.

CONCLUSION

It is crucial that biofiltration strips have vegetation coverage of at least 65% to achieve pollutant removal to improve water quality. Soil density, compaction and infiltration must be known to understand treatment effects. Substantial reduction in pollutant concentrations and load reduction occurs in vegetated areas adjacent to highways, even in areas not originally designed for treatment.

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