Performance-Based Ranking of Treatment BMPs

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Executive Summary

The purpose of this project is to create an updated performance-based ranking of Department-approved treatment BMPs for use in the development of statewide BMP selection guidelines.

In the current Project Planning and Design Guidelines (PPDG), the selection of stormwater Best Management Practices (BMPs) is based on a preliminary analysis of BMP performance data collected by the Department as of summer 2004. This project was designed to improve and update the previous analysis in three ways. First, a more scientifically defensible mixed-model statistical analysis was undertaken that identified differences in performance due to BMP type, separate from differences due to location. Second, the limited load analysis performed in 2004 was expanded to include all TDCs. BMP rankings by load reduction don't always correspond to those by concentration reduction because of the role of infiltration in reducing discharge volumes. Third, the data set was substantially expanded to include new field data collected since 2004. The data set used in this analysis came from the Retrofit Pilot Program, the District 2 Sand Filter Study, and the RVTS Studies.

Methodology

Comparing BMPs on an equal basis is difficult because different BMPs were tested under a variety of site-specific conditions. Influent concentrations, in particular, vary from storm to storm and site to site. To compare BMPs on an equal basis, the field results were extrapolated, as needed, to typical runoff conditions (the median loads and concentrations) in the statistical analysis. This approach was partially successful for concentration rankings, but not for load rankings. For the concentration data, the extrapolation introduced statistical uncertainty, which contributed to BMPs being clustered into few, relatively large groups whose members were statistically indistinguishable by performance. For the load data, the result was even less conclusive, with almost no statistical distinctions among BMPs. Consequently, substantial post-statistical analyses were required. For concentration ranking, a simple regrouping procedure was used to assign all the BMPs into three tiers: more effective, less effective, and not effective. For the load rankings, the ambiguous statistical results were abandoned and a separate data-based analysis, the sum of loads method, was substituted.

In the sum of loads method, the overall load removal was calculated for all monitored storms at each study location. It became obvious that load removal is affected greatly by infiltration, so BMP performance rankings were developed for two different levels of runoff infiltration: greater than 50 percent and 20 to 50 percent. Infiltration that was less than 20 percent was considered inconsequential to load reduction, so the concentration rankings are suggested for these sites.

Results

The rankings are shown in Tables 4.1 for concentration and 4.2 for load removal. All currently approved BMPs are included in the lists. Biofiltration strips are subdivided into relative size categories, and Austin-style filters are subdivided into their relative construction types: concrete lined vs. earthen. Four tiers of performance are defined. Tier 0 includes total infiltration BMPs (basins and trenches). The relatively more effective BMPs are in Tier 1. The relatively less effective BMPs are in Tier 2. Tier 3 includes those BMPs with inconsequential or statistically undetectable constituent reductions. Separate rankings are presented for each Target Design Constituent (TDC). Rankings are also provided for three additional proposed TDCs.

The tables are designed to be used by designers in their initial BMP selections to meet specified water quality goals for specified TDCs. Within each tier multiple BMPs are thought to offer equivalent performance. A hypothetical example application illustrating the use of the tables is presented in Appendix E. In many cases controlling a specific TDC may not be the water quality goal. Here, a more general Maximum Extent Practicable (MEP) standard may be more appropriate. MEP was not considered in creating these TDC-based rankings. Methods for using the results of the TDC results for MEP ranking are explored in Appendix B.

Qualifiers

Selecting BMPs for a particular site requires consideration of many factors besides water quality, such as safety, cost, and ease of maintenance. These additional issues are not reflected in the rankings, which are based solely on water quality.

The rankings are useful for selecting BMPs based on relative treatment performance, but they are not a method for predicting performance at any specific site. In particular, the concentration rankings, which are based on typical Caltrans conditions, will not be accurate for clean sites because most treatment technologies are less effective on low runoff concentrations than on high concentrations. Further, the concentration rankings cannot be used to estimate how often a concentration standard might be exceeded.

The load reduction rankings, because they are based on the sum of loads method using data from all existing test sites, do not necessarily represent performance under typical Caltrans conditions. To better estimate performance for typical conditions, preliminary ranks based on raw numerical results were adjusted using engineering judgment and anecdotal evidence from the field.

Finally, the percent of runoff that infiltrates at a particular site is relatively easy to measure after construction, but is difficult to estimate before construction. It depends on site conditions (e.g., soil type) and local hydrology (i.e., rainfall intensities). In addition, BMP design can influence this parameter by changing the area of exposed soil for infiltration (think broad, shallow detention basins vs. narrow, deep ones.) Further method development is needed to aid project engineers in this regard.

1 Introduction

1.1 Purpose

The purpose of the technical memorandum is to present a performance-based ranking of Department-approved treatment BMPs for development of statewide BMP selection guidelines. These rankings should be used in conjunction with project site conditions and professional judgment for an overall assessment of feasibility of treatment BMPs. The goal was to determine whether a particular BMP would likely have equivalent performance to all other BMPs for given site conditions. The result is a classification of BMPs into tiers, with performance of all BMPs within a tier being substantially the same for typical highway runoff conditions.

The Department's BMP selection process is contained in the Project Planning and Design Guidelines (PPDG). The latest version is based exclusively on results from the BMP Retrofit Pilot Program (Caltrans, 2004). This document substantially expands on that analysis by including additional data from the Roadside Vegetated Treatment Sites (RVTS) Study and the District 2 Sand Filter Study. In addition, the statistical analysis is more sophisticated than that used in the Retrofit Pilot Program. This analysis focuses on the "target design constituents" (TDCs) defined in the PPDG. The approved BMPs, current and potential TDCs, and the approach to BMP ranking are further discussed in this section.

1.2 BMP Types

Table 1.1 contains the treatment BMPs considered in ranking procedures and the number of installations of each.

Table 1.1 Approved Treatment BMPs Considered in Rankings

BMP Type[a]	Number of Locations
Austin Sand Filters, lined[b], full-sedimentation	5
Austin Sand Filters, unlined[b], one full and one partial-sedimentation	2
Delaware Sand Filters	1
Detention Basins, lined	4
Detention Basins, unlined	1
Multi-Chambered Treatment Train (MCTT)	2
Strips – short (with a hydraulic residence time ≤ 5 minutes)	16[c]
Strips – long (with a hydraulic residence time > 5 minutes)	6[c]
Swales	6
Wet basins	1

[a] Infiltration basins and trenches could not be numerically compared to other BMPs because there was no effluent water to be characterized for comparison. They are understood to be a superior BMP whenever site conditions allow infiltration of the volume of stormwater that results from the design storm.

[b] Lined and unlined Austin sand filters were not separated in the statistical analysis of performance.

[c] In Section 3, strips were reclassified by hydraulic loading, expressed as the ratio of strip area to drainage area (A_S/A_D). See Table 1.3 for a breakdown by HRT and A_S/A_D.

1.3 Target Design Constituents (TDCs)

Target design constituents (TDCs), as defined in the PPDG, meet two criteria: (1) They are discharged at concentrations that are potentially higher than receiving water quality objectives in impaired watersheds. (2) Their concentrations are reduced by Caltrans-approved treatment BMPs.[1]

The current TDC list follows:

- Sediments (measured as total suspended solids [TSS])
- Phosphorus (total)
- Nitrogen (total)[2]
- Copper (total and dissolved)
- Lead (total and dissolved)
- Zinc (total and dissolved)
- General metals (unspecified metals) (Caltrans, 2007)

Although they are not listed as TDCs in the PPDG, total cadmium, chromium, and nickel were added to this analysis because recent analysis of pilot data revealed that typical highway concentrations are reduced by approved BMPs (see Appendix A).

1.4 Application Scenarios

Project-specific conditions like topography, spatial constraints, and safety determine the feasibility of BMPs at a particular project. Since multiple BMPs may be feasible, ranking BMPs gives designers a tool to maximize the benefit of BMP deployment.

Benefit is usually measured in load reduction or concentration reduction. The most appropriate benefit to the receiving water may be inferred by its regulatory scenario. The scenarios are considered in order of most-to-least prescriptive, so TMDLs are considered first, followed by cases where a waterbody is 303(d)-listed without a TMDL, and finally where the maximum extent practicable (MEP) standard applies without any 303(d) listing.

1.4.1 TMDLs

TMDLs are prescriptive and dischargers must comply with whatever standard (concentration or load) is dictated. In some cases treatment is assumptive based on a level of BMP deployment of specified BMPs (e.g., Los Angeles River Trash TMDL). In other cases, the Department may not be required to implement specific treatment BMPs

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[1] If a constituent is removed in a BMP solely by infiltration, it is not currently included in the TDC list. If the second criterion is interpreted to include removal by infiltration (i.e., load removal), then the TDC list could be expanded to include all pollutants of concern. For example, TDS is not a TDC because currently approved BMPs do not reduce concentrations, but TDS load is reduced by infiltration.

[2] Total nitrogen was listed based on reductions of TKN and NO_3-N (OWP, 2004).

(e.g., Garcia River Sediment TMDL). There are other cases where Regional Water Quality Control Boards have recognized that the Department's current efforts (without treatment BMP retrofitting, or with limited construction of strips and swales) were sufficient to comply with the TMDL implementation plan (Caltrans, 2008b). Because of these different regulatory approaches, the performance rankings are not very useful for identifying compliant BMPs for any particular TMDL.

1.4.2 303(d)-Listed Receiving Waters

For 303(d)-listed waters, science-based BMP selection requires additional analysis (and possible data collection) to answer the following questions:

1. What is the water quality objective?

Water quality objectives are found in basin plans established by RWQCBs. However, some objectives vary according to other parameters such as hardness and temperature. The exact value to which Department discharges should be compared may require site-specific analysis.

2. Do the Department's untreated discharges for a particular project violate the water quality standard?

Regional or site-specific analysis of water quality may show that stormwater quality is different from what is assumed using statewide statistics. Recent analysis by the Department shows regional differences for highway discharge quality and a strong correlation to AADT/lane (Caltrans, 2009a).

3. Which treatment BMPs meet the water quality standard?

An effluent analysis of BMPs with respect to the concentrations from the first question is required to determine which BMPs discharge at concentrations that are compliant with water quality objectives. The analysis here does not differentiate between BMPs relative to complying with any particular concentration standard. The concentration rankings here are no more than an identification of comparable BMPs for a particular influent condition.

1.4.3 MEP-based Discharge Prohibitions

The Permit does not allow the discharge of pollutants without the implementation of BMPs[3] to the maximum extent practicable (MEP). This requirement is independent of the condition of the receiving water or the effect of any discharge to it. Thus the MEP requirement is applicable even in unimpaired watersheds. In many cases, untreated Caltrans discharges contain concentrations of TDCs that exceed the concentrations in

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[3] Treatment BMPs are only one of a host of BMPs used by the Department (Caltrans, 2003) and treatment BMPs may not always be appropriate for every pollution-control opportunity.

unimpaired receiving waters. When this happens, receiving water concentrations increase as shown in mass balance calculations. Minimizing Caltrans loads (via either concentration or volume) will minimize concentration increases in receiving waters.

Appendix B suggests BMP ranking to comply with the MEP standard.

1.5 Data Sources

Table 1.2 lists the location names of the BMPs used in this analysis. Department-sponsored studies were selected that tested approved BMPs and had well-documented characteristics comparable to the current design standards in the PPDG. Excluding studies outside the Department eliminated the need to perform detailed design reviews of hundreds of BMPs and it avoided the analysis of BMPs under hydrologic conditions atypical of California.

Table 1.2 Data Sources by Study and Location

BMP Type[a]	Study	Location Name, Runoff Type[a], District
Austin Sand Filters	BMP Retrofit Pilot Program[b] (Retrofit)	Eastern MS, D-7; Foothill MS, D-7; Termination MS, D-7; La Costa P&R, D-11; SR-78/I-5 P&R, D-11
	District 2 Sand Filter Study[c]	I-5/Mountain Gate Hwy (unlined, combined or partial sedimentation), D-2; Mt. Shasta MS (unlined, combined or partial sedimentation), D-2
Delaware Sand Filters	Retrofit	Escondido MS, D-11
Detention Basin, lined	Retrofit	I-5/I-605 Hwy, D-7
Detention Basin, unlined	Retrofit	I-5/I-605 Hwy, D-7; I-605/SR-91 Hwy, D-7; I-5/SR-56 Hwy, D-11; I-15/SR-78 Hwy, D-11; I-5/Manchester Hwy, D-11
Multi-Chambered Treatment Train (MCTT)	Retrofit	Lakewood P&R, D-7; Via Verde P&R, D-7
Strips with a hydraulic residence time ≤ 5 minutes	Roadside Vegetated Treatment Sites (RVTS)[d, e]	Irvine (3m and 6m) Hwy, D-12; Rafael (8.3m) Hwy, D-4; Sacramento (1.1, 4.6, 6.6m, and 8.4m) Hwy, D-3; Redding (2.2, and 4.2m) Hwy, D-2; Onofre (1.3 and 5.3m) Hwy, D-11; Yorba Linda (1.9m, 4.9m, and 7.6m) Hwy, D-12; Cottonwood (9.3m) Hwy, D-2; D-7
	Retrofit	Altadena MS (8m)
Strips with a hydraulic residence time > 5 minutes	RVTS[e]	Onofre (9.9m) Hwy, D-11; Yorba Linda (13m) Hwy, D-12; Irvine (13m) Hwy, D-12; Redding (6.2m) Hwy, D-2
	Retrofit	I-605/SR-91 (8m) Hwy, D-7; Carlsbad (8m) MS, D-11
Swales	Retrofit	Cerritos (SR-91) Hwy, D-7; I-5/I-605 Hwy, D-7; I-605/Del Amo Hwy, D-7; SR-78/Melrose Hwy, D-11; I-5/Palomar Hwy, D-11
Wet basins	Retrofit	I-5/LaCosta Hwy, D-11

[a] Runoff Types: MS = maintenance station runoff; P&R = park and ride runoff; Hwy = highway runoff

[b] Study Report: BMP Retrofit Pilot Program Final Report (Caltrans, 2004)

[c] Study Report: Caltrans Statewide Sand Filter Study (Caltrans, 2007)

[d] Study Report: Roadside Vegetated Treatment Sites (RVTS) Study, Summary Report (Caltrans, 2008a).

[e] The Moreno Valley RVTS strips were not included in the statistical analysis because the vegetation cover (around 20%) was far below design standards for new strips (70%) and this was the likely cause for poor performance.

The three studies contributing data are the Roadside Vegetated Treatment Sites (RVTS) Study, the District 2 Sand Filter Study, and the BMP Retrofit Pilot Program (Retrofit). All performance data from the District 2 Sand Filter Study and the Retrofit study were considered. The RVTS is ongoing and water quality data through the 2006/2007 wet season were used in the statistical analysis. Data through the 2007/2008 wet season were considered in the post-statistical analysis (Section 3.2).

In the post-statistical analysis for strips, hydraulic residence time (HRT) did not correlate well with load reduction. Instead, the ratio of the strip area to the drainage area was used (A_S/A_D). A similar approach to strip design has been used by other agencies such as CASQA. The CASQA BMP handbook (2003) suggests a minimum ratio of 0.25. In the Caltrans data, there were a few systems that did not quite meet the 0.25 criterion but had good performance, so 0.2 was chosen in order to include those strips in a potentially high-performing group of strips. Table 1.3 shows both the HRT and area ratio.

Table 1.3 Classification of Strips by Hydraulic Residence Time (HRT) and Ratio of Strip Area to Watershed Drainage Area (A_S/A_D).

	HRT[a] (min)	*Strip Area / Watershed Area[b]*	*Study*
Altadena	3.2	0.02	Retrofit
Carlsbad	6.2	0.07	Retrofit
Cottonwood, District (9.3m)	5.0	0.47	RVTS
I-605/SR-91	9.2	0.24	Retrofit
Irvine, District 12 (13m)	7.9	0.28	RVTS
Irvine, District 12 (3m)	2.3	0.12	RVTS
Irvine, District 12 (6m)	4.9	0.27	RVTS
Rafael, District 4 (8.3m)[c]	3.7	0.26	RVTS
Redding, District 2 (2.2m)	2.2	0.16	RVTS
Redding, District 2 (4.2m)	4.0	0.26	RVTS
Redding, District 2 (6.2m)	5.6	0.34	RVTS
Sacramento, District 3 (1.1m)	1.3	0.06	RVTS
Sacramento, District 3 (4.6m)	2.7	0.22	RVTS
Sacramento, District 3 (6.6m)	3.7	0.27	RVTS
Sacramento, District 3 (8.4m)	4.6	0.33	RVTS
San Onofre, District 11 (1.3m)	1.1	0.06	RVTS
San Onofre, District 11 (5.3m)	4.0	0.18	RVTS
San Onofre, District 11 (9.9m)	6.0	0.28	RVTS
Yorba Linda, District 12 (1.9m)	1.2	0.05	RVTS
Yorba Linda, District 12 (13m)	6.5	0.21	RVTS
Yorba Linda, District 12 (4.9m)	3.0	0.13	RVTS
Yorba Linda, District 12 (7.6m)	4.7	0.21	RVTS

[a] HRT were based on a constant intensity of 0.2 inches per hour and a Manning's n of 0.2 (Appendix A).

[b] Strip dimensions were taken from the RVTS Summary Report (Caltrans, 2008a) and the As-Builts of the BMP Retrofit Pilot Program Final Report, Appendix G (Caltrans, 2004).

[c] San Rafael drainage area was adjusted from 0.296 ha to 0.069 ha based on an aerial photograph that showed 6 lanes and shoulders on each side. Shoulders and lanes were estimated at 4 meters each.

2 Statistical Analysis

The statistical analysis is used to rank performance for cases where concentration reduction has a higher priority than load reduction. Due to issues with the application of the statistical model to loads, the load analysis in this section was not used in the final BMP rankings for load reduction. The final method employed for ranking BMPs by load reduction is described in Section 3.

2.1 Statistical Methodology

Recent literature acknowledges the problems with using percent reduction as the sole measure of BMP performance (Strecker et al., 2001; Minton, 2005, p. 335). This is because stormwater influent is highly variable and many BMPs do not demonstrate a constant relationship between influent and effluent quality. Influent variability is observed among study locations, not just among storms at a single study location. Percent reduction can be highly influenced by pollutant levels and exclusive consideration of percent reduction unfairly judges BMPs that were exposed to unusually low pollutant levels. Exclusive consideration of effluent levels, however, would unfairly judge BMPs that were exposed to unusually high pollutant levels.

Consequently, effluent levels are now commonly considered alongside percent reduction. This approach often compares summary statistics (percentiles, medians, etc.) among BMP types for both effluent concentration and percent reduction. The problem is that it is difficult to make quantitative comparisons of performance because there are two performance metrics rather than one.

The statistical analysis here used an alternative approach, which compared BMP performance at a single influent level. The method has been previously used for BMP performance evaluations based on the expected concentration and uncertainty from a linear regression between influent and effluent (Barrett, 2004). This method was employed in the BMP Retrofit Pilot Program (Caltrans, 2004), where the mean event mean concentration (EMC) for the study was used as a “design concentration” by which the expected effluent concentration among the BMP types were compared using a linear regression against influent concentration. Confidence intervals were based on the two-parameter model. Since a single point of comparison is used, the comparison among BMPs is more equitable than comparing summary statistics from study reports in which test conditions vary considerably. This analysis does not require interpretation of graphical output or summary statistics. Selecting the point of comparison, however, is somewhat arbitrary and limits the use of the result where conditions are much different from the comparison point (see Section 2.3).

This project applied this concept within a mixed-model statistical analysis that compared the expected performance of all BMPs. The hypothesis tested was that a particular BMP had equivalent performance to all other BMPs. The statistical tests, to a pre-determined level of confidence, determined which BMPs, if any, were statistically different at the point of comparison. The analysis used the median concentration and load of all influent monitoring data for the point of comparison for concentration-based and load-based rankings, respectively.

A more detailed discussion of this statistical method is contained in Appendix C.

2.2 Statistical Results

The results of the statistical analyses of BMP performance with respect to concentration reduction are shown in Table 2.1. The table is organized by constituent – existing TDCs (sediment, phosphorus, copper, lead, and zinc) followed by proposed TDCs (cadmium, chrome, and nickel). For each constituent, the BMPs are listed in order of descending estimates of treatment performance (i.e., ascending estimates of effluent concentration), so that apparently better performing BMPs are listed first. The columns in the table represent statistically similar[4] groups (Groups 1 through 4). BMPs with "X" marks in the same column were not found to be statistically distinguishable from each other. For instance, under "sediment," the wet basin, MCTT, Delaware filter, Austin filter, and long strips belong to statistical Group 1, meaning their performances were not statistically distinguishable. Inside the group, the wet basin showed the lowest estimated effluent concentration calculated from the standard influent concentration, the MCTT showed the next lowest, and so on. As can be seen, there is significant overlap between statistical groups: most of the BMPs in Group 1 also belong to Group 2; some belong to three different statistical groups. Generally speaking, BMPs whose effluent concentration data sets are highly variable overlap several groups.

A number of BMPs listed in Table 2.1 are shown in parentheses (e.g., MCTT and wet basins under "total phosphorus"). Statistical comparisons were made of influent and effluent concentrations as part of the Retrofit Pilot Program (Caltrans, 2004) and in separate in-house analyses for the proposed TDCs (Appendix A). For the BMPs shown in parentheses either (1) the influent and effluent concentrations in the Retrofit Pilot Program were statistically indistinguishable (i.e., there was no apparent treatment), or (2) the influent and effluent were distinguishable but the effluent concentration was higher than the influent (i.e., the BMP exported the TDC). Similar analyses for the proposed TDCs (cadmium, chromium, and nickel) were done in-house. How to consider these BMPs in a ranking scheme will be discussed in Section 3, Post-Statistical Analysis.

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[4] Statistically similar groups of BMPs are those BMPs where the study data does not provide sufficient evidence to say that any of the BMPs in the group would behave differently in future applications. These are also referred to as BMPs that are not statistically distinguishable.

2.2.1 Concentration Results from Mixed Model

Table 2.1 BMP Rankings by Concentration Reduction

Constituent	**BMP**	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Existing TDCs					
Sediment (TSS)	Wet basin	X			
	MCTT	X	X		
	Delaware filter	X	X	X	
	Austin filter	X	X		
	Strip – HRT>5	X	X	X	X
	Strip – HRT<5		X	X	X
	EDB			X	X
	Swale				X
	(EDB – lined)				X
Phosphorus (total)	Delaware filter	X	X		
	(MCTT)	X			
	Austin filter	X			
	EDB	X	X		
	(EDB – lined)	X	X		
	Strip – HRT<5	X	X		
	(Wet basin)	X	X		
	(Swale)		X		
	(Strip – HRT>5)	X	X		
Nitrogen (total)	(see discussion on load in Section 3.2.3)				
Copper (total)	Strip – HRT<5	X			
	Wet basin	X	X		
	(MCTT)	X	X	X	
	Delaware filter	X	X	X	X
	Austin filter		X	X	X
	Strip – HRT>5		X	X	X
	Swale			X	X
	(EDB – lined)			X	X
	EDB				X
Copper (dissolved)	Strip – HRT<5	X			
	(Delaware filter)	X	X		
	(MCTT)	X	X	X	
	Strip – HRT>5	X	X	X	
	Wet basin		X	X	
	(EDB – lined)		X	X	
	Swale		X	X	
	(Austin filter)		X	X	
	(EDB)			X	

(Table 2.1 continued)

Constituent	BMP	Group 1	Group 2	Group 3	Group 4
Lead (total)	Wet basin	X			
	Austin filter	X			
	MCTT	X			
	Delaware filter	X	X	X	
	Strip – HRT<5	X	X		
	Strip – HRT>5	X	X	X	
	Swale		X	X	
	EDB			X	
	(EDB – lined)			X	
Lead (dissolved)	Delaware filter	X			
	(MCTT)	X			
	Strip – HRT<5	X			
	Austin filter	X			
	Wet basin	X	X		
	EDB	X	X		
	(EDB – lined)	X	X		
	Strip – HRT>5	X	X		
	Swale		X		
Zinc (total)	Delaware filter	X			
	MCTT	X	X		
	Wet basin	X	X	X	
	Strip – HRT<5	X	X	X	
	Swale			X	
	Austin filter			X	
	Strip – HRT>5		X	X	
	EDB			X	
	(EDB – lined)			X	
Zinc (dissolved)	MCTT	X			
	Wet basin	X	X	X	
	Austin filter	X	X		
	(EDB – lined)	X	X	X	X
	(EDB)		X	X	
	Strip – HRT>5		X	X	X
	Swale			X	X
	Strip – HRT<5			X	X
	Delaware filter				X

(Table 2.1 continued)

Constituent	**BMP**	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Proposed TDCs					
Cadmium (total)	Strip – HRT<5	X			
	Wet basin	X	X	X	
	Austin filter	X	X		
	Delaware filter	X	X	X	
	Strip – HRT>5	X	X	X	
	Swale	X	X	X	
	EDB		X	X	
	(MCTT)		X	X	
	(EDB – lined)			X	
Chromium (total)	Wet basin	X			
	(MCTT)	X			
	Delaware filter	X			
	(Strip – HRT<5)	X			
	Austin filter	X			
	EDB	X			
	Swale	X			
	(EDB – lined)	X			
	Strip – HRT>5		X		
Nickel (total)	Strip – HRT<5	X			
	(Delaware filter)	X	X		
	EDB	X	X		
	Swale	X	X		
	(EDB – lined)	X	X		
	Wet basin	X	X		
	Austin filter		X		
	(MCTT)		X		
	Strip – HRT>5	X	X		

2.2.2 Load Results from Mixed Model

The results of the statistical analyses of BMP performance with respect to load reduction are shown in Table 2.2. As with the concentration results, the BMPs are listed in order of descending point estimates of treatment performance (i.e., ascending median effluent concentration) and columns are shown for the different statistically similar groups. BMPs with "X" marks in the same column were not found to be statistically distinguishable from each other.

Loads were calculated by multiplying event mean concentrations by volumes of runoff entering and exiting the BMPs. Load reduction can be accomplished by concentration reduction and/or volume reduction. Consequently, the listing order is somewhat different from that for concentration reduction. BMPs with a significant infiltration capacity – strips, swales, and to a lesser degree EDBs – are listed higher than they were in the concentration list.

A noticeable difference between the concentration results and the load results is the fewer number of statistical groups in the load results. For instance, all of the BMPs belong to only one statistical group for sediment and lead. For copper (total and dissolved), all but one BMP belong to one group and all the BMPs belong to another. What this means is that there is so much variation in the data sets that it is difficult to statistically distinguish a BMP from other BMPs. Using these results, it isn't possible to derive a load reduction ranking. Further discussion of these issues is contained in the next section.

Table 2.2 BMP Rankings by Load Reduction

Constituent	BMP	Group 1	Group 2
Existing TDCs			
Sediment (TSS)	Swale	X	
	Strip – HRT<5	X	
	EDB	X	
	Austin filter	X	
	Delaware filter	X	
	MCTT	X	
	Strip – HRT>5	X	
	Wet basin	X	
	EDB – lined	X	
Phosphorus (total)	Swale	X	
	Strip – HRT<5	X	X
	Delaware filter	X	X
	EDB	X	X
	Strip – HRT>5	X	X
	Austin filter		X
	MCTT		X
	EDB – lined	X	X
	Wet basin		X
Nitrogen (total)			
Copper (total)	Swale	X	
	Strip – HRT<5	X	X
	EDB	X	X
	Delaware filter	X	X
	MCTT	X	X
	Austin filter	X	X
	EDB – lined	X	X
	Strip – HRT>5	X	X
	Wet basin	X	X
Copper (dissolved)	Swale	X	
	Strip – HRT<5	X	X
	Strip – HRT>5	X	X
	EDB	X	X
	Austin filter	X	X
	MCTT	X	X
	EDB – lined	X	X
	Delaware filter	X	X
	Wet basin	X	X

(Table 2.2 continued)

Constituent	BMP	Group 1	Group 2
Lead (total)	Swale	X	
	Strip – HRT<5	X	
	Strip – HRT>5	X	
	Delaware filter	X	
	Austin filter	X	
	MCTT	X	
	EDB	X	
	Wet basin	X	
	EDB – lined	X	
Lead (dissolved)	Swale	X	
	Strip – HRT>5	X	X
	Strip – HRT<5	X	X
	EDB		X
	Austin filter		X
	MCTT		X
	EDB – lined	X	X
	Delaware filter		X
	Wet basin		X
Zinc (total)	Swale	X	
	Strip – HRT<5	X	X
	Delaware filter	X	X
	EDB	X	X
	Austin filter		X
	MCTT	X	X
	Wet basin	X	X
	EDB – lined	X	X
	Strip – HRT>5	X	X
Zinc (dissolved)	Swale	X	
	Delaware filter	X	X
	Strip – HRT<5	X	X
	Strip – HRT>5	X	X
	EDB		X
	Austin filter		X
	MCTT	X	X
	EDB – lined	X	X
	Wet basin	X	X

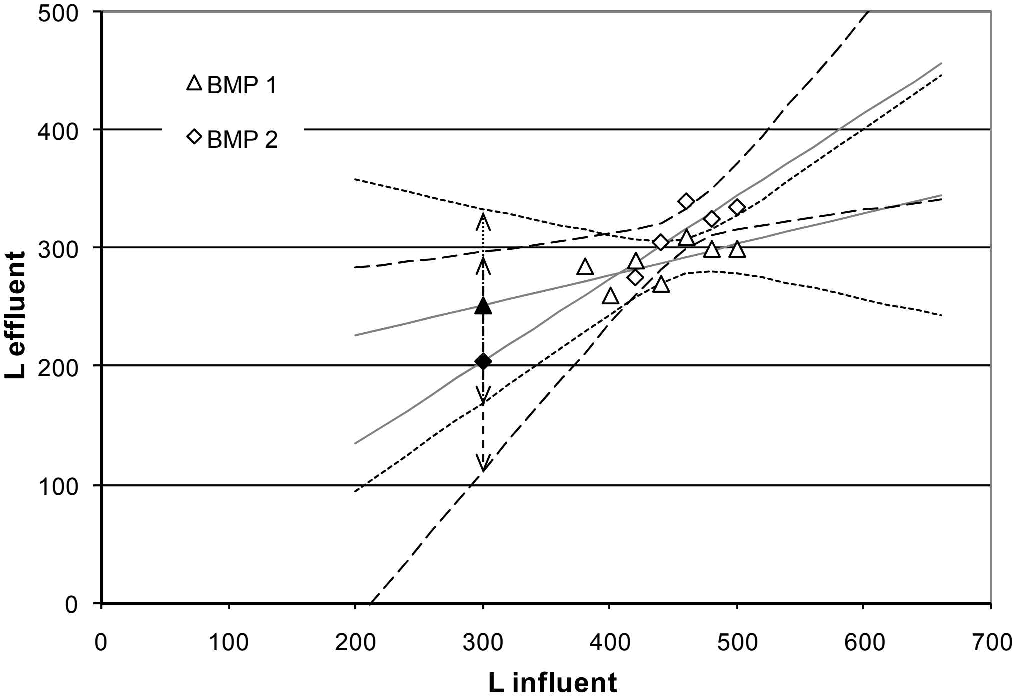
(Table 2.2 continued)

Constituent	BMP	Group 1	Group 2
Proposed TDCs			
Cadmium (total)	Swale	X	
	Strip – HRT<5	X	X
	Strip – HRT>5	X	X
	EDB		X
	Delaware filter	X	X
	Austin filter		X
	EDB – lined	X	X
	MCTT		X
	Wet basin		X
Chrome (total)	Swale	X	
	Strip – HRT<5	X	X
	Strip – HRT>5	X	X
	EDB		X
	Delaware filter	X	X
	Austin filter		X
	EDB – lined	X	X
	Wet basin		X
	MCTT		X
Nickel (total)	Swale	X	
	Strip – HRT<5	X	X
	Strip – HRT>5	X	X
	EDB		X
	Delaware filter	X	X
	Austin filter		X
	EDB – lined	X	X
	MCTT		X
	Wet basin		X

2.3 Critique of the Statistical Approach

The goals of the statistical approach were to: (1) develop a ranking system based on field performance, (2) differentiate among BMPs using a statistically defensible method, and (3) compare BMPs on a consistent basis by using a common influent value. This is a data-driven approach. Data-driven approaches contrast with mechanism-driven approaches in which the treatment *potentials* of various BMPs are based on the fundamental processes incorporated in those BMPs (Scholes et al., 2008). One shortcoming of this approach is judging the relative importance of different treatment processes (e.g., sedimentation vs. filtration in an Austin sand filter). Another problem is the difficulty of estimating the effects of many site-specific factors on treatment performance. Examples include particle size distribution and composition, temperature, dissolved vs. particulate pollutants, the adsorption capacity of the BMP, and the infiltration capacity of the site. Because data are collected at real facilities, these effects are included in data-driven ranking systems. Ironically, this is also the shortcoming of a data-driven system. Rankings are based on the available data sets, which may or may not be representative. For example, in the Retrofit Pilot Program both MCTTs were constructed at park-and-ride lots, whose runoff concentrations were significantly lower than highway concentrations.

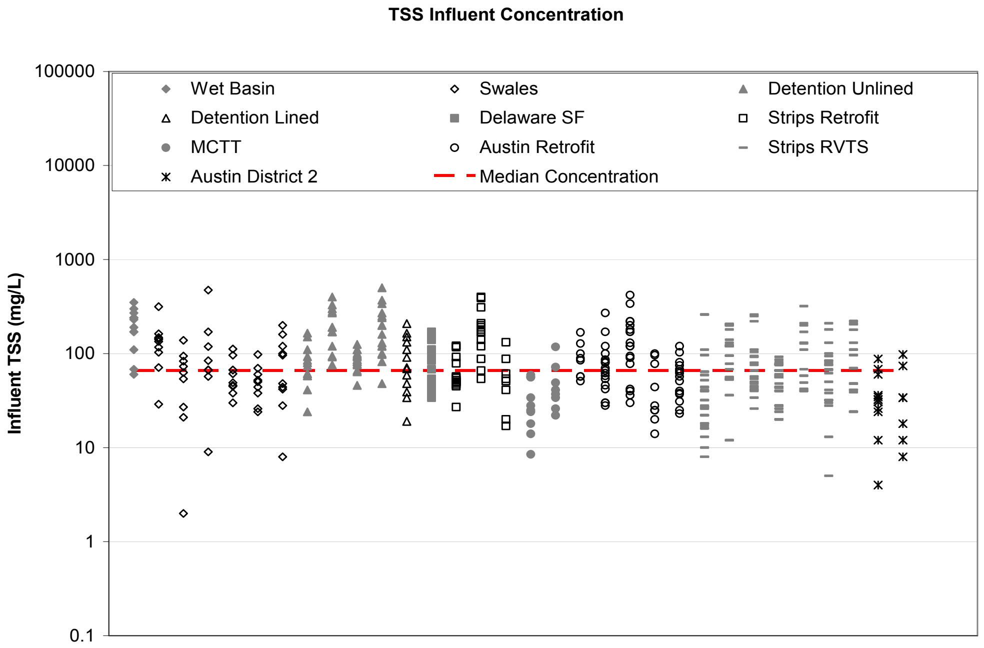
A theoretical advantage of a data-driven ranking system over a mechanism-based system is the ability to make statistically defensible statements about whether the performances of two BMPs are truly different. This is a particular problem with small data sets, as illustrated in Figure 2.1. In this figure two hypothetical BMPs with overlapping data sets are compared. Different regression lines relating influent and effluent loads (or concentrations) can be drawn for the two data sets, but most observers would have difficulty claiming that these two data sets are truly different and statistical analysis supports this position. Confidence intervals are shown as dotted lines in this plot. As can be seen, the confidence intervals for the two regression lines overlap, indicating that the two data sets cannot be said to be statistically distinguishable. For many BMPs, there aren't many data and the data that are available are scattered because of the difficulty in making field measurements, differences in site conditions, and variable hydrologic characteristics. Data sets that overlap would be placed in the same statistical groups as discussed above for Table 2.1 and 2.2.



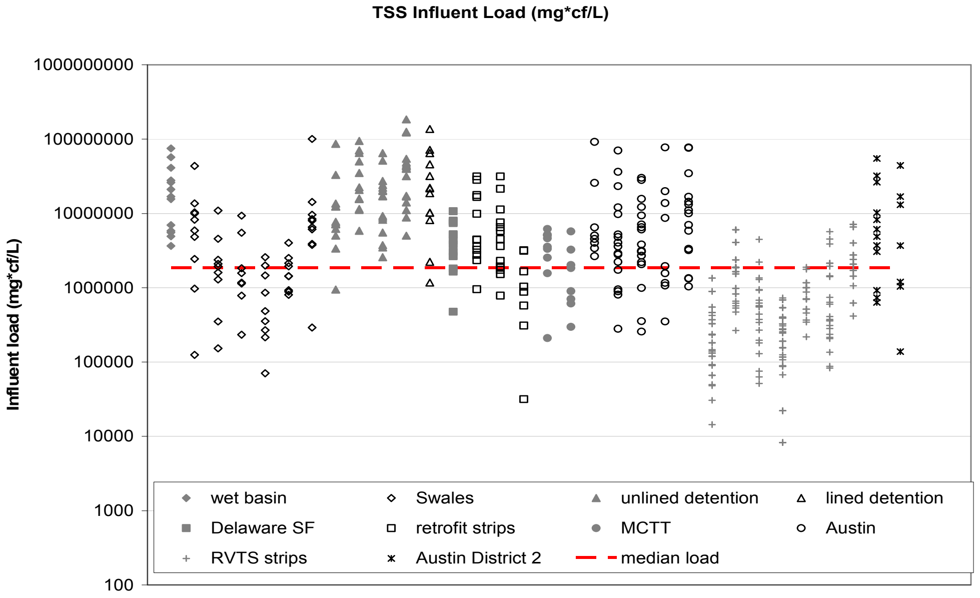
Note: Confidence intervals are shown as the vertical dashed and dotted lines with arrows. Point estimates are the solid black triangle and diamond. Confidence intervals for effluent estimates calculated from the regression line expand as the distance between the hypothetical influent x-value and the mean x-value of the data increases.

Figure 2.1 Comparison of Two Hypothetical BMPs with Overlapping Data Sets

The third goal of the statistical approach was to compare BMPs on a consistent basis by using a common influent value. Influent concentrations and loads varied considerably by site. In Figure 2.2, the influent concentrations and load values for each storm at each site are plotted for each BMP pilot facility. The median concentrations and loads used in the UCD statistical analysis are shown by horizontal dashed lines. The raw results are contained in Appendix C. As can be seen, there was significant variation, especially considering that the concentration and load values are plotted on logarithmic scales. One cause of this “spread” in the data is the variation in project drainage area. Drainage area directly affects loading because it directly relates to the volume of runoff. At the onset of this project most BMP drainage areas (i.e., those from the Retrofit Pilot Program) were between 2 to 6 acres which are similar in scale. Adding the RVTS data to this project exacerbated the differences in loadings between BMP locations because the RVTS sites were generally much smaller than the Retrofit Pilot Program sites. In hindsight, the statistical analysis should have been performed on load normalized by drainage area.



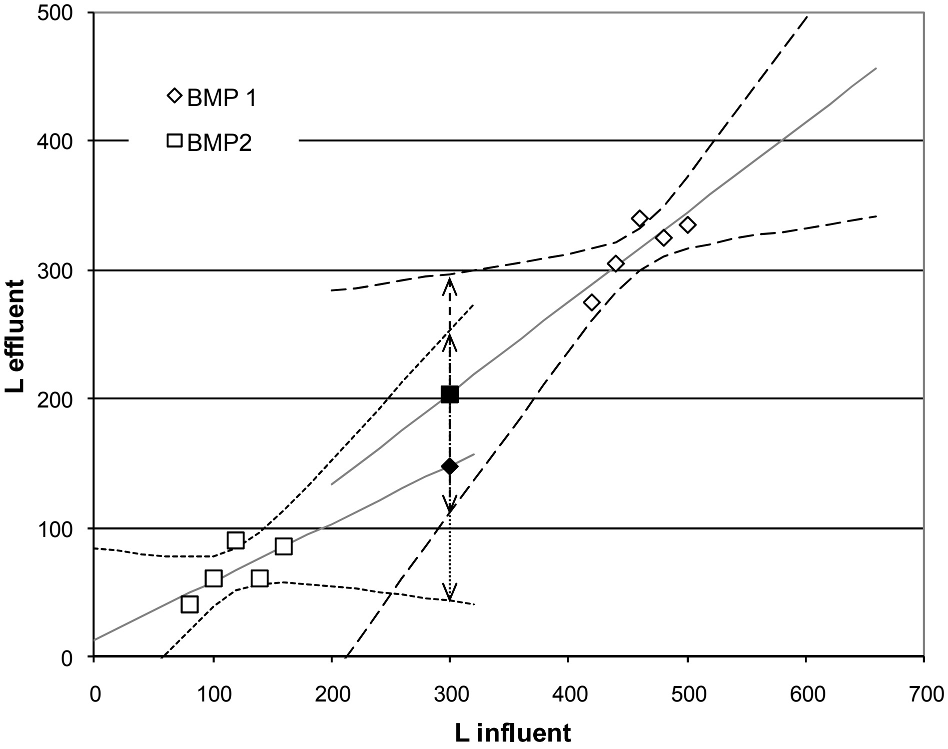
(a) Influent concentrations for individual BMP pilot sites compared to the median concentration used in the UCD statistical analysis.



(b) Influent loads for individual BMP pilot sites compared to the median load used in the UCD statistical analysis. Note that the data shown do not account for varying drainage areas.

Figure 2.2 Range of Influent Concentrations and Loads Compared with the Median Values Used in the Mixed-Model Statistical Analysis

A limitation of the mixed model approach is that the rankings based on a single point of comparison, whether influent load or concentration, are not applicable for future projects where the influent conditions are substantially different. In regression analysis, the confidence intervals of the predicted values increase as x-values at the point of comparison deviate from the mean *x* value of the data. This is illustrated in Figure 2.3 for two non-overlapping data sets. In the figure, prediction of BMP performance (y-values) are being attempted at a common influent value. Because of the extrapolation involved in making this point-estimate, the confidence intervals for the two regression lines are wide enough to overlap. This means the two BMP performances cannot be said to be statistically distinguishable and they would be placed in the same statistical group. This effect was particularly problematic for the load-based statistical results. While the TSS concentrations shown in Figure 2.3 generally span a two-log scale, the load values span a four-log scale. Further, the point of comparison is more distant from the loading observed for wet basin, detention basins, sand filters, and RVTS strips. The result is that only two statistical groups could be distinguished, as shown in Table 2.2.



Note: Confidence intervals are shown as the vertical dashed and dotted lines with arrows. The solid black triangle and diamond are estimates of effluent at a hypothetical influent value of 300. Confidence intervals for effluent estimates calculated from the regression line expand as the distance between the hypothetical influent x-value and the mean x-value of the data increases. Although the estimates may reflect the different treatment efficiencies of the BMPs, the expanded confidence intervals overlap, which prevents finding a statistical difference between the two BMP performances.

Figure 2.3 Comparison of Two Hypothetical Non-overlapping BMP Regressions

The end result is that the purely statistical approach does not generate useful results with regards to ranking BMPs. For the concentration results, some additional (post-statistical) analysis is needed to transform the statistical results into a ranking system. For the load results, a different, less statistical approach is needed to create a useful ranking. In the next section, four methods for estimating loads are explored and one is implemented.

3 Post-Statistical Analysis

In this section, the results of the statistical analysis of the concentration data are manipulated to create a ranking. Four methods for estimating loads are explored and one is implemented to create a load-based ranking.

3.1 Concentration

At first glance, the classifying of BMPs into statistically similar groups (Table 2.1) appears somewhat confusing and not useful for selecting BMPs. In this section, the BMPs that appear to be statistically ineffective will be re-examined and in some cases reclassified. Then, a method for simplifying the overall BMP list will be presented.

As noted in Section 2, some BMPs either had influent and effluent concentrations that were statistically indistinguishable, or had effluent concentrations that were higher than the influent concentrations. Ordinarily, a lack of statistical difference between influent and effluent would indicate that the BMP was not providing measurable treatment. Before dismissing such BMPs, it is useful to look at the data and the circumstances to see if there are mitigating circumstances that might influence how these BMPs are to be classified (i.e., low influent concentration).

A full listing of the questionable BMPs and associated TDCs is provided in Table 3.1. For each BMP, a discussion of the data set and other pertinent information is provided, as well as a conclusion about whether or not to accept the statistical result (i.e., no treatment). There are several recurring themes. In some cases, particularly for dissolved metals, the BMPs in question don’t incorporate treatment mechanisms that are expected to be effective for these TDCs. A statistical conclusion that the BMP is ineffective is reasonable and should be allowed to stand. Another recurring circumstance is the “clean” site. In these cases, the TDC runoff concentrations were very low, near the reporting limit. This had two effects on the statistical analysis. First, variations in very small influent concentrations can have relatively large effects on removal rates strictly because of the mathematics involved. Second, the reporting limit (RL) may be acting as a kind of boundary that might mask the true treatment effectiveness. Even though the true concentrations may be lower, many effluent concentrations are reported at the RL. If the influent concentration is close to the RL, as is the case for several TDCs (dissolved copper, dissolved lead, cadmium, chromium, and nickel), little treatment is reported. Given the variation in the data, the small treatment values can easily be deemed insignificant in a statistical analysis. This phenomenon was not used indiscriminately to overrule the statistical result. As noted in the table, some BMPs are effective at relatively high influent concentrations but appear to lose their treatment effectiveness at low concentrations.

Table 3.2 is a worksheet for a method of ranking BMPs by concentration reduction whose use will be described below. Based on the considerations documented in Table 3.2, BMPs that are considered to be ineffective are printed in strikeout font. The listing of BMPs in statistically similar groups (Table 2.1) can be simplified by considering how this list would be used in design. The multiple statistically similar groups appear to be a hindrance, but they are not. Assume that a designer is tasked with choosing BMPs in order of effectiveness. Looking at Table 3.2, he or she would choose a BMP from Group 1. For "sediment," Group 1 includes the wet basin, MCTT, Delaware filter, Austin filter, and long strip. Because all of the BMPs in the group are similar in terms of performance, it doesn't matter which BMP is chosen. Presumably, the designer will choose the BMP that is most feasible or economical for the project. If none of the BMPs in Group 1 are appropriate for the project at hand, the designer must look outside of Group 1, but not necessarily in Group 2. In Table 3.2, all of the Group 1 BMPs are marked with an "O." If none of the Group 1 BMPs are feasible, only the BMPs marked by "X" are available. In "sediment", these include the short strip, EDB, swale, and lined EDB. What's important to notice is that all of these BMPs are members of Group 4. Thus in practice, the four groups collapse into two statistically similar groups. Further examination of Table 3.2 shows that this pattern repeats for all of the TDCs. The number of BMPs in different groups varies, but in no case are there more than two practical groups (marked with X's and O's).

As noted above, the ineffective BMPs are shown in Table 3.2 in strikeout font. Being ineffective, they need to be separated from the effective BMPs. Thus, all of the BMPs can be assembled into one of three groups: a "more effective" group, a "less effective" group, and a "not effective" group. This is shown in Table 3.3, where the groups are labeled "tiers." To maximize concentration reduction, designers should first try to use a BMP from Tier 1 and look to Tier 2 if the Tier 1 BMPs are not feasible. To assure that a TDC of interest is removed, BMPs listed in Tier 3 (not effective) should be avoided. For example, if phosphorus is the TDC of interest, the MCTT, wet basin, long strip, and swale should not be chosen. If sediment is the TDC of interest, these BMPs are legitimate candidates for selection because they belong to Tiers 1 and 2. What the designer must realize is that choosing one of these BMPs for sediment reduction will not provide treatment for phosphorus. If both TDCs are a concern, then a BMP that is listed in Tiers 1 and 2 for both TDCs, such as the Austin filter, should be chosen.

Table 3.1 Commentary on Lack of Concentration Reduction Effectiveness for Selected BMPs

TDC	**BMPs**	**Commentary on Apparent Lack of Concentration Reduction Effectiveness for BMPs shown in parentheses in Table 2.1**
All TDCs	EDB – lined	The lack of performance could be attributed to design shortcomings. The lined detention basin was constructed with a surface lining of concrete on the invert and sides of the basin. Since it was lined, energy dissipation was not used. The primary high-flow bypass was the outlet structure (an online configuration). The combination of no energy dissipation and an online configuration may have contributed to the resuspension that was observed during the study (Caltrans, 2004). Despite export during some events, the mean concentration for all storms always decreased for every TDC. Adding energy dissipation or using an offline configuration may have resulted in statistically significant results. Based on the design studied, the lined detention basin is conservatively left in the ineffective performance category for all TDCs.
Existing TDCs		
Phosphorus (total)	MCTT	Because this BMP may be leaching phosphorus from the peat filter media, it is thought that the statistical result is correctly indicating ineffective removal.
	Wet basin	Other than sedimentation, this BMP has no particular phosphorus removal mechanism. Consequently, it is thought that the statistical result correctly indicates that this is ineffective for total-P.
	Strip – long Swale	In the Retrofit Pilot Program these BMPs were planted with salt grass, which takes up phosphorus from the soil and excretes it through its leaves where it can be picked up by passing stormwater. Consequently, the Retrofit result may not be representative. On the other hand, it is also possible to leach phosphorus from the soil in these BMPs. Without a way to determine the relative magnitudes of these two effects, there isn't any basis for refuting the statistical result.
Copper (total)	MCTT	Filtration in the MCTT should be as effective at removing particulate copper as other filtration BMPs which did show statistically significant treatment. In addition, this BMP is thought to be effective at removing dissolved copper (see below). In this case, the general statistical result is thought to have been based on an evaluation of treatment effectiveness that is distorted by the exceptionally low influent concentrations.
Copper (dissolved)	MCTT	The MCTT contains a peat filter, which has been shown to be effective at removing dissolved copper (Pitt, 2002). At the MCTT test sites, though, copper concentrations were exceptionally low. At one site with an average influent concentration of 11µg/L, treatment was observed; at the other site, with an influent concentration of 3.3 µg/L, treatment was not observed. The median highway runoff concentration is 11 µg/L. The preponderance of evidence, including the fact that treatment was observed at runoff concentrations close to the median highway value, leads to a conclusion that, at least for typical highway runoff concentrations, there will be treatment.
	Austin filter EDB	These BMPs do not utilize treatment mechanisms known to be effective at low concentrations of dissolved metals, such as is typical with copper, so it is thought that the statistical results correctly indicate that these BMPs are ineffective for this TDC.

(Table 3.1 continued)

TDC	BMPs	Commentary on Apparent Lack of Concentration Reduction Effectiveness for BMPs shown in parentheses in Table 2.1
	Delaware filter	The Delaware filter had a median influent of 5.6 μg/L, which is almost half the median statewide concentration. Still, the filter had an average concentration reduction of 40% but the p-value for the significance test was 0.124 which is just over the 0.1 criterion. Because there was only one installation and 18 storm events, it is thought that the Delaware filter will be effective in reducing typical highway runoff concentrations. The Delaware had better performance than Austin filters, which may be because of reduced loading rates to the sand bed.
Lead (dissolved)	MCTT	At the MCTT test sites, the dissolved lead concentrations were very low, at or below the reporting limit for most storms. In this case, the general statistical result is thought to have been based on an evaluation of treatment effectiveness that is distorted by the exceptionally low influent concentrations. The MCTT contains a peat filter, which has been shown to be effective at removing dissolved lead (Pitt, 2002). Accordingly, the MCTT should be considered an effective BMP for this TDC.
Zinc (dissolved)	EDB	These BMPs do not utilize treatment mechanisms known to be effective for dissolved metals, so it is thought that the statistical results correctly indicate that these BMPs are ineffective for this TDC.
Proposed TDCs		
Cadmium (total)	MCTT	Although filtration in the MCTT should remove particulate cadmium and literature sources document the removal of other dissolved metals, the data set doesn't provide any evidence to refute the statistical result.
Chromium (total)	MCTT	Filtration in the MCTT should be as effective at removing particulate chromium as other filtration BMPs, which did show statistically significant treatment. Results from the Retrofit Pilot Program are mixed. One site had only four influent chromium measurements and two of these were at the reporting limit. Influent concentrations at the other site were higher; effluent concentrations were at the RL; and all but one of the runoff events showed treatment. Because the median highway concentration is higher than the average study concentration, it is thought that the MCTT should provide treatment in highways settings.
	Strip – HRT<5	These BMPs appear to have insufficient residence time for effective chromium reduction. Strips – HRT>5 were more effective.
Nickel (total)	MCTT	Although filtration in the MCTT should remove particulate nickel and literature sources document the removal of other metals, the data set doesn't provide any evidence to refute the statistical result.
	Delaware filter	The Delaware filter missed a determination of statistical significance by a fairly small margin. The number of data points was limited (only 9 storms) and the average influent concentration was 6.3 μg/L while the statewide highway mean was 11.05 μg/L. Despite these challenges, the point estimate for reduction of mean concentration was 64 percent, which is comparable to the reduction of other total metals (53 to 92 percent). Consequently, it is thought that the Delaware filter will be effective in reducing typical highway runoff concentrations of total nickel.

Table 3.2 Worksheet for BMP Rankings by Concentration Reduction

Constituent	**BMP**	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Existing TDCs					
Sediment (TSS)	Wet basin	O			
	MCTT	O	O		
	Delaware filter	O	O	O	
	Austin filter	O	O		
	Strip – HRT>5	O	O	O	O
	Strip – HRT<5		X	X	X
	EDB			X	X
	Swale				X
	(~~EDB – lined~~)				X
Phosphorus (total)	Delaware filter	O	O		
	(~~MCTT~~)	O			
	Austin filter	O			
	EDB	O	O		
	(~~EDB – lined~~)	O	O		
	Strip – HRT<5	O	O		
	(~~Wet basin~~)	O	O		
	(~~Swale~~)		X		
	(~~Strip – HRT>5~~)	O	O		
Nitrogen (total)	(see discussion on load in Section 3.2.3)				
Copper (total)	Strip – HRT<5	O			
	Wet basin	O	O		
	(MCTT)	O	O	O	
	Delaware filter	O	O	O	O
	Austin filter		X	X	X
	Strip – HRT>5		X	X	X
	Swale			X	X
	(~~EDB – lined~~)			X	X
	EDB				X
Copper (dissolved)	Strip – HRT<5	O			
	(Delaware filter)	O	O		
	(MCTT)	O	O	O	
	Strip – HRT>5	O	O	O	
	Wet basin		X	X	
	(~~EDB – lined~~)		X	X	
	Swale		X	X	
	(~~Austin filter~~)		X	X	
	(~~EDB~~)			X	

(Table 3.2 continued)

Constituent	**BMP**	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Lead (total)	Wet basin	O			
	Austin filter	O			
	MCTT	O			
	Delaware filter	O	O	O	
	Strip – HRT<5	O	O		
	Strip – HRT>5	O	O	O	
	Swale		X	X	
	EDB			X	
	(~~EDB – lined~~)			X	
Lead (dissolved)	Delaware filter	O			
	(MCTT)	O			
	Strip – HRT<5	O			
	Austin filter	O			
	Wet basin	O	O		
	EDB	O	O		
	(~~EDB – lined~~)	O	O		
	Strip – HRT>5	O	O		
	Swale		X		
Zinc (total)	Delaware filter	O			
	MCTT	O	O		
	Wet basin	O	O	O	
	Strip – HRT<5	O	O	O	
	Swale			X	
	Austin filter			X	
	Strip – HRT>5		X	X	
	EDB			X	
	(~~EDB – lined~~)			X	
Zinc (dissolved)	MCTT	O			
	Wet basin	O	O	O	
	Austin filter	O	O		
	(~~EDB – lined~~)	O	O	O	O
	(~~EDB~~)		X	X	
	Strip – HRT>5		X	X	X
	Swale			X	X
	Strip – HRT<5			X	X
	Delaware filter				X

(Table 3.2 continued)

Constituent	**BMP**	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Proposed TDCs					
Cadmium (total)	Strip – HRT<5	O			
	Wet basin	O	O	O	
	Austin filter	O	O		
	Delaware filter	O	O	O	
	Strip – HRT>5	O	O	O	
	Swale	O	O	O	
	EDB		X	X	
	(~~MCTT)~~		X	X	
	(~~EDB – lined~~)			X	
Chromium (total)	Wet basin	O			
	(MCTT)	O			
	Delaware filter	O			
	~~(Strip – HRT<5)~~	O			
	Austin filter	O			
	EDB	O			
	Swale	O			
	(~~EDB – lined~~)	O			
	Strip – HRT>5		X		
Nickel (total)	Strip – HRT<5	O			
	(Delaware filter)	O	O		
	EDB	O	O		
	Swale	O	O		
	(~~EDB – lined~~)	O	O		
	Wet basin	O	O		
	Austin filter		X		
	(~~MCTT~~)		X		
	Strip – HRT>5	O	O		

Table 3.3 BMP Rankings by Concentration Reduction

	Constituents		
Existing TDCs			
	TSS	**Phosphorus (total)**	**Nitrogen (total)[a]**
	Tier 1 – More Effective		
	Wet basin MCTT Delaware filter Austin filter Strip – HRT>5	Delaware filter Austin filter EDB Strip – HRT<5	---
	Tier 2 – Less Effective		
	Strip – HRT<5 EDB Swale	---	---
	Tier 3 –Not Effective		
	EDB – lined	EDB – lined MCTT Wet basin Strip – HRT>5 Swale	---
	Copper (total)	**Copper (dissolved)**	**Lead (total)**
	Tier 1 – More Effective		
	Strip – HRT<5 Wet basin (MCTT) Delaware filter	Strip – HRT<5 (Delaware filter) (MCTT) Strip – HRT>5	Wet basin Austin filter MCTT Delaware filter Strip – HRT<5 Strip – HRT>5
	Tier 2 –Less Effective		
	Austin filter Strip – HRT>5 Swale EDB	Wet basin Swale	Swale EDB
	Tier 3 – Not Effective		
	EDB – lined	EDB – lined Austin filter EDB	EDB – lined

(Table 3.3 continued)

	Lead (dissolved)	**Zinc (total)**	**Zinc (dissolved)**
	Tier 1 – More Effective		
	Delaware filter (MCTT) Strip – HRT<5 Austin filter Wet basin EDB Strip – HRT>5	Delaware filter MCTT Wet basin Strip – HRT<5	MCTT Wet basin Austin filter
	Tier 2 – Less Effective		
	Swale	Swale Austin filter Strip – HRT>5 EDB	Strip – HRT>5 Swale Strip – HRT<5 Delaware filter
	Tier 3 –Not Effective		
	EDB – lined	EDB – lined	EDB – lined EDB
Proposed TDCs			
	Cadmium (total)	**Chromium (total)**	**Nickel (total)**
	Tier 1 – More Effective		
	Strip – HRT<5 Wet basin Austin filter Delaware filter Strip – HRT>5 Swale	Wet basin (MCTT) Delaware filter Austin filter EDB Swale	Strip – HRT<5 (Delaware filter) EDB Wet basin Swale Strip – HRT>5
	Tier 2 –Less Effective		
	EDB	Strip – HRT>5	(Austin filter)
	Tier 3 – Not Effective		
	EDB – lined MCTT	EDB – lined Strip – HRT<5	EDB – lined MCTT

[a] Total nitrogen was not considered in this analysis. The development of a load-based ranking based is contained in Section 3.2.3.

3.2 Load

Because of the difficulty of ranking by load with the mixed-model, four other methods were considered. These methods are titled "sum of loads," "regression," "log-means," and "mixed-model on concentration." All the methods share a common shortcoming – the inability to statistically differentiate BMPs because each method generates only one data point per test site. For those BMPs tested at multiple sites, confidence intervals could be calculated. Most BMPs, though, have been tested at only a few sites each, so there are too few data points to support a confidence interval calculation.

<u>Method 1: Sum of Loads</u> (based on location-specific concentration and volume): The sum of loads is the load reduction efficiency calculated from the total masses entering and exiting the BMP. The total mass is the sum of the masses for each storm, calculated as the product of concentration and volume. The result can be viewed as the overall load

reduction efficiency for each site during the study period. Mathematically, this method can be described by equation 1.

$$\eta = \frac{\sum\limits_{storms} C_i V_i - \sum\limits_{storms} C_e V_e}{\sum\limits_{storms} C_i V_i} \qquad \textbf{(Equation 1)}$$

Where
C_i, V_i = influent concentrations and volumes, respectively
C_e, V_e = effluent concentrations and volumes, respectively

The advantages of this method are that: (1) it avoids assumptions about regressions or statistical models, and (2) it incorporates the relationship between storm size and concentration. The shortcoming of the method is that it does not include a means to compare BMP performance at common influent values. In other words, BMPs that were tested at clean sites are directly compared against BMPs tested at dirty sites with no allowance made for the different site conditions.

Method 2: Regression (based on location-specific concentration and volume): In this method, concentration reductions are based on linear regression models relating influent and effluent data for each site separately. Effluent concentrations are calculated at the influent point of comparison from the statistical analysis (i.e., the median influent concentration from all BMP study data). These values are used to calculate the concentration treatment efficiency (η_C). Infiltration is calculated from the differences between the cumulative influent and effluent volumes. Because load removal is directly proportional to infiltration, the fraction of water that infiltrates can be considered a treatment efficiency due to infiltration (η_I). The overall efficiency can be calculated from equation 2.

$$\eta = \eta_C + \eta_I - \eta_C \eta_I \qquad \textbf{(Equation 2)}$$

Where
η_C = concentration reduction efficiency = $(C_i - C_e)/C_i$
η_I = fraction of volume that infiltrates = $(\Sigma V_i - \Sigma V_e)/\Sigma V_i$

The advantages of this method are that: (1) it uses site-specific regression equations that avoid the assumption that one linear relationship between influent and effluent is applicable to other locations, and (2) all sites are compared at the same influent concentration. The shortcomings are that: (1) the assumption of a linear relationship over the entire range of influent concentrations (especially low values) is probably incorrect, (2) restricting the data used in the regression to a single site increases the sensitivity to unusual conditions at that site, (3) the relationship between water quality and runoff volume generated by different storm sizes is lost in using the linear regression, and (4) independently analyzing water quality at each location often results in unrealistic regressions. Some regressions, for example, had negative slopes that predicted concentration reductions greater than 100 percent at the median influent value.

Method 3: Log mean (based on location-specific volume): This is a variation on the method used in the BMP Retrofit Pilot Program (Caltrans, 2004). Concentration data from all sites associated with a particular BMP were aggregated and geometric means were calculated for the influent and effluent concentrations. The resulting means were transformed back into real values and multiplied by the summed influent and effluent volumes to calculate the load removal efficiency. While the Retrofit study used aggregated volumes for all locations of the same BMP type, Method 3 uses location-specific volumes. This process is described in equation 3.

$$\eta = \frac{\left(C_{iGM} \sum_{storms} V_i - C_{eGM} \sum_{storms} V_e \right)}{C_{iGM} \sum_{storms} V_i} \qquad \textbf{(Equation 3)}$$

Where
V_i, V_e = influent and effluent volumes for each site
C_{iGM}, C_{eGM} = geometric means of the influent and effluent concentrations respectively.

The geometric means are based on the aggregated data from all sites associated with the particular BMP. They are calculated from equation 4.

$$C_{GM} = anti\log\left(\frac{\sum_{storms\ and\ sites} \log C}{n_{storms\ and\ sites}} + \frac{s^2}{2} \right) \qquad \textbf{(Equation 4)}$$

Where
s^2 = variance of the log-transformed data

The advantage of this method is that it uses all the data for BMPs of a single type, which simulates a single BMP installation experiencing the full range of influent conditions seen at all locations where that BMP was installed. This violates statistical rules, but makes some engineering sense because influent concentration appears to be the most important location-specific factor affecting concentration reduction. Testing over a wide range of influent concentrations better represents potential field conditions than testing over narrow ranges. On the other hand, infiltration is affected by the soils at each location, so infiltration analysis should be performed site by site. The method's shortcomings are that: (1) the water quality data are pseudo-replicated, (2) there is no adjustment for BMPs that were tested under different site conditions (i.e., clean vs. dirty sites), and (3) any relationship between volume and water quality is lost because load is computed from aggregated concentrations and site-specific volumes.

Method 4: Mixed-model on concentration (based on location-specific volume): The mixed model on concentration method is similar to the log mean method in that each type of BMP uses a single concentration reduction that is specific to that BMP type for a particular constituent and is not location-specific. In this case, though, the concentration treatment efficiency (η_C) comes from the statistical mixed-model analysis for concentration. This efficiency is calculated at a common point of comparison (i.e., the median influent concentration from all BMP study data). Infiltration efficiency is calculated from the cumulative volumes for each location as in Methods 2 and 3. The overall load reduction efficiency is calculated from Equation 2.

The advantage of the mixed-model method is that it compares all BMPs at a single influent concentration, which manages for differences in influent study conditions. The shortcomings are that: (1) it ignores any relationship between concentration and volume, (2) the result may not be applicable to projects where the influent concentrations are substantially different from the point of comparison used in the analysis, and (3) it obscures the actual variability of load removal among BMP locations.

Comparison of Methods: For comparison purposes, these four methods are shown in Figure 3.1 for swales treating dissolved copper. A dissolved constituent was selected because it is more reliant on the location-specific removal mechanism (infiltration). Methods 1 and 2 have the widest range because they use location-specific concentration results, while Methods 3 and 4 use one concentration reduction value for all locations of a certain BMP type. Method 2 should be avoided because it results in spurious relationships between influent and effluent, which introduces artificial variability. Methods 2, 3, and 4 all apply some scheme to control for site differences, but each of these methods obscures potentially important relationships to load removal. Method 1 is preferred because it makes no assumptions on concentration-volume relationships and on the linearity of concentration curves across various site conditions, and thus it is the truest measure of overall load reduction at each location. The downside is that Method 1 requires a location-by-location examination of influent conditions to assure that test concentrations were typical of statewide highway concentrations.

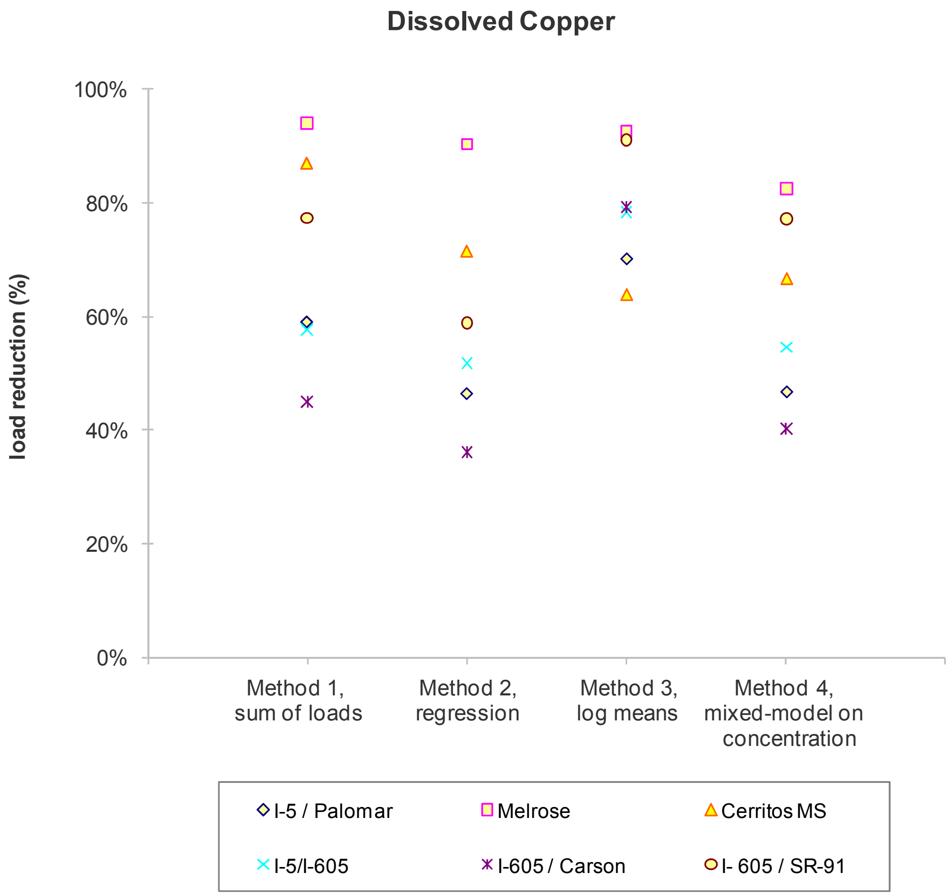


Figure 3.1 Comparison of Load Calculation Methods

Ranking Procedure Using the Sum of Loads Results. BMP rankings were created by examining the load removal efficiencies for each BMP as calculated from the sum of loads method. Separate BMP rankings were created for different levels of infiltration because infiltration has a direct impact on load removal and because infiltration is highly site specific. The three chosen infiltration ranges are: (1) less than 20 percent, (2) 20 to 50 percent, and (3) greater than 50 percent. Broad infiltration ranges were chosen so that a project designer would need only a rough estimate of infiltration to determine which BMP ranking to use. The selected ranges are broad enough so that at least one BMP of each type is observed in each infiltration range, with a couple of exceptions. These exceptions are discussed in the following 12 subsections that address the TDCs individually.

To create the rankings, the load reduction at each study location was plotted against the observed infiltration. An example plot is shown in Figure 3.2 for six hypothetical BMPs. This type of plot is used for each TDC in the following 12 subsections. The percent load reduction is plotted on the vertical axis and the percent infiltration is plotted on the horizontal axis. Vertical lines are placed at 20 and 50 percent infiltration to show the chosen infiltration ranges. Heavy dashed lines are used to denote the BMP performance groups within the two higher infiltration ranges. In the lowest range (less than 20 percent), infiltration does not play a substantial role in load reductions, so the concentration rankings are used from the statistical mixed model results (Section 3.1). The exception is total nitrogen. Because total nitrogen was not analyzed by the statistical model, its performance for infiltration less than 20 percent was based on the sum of loads.

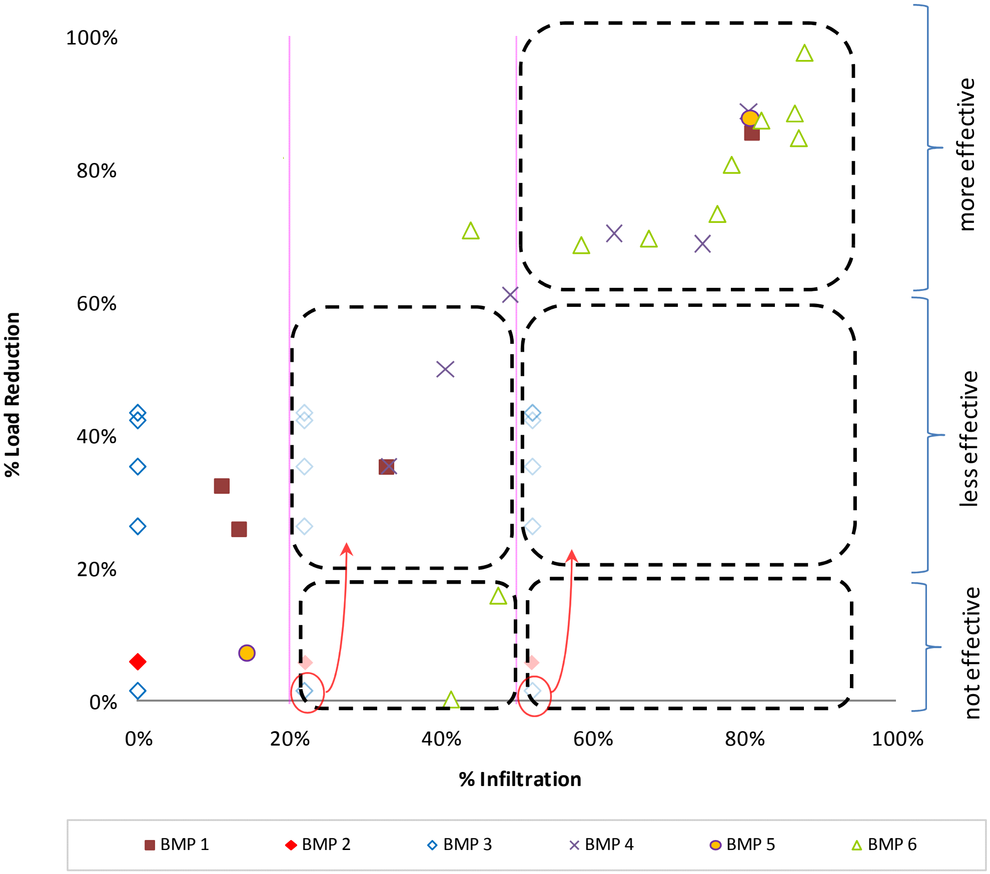


Figure 3.2 Example of Load Reduction Graph

Performance groups are described as they were for concentration: (1) “more effective,” (2) “less effective,” and (3) “not effective.” BMPs that reduced load by more than 60 percent are considered “more effective.” BMPs that reduced load from around 20 to about 60 percent are considered “less effective.” Load reduction below 20 percent is considered inconsequential so BMPs that fall in this performance group are classified as “not effective.” Small shifts in these ranges were made on a case-by-case basis. These are described in the TDC subsections below.

To be conservative, BMPs are classified in the lowest performance group in which they occur unless a reclassification is justified. Reclassification can occur because of unusual influent conditions. Load reduction estimates based on low concentrations, especially near the reporting limit, can result in unreliable load reduction estimates for typical highway runoff concentrations. In this case, meeting one of two additional conditions justifies an upgrade in performance classification: one is the existence of a removal mechanism that predicts better performance than what was observed; the other is the overwhelming occurrence of better treatment at other locations using that BMP. All upward adjustments to load reduction are shown in the figures as light red circles and curved arrows that point to the performance group where the BMP is newly reclassified. Where BMP performance spans more than one performance group, the discussion of whether a reclassification is warranted is provided within the "special cases" section within the TDC subsections.

By design, some BMPs do not infiltrate, regardless of underlying soil conditions. This is because of impermeable liners or construction materials (e.g., concrete vaults). For ranking, it is helpful to show how non-infiltrating BMPs compare within the two higher infiltration ranges. For this reason, the non-infiltrating and infiltrating BMPs are also plotted at 22 percent and 52 percent infiltration. A lighter shade is used to remind the reader that these are phantom infiltration values.

To illustrate how the ranking assignments are made, consider the hypothetical load reduction graph in Figure 3.2. Each symbol represents a separate pilot location. As can be seen, there are many BMP6 pilot facilities and only one BMP2 site. The percent load reductions are calculation results from the sum of loads method. BMP2 and BMP3 are lined BMPs with no infiltration, so their symbols are plotted on the y-axis and are repeated in faded type on the left-hand edges of the boxes. The rankings resulting from this graph are shown in Table 3.4.

For the infiltration <20% range, BMPs would be ranked according to the concentration rankings arising from the mixed-model analysis, regardless of their plotting positions on the graph.

Using the above classification rules, individual BMPs in the Figure 3.2 example are classified into performance rankings as described in the following:

- BMP2 would be classified "not effective" in all infiltration ranges.
- BMP1 would be classified "more effective" in the high infiltration range and "less effective" in the middle infiltration range in accordance with the plotting positions of the symbols. (In the low infiltration range, BMP1's classification would depend on its concentration ranking.)
- Like BMP1, BMP4 would be classified "more effective" in the high infiltration range and "less effective" in the middle infiltration range. It would be classified according to its concentration ranking in the lowest infiltration range.
- BMP5 would be classified "more effective" in the upper infiltration range. In the lowest infiltration range, it is likely to be "not effective" based on its plotting position (although its official ranking would be based on concentration). In this case the performance in the middle infiltration range is interpolated between the observations in the other ranges, resulting in a "less effective" assignment. Because this assignment is not directly supported by a data point, BMP5 is marked with parentheses in the ranking table (see Table 3.4).

- BMP6 is classified “more effective” in the high infiltration range in accordance with its plotting positions. In the middle infiltration range, there is one site with high treatment and two sites with low treatment. To be conservative, when the load reduction results are distributed among different rankings, the original data are examined to determine whether there are any mitigating factors. If none are found, the lowest ranking is assigned. Accordingly, BMP6 is classified as “not effective” in the middle infiltration range.
- Most BMP3 test locations showed moderate load reduction, though one site showed very little reduction. Examining the original data, it was found that the influent concentrations for this TDC were much lower than typical highway values, and effluent concentrations were often at the reporting limit. Consequently, the differences between influent and effluent values were small, leading to a low load reduction percentage. In this case, it was judged that the load reduction results are not representative of typical highway conditions, particularly as evidenced by the performance of the BMP at other sites, and so the BMP was shifted up to the “less effective” category. This shift is shown in the graph by the arrows. Because of this shift, BMP3 is shown in parentheses in Table 3.4.

Table 3.4 Example Organization of Performance Group from Figure 3.2 Observations

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
TDC1	**Tier 1 -- More Effective**		
	---	---	BMP1 BMP4 BMP5 BMP6
	Tier 2 -- Less Effective		
	BMP1 BMP3 BMP4 BMP5	BMP1 (BMP3) BMP4 (BMP5)	(BMP3)
	Tier 3 -- Not Effective		
	BMP2 BMP6	BMP2 BMP6	BMP2

In the subsections that follow, similar tables are used to group the BMPs according to performance plots for each TDC. Because lined extended detention basins, concrete Austin filters, Delaware filters, and MCTTs did not infiltrate, their symbols are repeated in the two higher infiltration ranges in Figures 3.3 through 3.14. The wet basin has an underlying impermeable liner, though it did show minor losses (around 10 percent). Assuming that these results are not due to measurement error, the losses could be due to evapotranspiration or to infiltration through the soil on the edge of the basin, which is only inundated during storm events. Consequently the wet basin is treated as a non-infiltrating BMP and its load removal is shifted in the same manner as other non-infiltrating BMPs.

The load removal analysis for each TDC follows.

3.2.1 TSS

Figure 3.3 shows the overall TSS load removal efficiencies for each BMP test site, which are plotted according to infiltration efficiency for each BMP installation. In this case, only one "less effective" BMP location was observed. All other BMPs had load removals that are scattered throughout the "more effective" load reduction range.

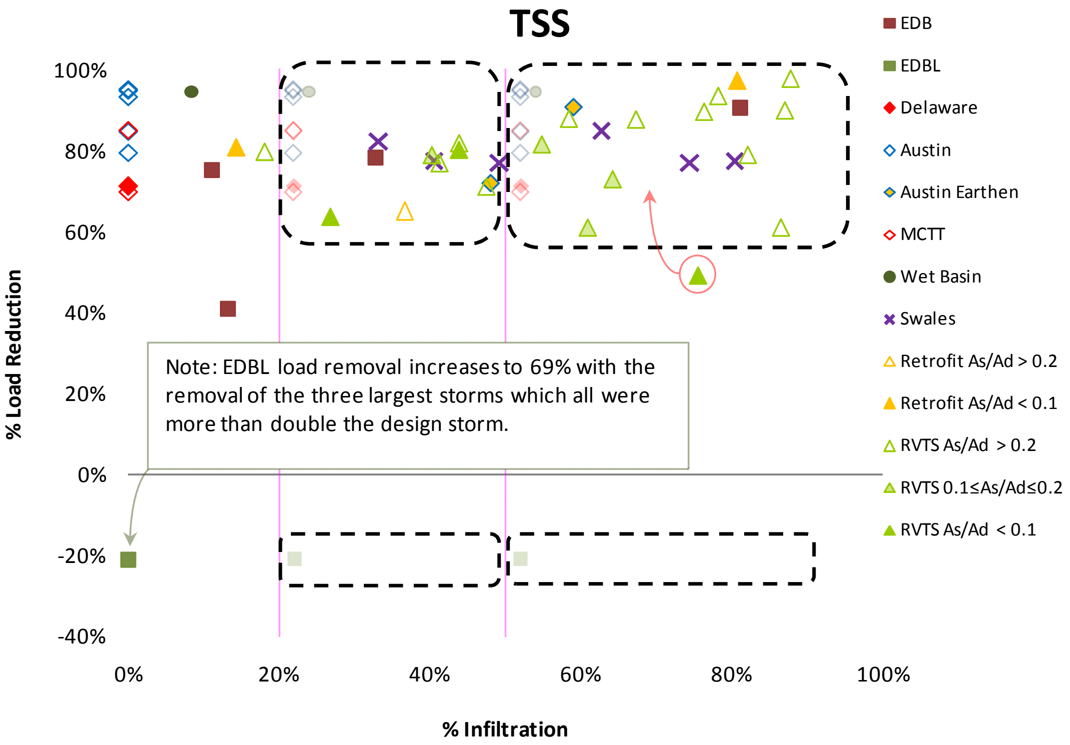


Figure 3.3 TSS Removal and Infiltration

<u>*Special cases*</u>

Strips $A_S/A_D < 0.1$. The performance of this BMP spans more than one performance category for the highest infiltration range. All strips are classified as "more effective" for both infiltration ranges above 20 percent. Only one BMP, the strip at Yorba Linda with a length of 2.2 meters from the edge of pavement, had a load reduction less than 60 percent. This data point is identified on Figure 3.3 with a red circle and the performance category reclassification is shown by a curved arrow. Though infiltration was greater than 60 percent, load reduction was less, which was caused by an increase in TSS concentration; the average concentration increased from 104 mg/L to 167 mg/L. This could be attributed to erosion of the sparsely vegetated area adjacent to the pavement that provides a "fire break." In cases where the strip is fairly short, the fire break consumes a relatively large portion of the strip, and the remaining vegetation downstream may be insufficient to remove eroded sediment. This is not conclusive because there were other strips with similar proportions of fire break that performed better, but it may indicate that additional erosion control measures may be needed to assure that the fire break area is not a sediment source for strips $A_S/A_D < 0.1$.

EDB – lined. See commentary on concentration performance grouping in Table 3.1.

<u>*Ranking*</u>

The load rankings for TSS are shown in Table 3.5. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.3.

Table 3.5 BMP Load Rankings for TSS

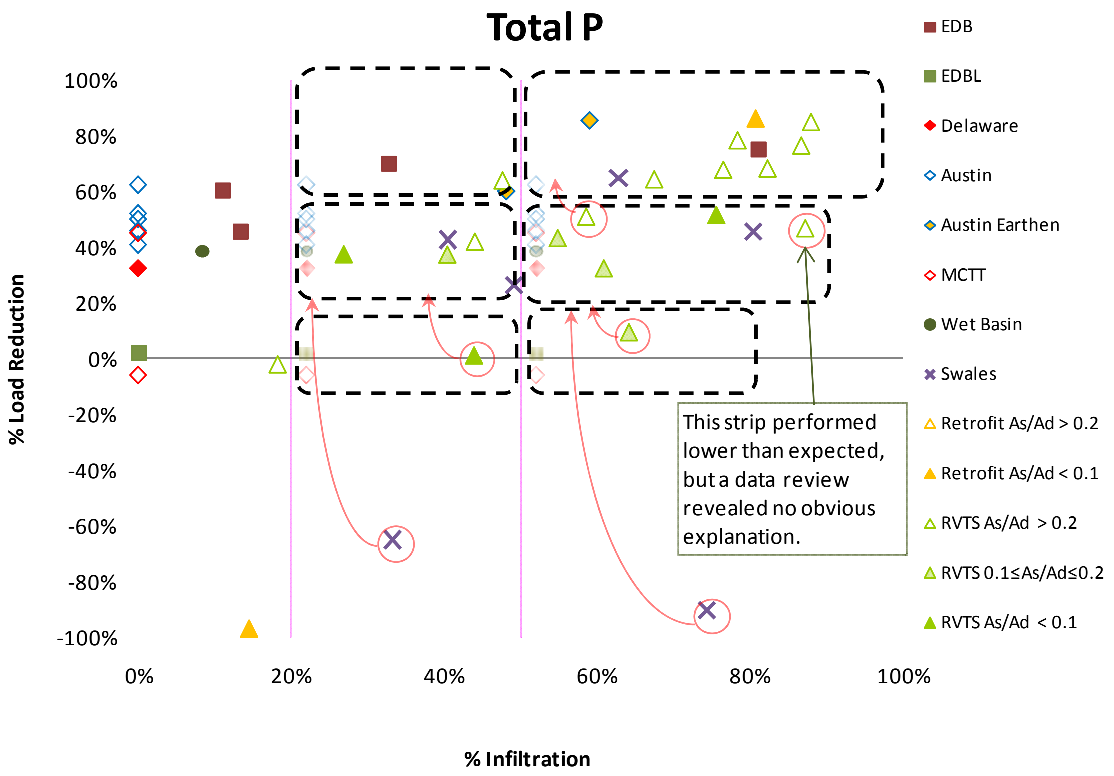
Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
TSS	**Tier 1 -- More Effective**		
	Wet basin MCTT Delaware filter Austin filter Strip – HRT>5	Austin filter – both Delaware filter EDB MCTT Strip – all Swale Wet basin	Austin filter – both Delaware filter EDB MCTT Strip – $A_S/A_D > 0.2$ Strip $0.1 < A_S/A_D < 0.2$ (Strip – $A_S/A_D < 0.1$) Swale Wet basin
	Tier 2 -- Less Effective		
	Strip – HRT<5 EDB Swale	---	---
	Tier 3 -- Not Effective		
	EDB – lined	EDB – lined	EDB – lined

<u>Notes</u>:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.2 Phosphorus, Total

Figure 3.4 shows the overall total phosphorus load removal and infiltration efficiencies for each BMP installation. Because of the distribution of load reduction values, the dividing line between "less" and "more" effective is 55 percent removal. Performance of the biofilters (strips and swales) is discussed in detail under special cases because performance measurements were complicated by the use of salt grass in the BMPs.



This strip performed lower than expected, but a data review revealed no obvious explanation.

Results not displayed:
Retrofit strip As/Ad > 0.2 at 37% infiltration and -503% load reduction (export from salt grass)
RVTS strip As/Ad > 0.2 at 41% infiltration and -132% load reduction (low influent concentrations)

Figure 3.4 Total Phosphorus Removal and Infiltration

Special cases

For reference, the statewide median total phosphorus concentration for highway runoff is 0.2 mg/L (Caltrans, 2009a).

MCTT. MCTT performance spans the ineffective and "less effective" performance categories. The MCTT is classified as ineffective for total phosphorus as discussed in the commentary on concentration performance groupings (Table 3.1). Though one location demonstrated load reduction effectiveness, the location that was ineffective had typical influent conditions and thus could not be ignored.

Swale. Swale performance spans multiple performance categories for both higher infiltration ranges. Swales are classified as "less effective" for both infiltration ranges. Two of six locations exported phosphorus, but this has been linked to the use of salt grass, which appeared to grow more vigorously at these two locations. The shift in performance categories for these two locations is denoted in Figure 3.4 with a red circle and curved arrow. Salt grass should be avoided if phosphorus is a TDC.

Strips. The load reduction behavior of strips is complicated by influent conditions and the type of vegetation used. For this reason, the classification of strips for total phosphorus reduction is based on RVTS locations because the Retrofit locations used salt grass, which has the ability to uptake phosphorus from the soil and excrete it from its leaves where the phosphorus is exposed to stormwater. Because of the complicated nature of classifying strips for phosphorus, <u>all</u> strip loading categories are discussed below, not just those where the load removal performance spans more than one performance category. The discussion is first organized by infiltration category, then by drainage area ratio. The following discussion of strip locations does not consider strips from the retrofit study.

All strips that had infiltration from 20 to 50 percent were classified in the "less effective" group.

Strip – $A_S/A_D > 0.2$ (infiltration 20 to 50%). These strips span all performance categories. These strips are classified as "less effective." Two of three locations that did not have salt grass (RVTS) were effective in total phosphorus load reduction. One location, the 6.2 m strip at Redding, exported total phosphorus, however, the median influent concentration was less than one third of the statewide highway median concentration. Effective reduction is expected for typical highway concentrations. The shift in performance categories for this location is denoted in Figure 3.4 with a red circle and curved arrow.

Strip – $0.1 < A_S/A_D < 0.2$ (infiltration 20 to 50%). These strips are classified as "less effective" based on performance at one location.

Strip – $A_S/A_D < 0.1$ (infiltration 20 to 50%). These strips span multiple performance categories. These strips are classified as "less effective." One of two locations had load reduction in the "less effective" range. The ineffective location had a median influent concentration that was less than one third of the statewide highway median concentration, which may have limited the effectiveness. Effective reduction is expected for typical highway concentrations.

Strips that had infiltration above 50 percent were classified according to their drainage area ratio, as described below.

Strip – $A_S/A_D > 0.2$ (infiltration above 50%). The performance of these strips spans the two effective performance categories. They are classified as "more effective" because six of eight locations that did not have salt grass (RVTS) had load reductions above 60 percent and these six locations had performance that was comparable to other BMPs in this performance category. One of the strips in the “less effective” range had very low influent concentrations. The shift in performance categories for this location is denoted in Figure 3.4 with a red circle and curved arrow. It is unclear why the remaining strip was in the less effective range so there is some risk of lower phosphorus removal at similar strips. These strips are classified as “more effective” because the overwhelming majority of similar strips had load reduction in this performance category.

Strip – 0.1 <A_S/A_D*<0.2 (infiltration above 50%)*. The performance of these strips spanned two performance categories. The strips are classified as “less effective” because two of three locations had load removal between 20 and 60 percent while the ineffective location had a median influent concentration that was less than one third of the statewide highway median concentration. This may have limited the effectiveness. Effective reduction is expected for typical highway concentrations.

Strip – A_S/A_D *<0.1 (infiltration above 50%)*. These strips are classified as “less effective” based on performance at one location.

Ranking

The load rankings for total phosphorus are shown in Table 3.6. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.4.

Table 3.6 BMP Load Rankings for Total Phosphorus

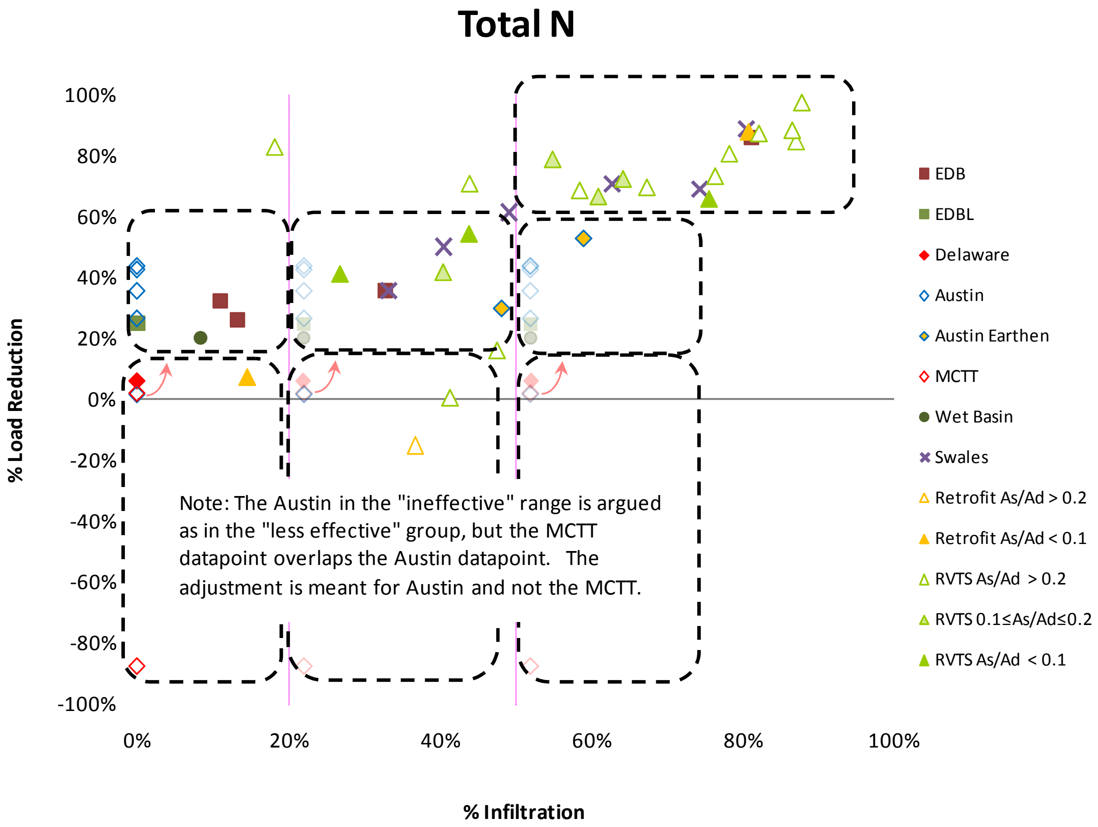
Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Phosphorus (total)	**Tier 1 – More Effective**		
	Delaware filter Austin filter EDB Strip – HRT<5	Austin filter – earthen EDB	Austin filter – earthen EDB (Strip – A_S/A_D>0.2)
	Tier 2 – Less Effective		
	---	Austin filter – concrete Delaware filter Strip – A_S/A_D>0.2 Strip – 0.1<A_S/A_D<0.2 (Strip – A_S/A_D <0.1) (Swale) Wet basin	Austin filter – concrete Delaware filter Strip – A_S/A_D<0.1 (Strip – 0.1<A_S/A_D<0.2) (Swale) Wet basin
	Tier 3 – Not Effective		
	EDB – lined MCTT Wet basin Strip – HRT>5 Swale	EDB – lined (MCTT)	EDB – lined (MCTT)

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- Strip classifications assume that salt grass is not planted. Pilot strips and swales planted with salt grass did not effectively reduce phosphorus.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.3 Nitrogen, Total

Figure 3.5 shows the overall total nitrogen load removal and infiltration efficiencies for each BMP installation. Total nitrogen was not analyzed for concentration performance using the statistical mixed model, so for infiltration less than 20 percent, load performance is based on the sum of loads method.



Note: The Austin in the "ineffective" range is argued as in the "less effective" group, but the MCTT datapoint overlaps the Austin datapoint. The adjustment is meant for Austin and not the MCTT.

Figure 3.5 Total Nitrogen Removal and Infiltration

<u>*Special cases*</u>

For reference, the statewide median total nitrogen concentration for highway runoff is 2.1 mg/L as nitrogen (Caltrans, 2009a). The median ammonium concentration is 0.53 mg/L as nitrogen; the median TKN concentration is 1.5 mg/L; and the median nitrate concentration is 0.61 mg/L.

Strips – all (infiltration between 20 and 50 percent). For mid-range infiltration, the performance of strips spanned all three performance categories. These strips are classified as ineffective because of inconsistent performance. Two strips reduced total nitrogen load by greater than 60 percent; one strip reduced load in the "less effective" range; and three were ineffective or caused an increase in load. The reasons for the wide range in performance are not apparent.

Austin filter − both. For infiltration less than 20 percent, the earthen Austin filter performance is based on the performance of the lined Austin filters. In this range all but one filter reduced total nitrogen load by 20 to 60 percent. The location that experienced near-zero reduction had a single event with an effluent TKN concentration of 8.8 mg/L, but only 0.74 mg/L TKN in the influent. Similar effluent spikes of TKN occurred at other filters. These infrequent occurrences, however, were outweighed by marginal reductions of total nitrogen influent concentration in the range of 2 to 4 mg/L. The Eastern maintenance station influent was different, with a median influent concentration of 1.24 mg/L, while the median influent at all sites that demonstrated total nitrogen reduction ranged from 1.4 mg/L to 3.26 mg/L. The statewide highway median concentration is 2.1 mg/L. Another unique characteristic of the poorly performing filter is that the median ammonium influent concentration was 40 percent lower than the next highest median concentration at the other filters. One reason that filters reduce total nitrogen is the nitrification of ammonium ion into nitrate. While nitrate concentrations typically increase, partial denitrification can decrease the total nitrogen load. The lower ammonium concentrations at the Eastern maintenance station may have limited the total nitrogen removal. The statewide median ammonium concentration, however, is only about 30 percent higher than the median concentration at Eastern. Consequently, Austin filters are classified as "less effective" for total nitrogen load removal, but reductions at sites only slightly cleaner than usual should not be expected. The shift in performance categories for this location is denoted in Figure 3.5 with a red curved arrow.

Swale (infiltration less than 20 percent). Swales were not observed in the infiltration range less than 20 percent. The load reductions for moderate infiltration are in the "less effective" category and the load reductions for high infiltration are in the "more effective" category. Extrapolating these results back to the infiltration range less than 20 percent results in a rough estimate of around 20 percent removal, but extrapolating this far may not be appropriate. To be conservative, the swale is classified as "not effective" for infiltration less than 20 percent.

Ranking

The load rankings for total nitrogen are shown in Table 3.7. The groups for all infiltration ranges are based on the groups identified in Figure 3.5.

Table 3.7 BMP Load Rankings for Total Nitrogen

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Nitrogen (total)	**Tier 1 -- More Effective**		
	---	---	EDB Strip – all Swale
	Tier 2 -- Less Effective		
	(Austin filter – both) EDB EDB – lined Wet basin	(Austin filter – concrete) Austin filter – earthen EDB EDB – lined Swale Wet basin	(Austin filter – concrete) Austin filter – earthen EDB – lined Wet basin
	Tier 3 -- Not Effective		
	Delaware MCTT Strip – all (Swale)	Delaware filter MCTT (Strip – all)	Delaware filter MCTT

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.4 Copper, Total

Figure 3.6 shows the overall total copper load removal and infiltration efficiencies for each BMP installation.

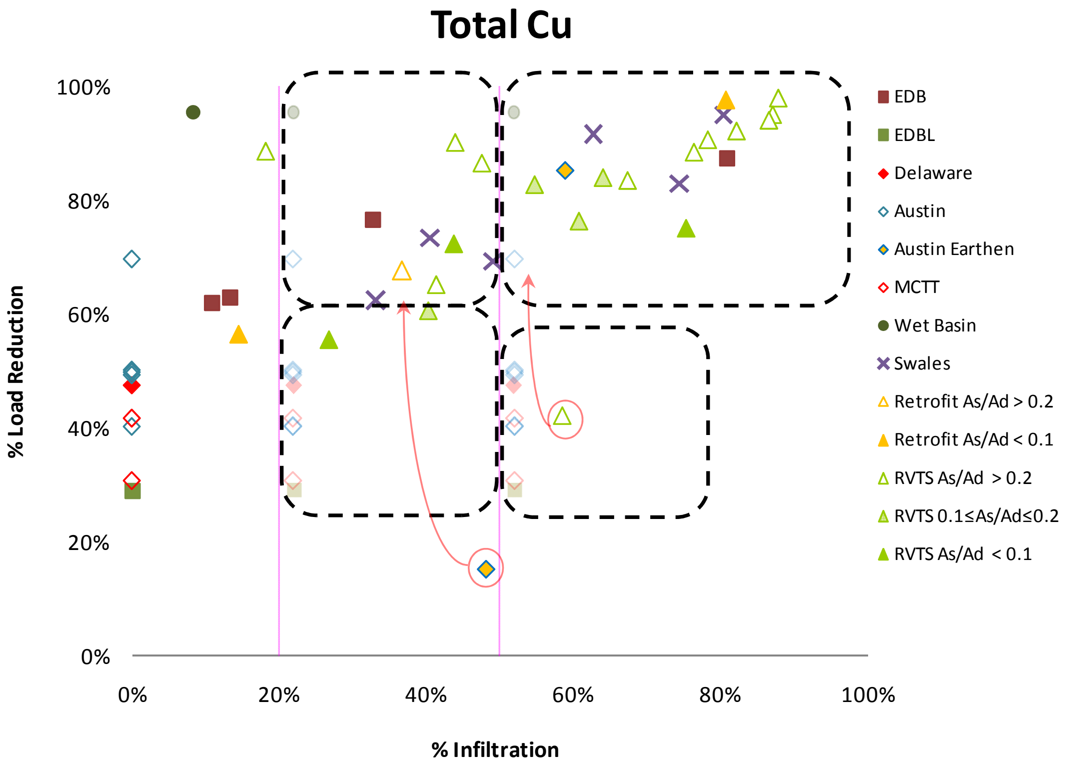


Figure 3.6 Total Copper Removal and Infiltration

Special cases

For reference, the statewide median total copper concentration for highway runoff is 23.2 µg/L (Caltrans, 2009a).

Austin filter– earthen. The Austin sand filter in the 20 to 50 percent infiltration range resulted in total copper removal of less than 20 percent. The median influent concentration was 3.6 µg/L, which is only 15 percent of the statewide highway median concentration. At more typical influent concentrations, the Austin filter is expected to perform better. The performance re-classification is shown in Figure 3.6 with a red circle and a curved arrow. The earthen Austin filter is classified as “more effective” because of interpolation between the lined filters and the earthen Austin filter above 50 percent infiltration. In Figure 3.6, the concrete Austin filters have a median load reduction of about 50 percent as indicated by the tight grouping of the center three load removal results. The earthen Austin above 50 percent infiltration has a load removal of 85 percent. Interpolating between these values gives a predicted load removal that is mostly in the “more effective” range.

Strips − all (infiltration greater than 50 percent). One strip with less than 50 percent infiltration was in the “less effective” category. The median influent concentration was 3.9 µg/L, which was 40 percent of the statewide highway median concentration. Higher percent load reduction is expected for more typical highway influent concentrations. Also, the overwhelming majority of strips are in the “more effective” range. Consequently, all strips are classified in the “more effective” group. The reclassification of performance category of this strip is indicated by a red circle and curved arrow.

Ranking

The load rankings for total copper are shown in Table 3.8. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.6.

Table 3.8 BMP Load Rankings for Total Copper

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Copper (total)	**Tier 1 – More Effective**		
	Strip – HRT<5 Wet basin (MCTT) Delaware filter	(Austin filter – earthen) EDB Strip – $A_S/A_D > 0.2$ Swale Wet basin	Austin filter – earthen EDB (Strip – $A_S/A_D > 0.2$) Strip – $A_S/A_D < 0.1$ Strip – $0.1 < A_S/A_D < 0.2$ Swale Wet basin
	Tier 2 – Less Effective		
	Austin filter Strip – HRT>5 Swale EDB	Austin filter – concrete Delaware filter EDB – lined MCTT Strip – $A_S/A_D < 0.1$ Strip – $0.1 < A_S/A_D < 0.2$	Austin filter – concrete EDB – lined Delaware filter MCTT
	Tier 3 – Not Effective		
	EDB – lined	---	---

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.5 Copper, Dissolved

Figure 3.7 shows the overall dissolved copper load removal and infiltration efficiencies for each BMP installation.

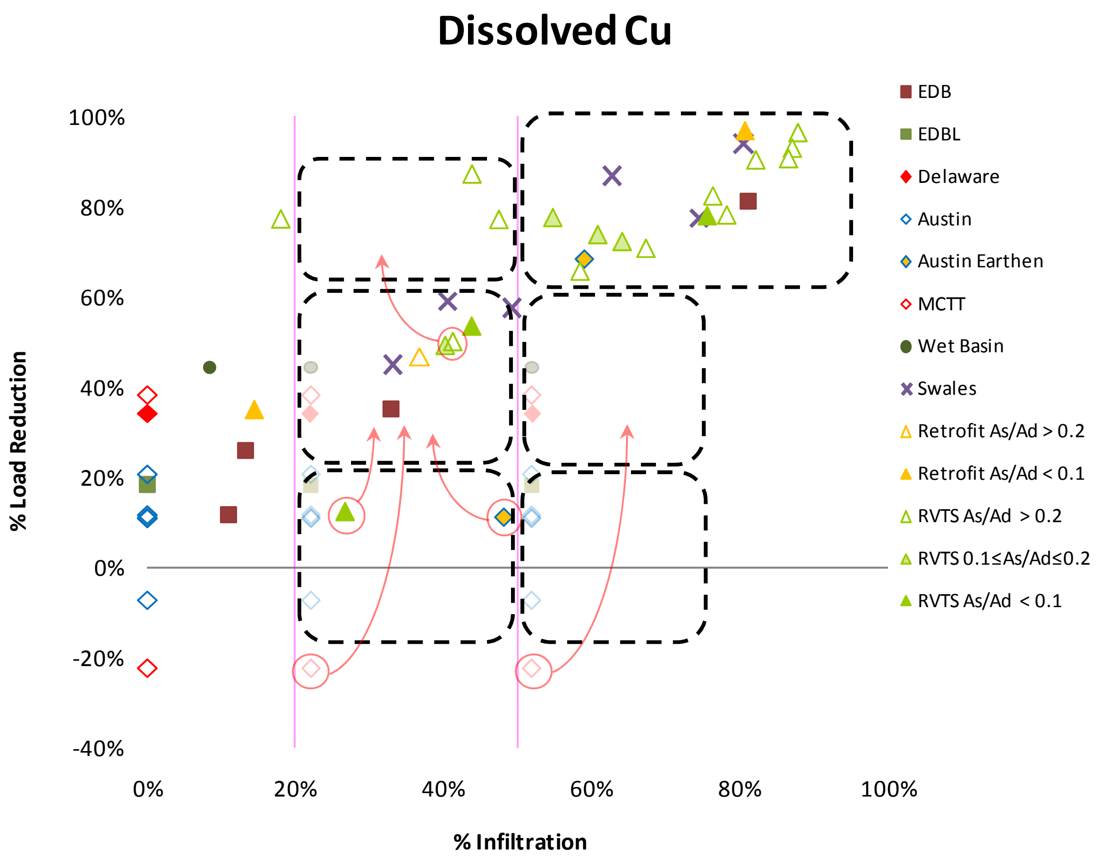


Figure 3.7 Dissolved Copper Removal and Infiltration

<u>*Special cases*</u>

For reference, the statewide median dissolved copper concentration for highway runoff is 10.1 µg/L (Caltrans, 2009a).

Austin filter – earthen (infiltration between 20 and 50 percent). The single earthen Austin filter in the moderate infiltration range was ineffective, but the median influent was 2.8 µg/L, which is only 28 percent of the median statewide highway concentration. Consequently, the load performance of earthen Austin filters in this range was interpolated between the concrete Austin filters with a median removal of about 10 percent and the other earthen Austin filter that had 68 percent load removal. This results in a re-classification as "less effective." Figure 3.7 shows the adjusted value with a red circle and a curved arrow.

MCTT. See commentary on concentration performance groupings (Table 3.1) for an explanation for the re-classification of the MCTT as “less effective.” The performance adjustment is shown in Figure 3.7 with a red circle and curved arrow.

EDB and EDB – lined. See commentary on concentration performance groupings (Table 3.1). EDBs are not effective for dissolved copper removal where infiltration is less than 20 percent. Unlined EDBs, however, are effective where infiltration is above 20 percent.

Strips $A_S/A_D > 0.2$. In the 20 to 50 percent infiltration range, one strip was in the “less effective” range, but the median influent was 2.2 µg/L. It is uncertain how these strips would perform at more typical highway concentrations. While there are no removal mechanisms in strips that would support a re-classification, Strips $A_S/A_D > 0.2$ are classified as “more effective” for this infiltration range because most of the observed results are in this performance category. Figure 3.7 shows the adjusted value with a red circle and a curved arrow.

Strip $0.1 < A_S/A_D < 0.2$. In the 20 to 50 percent infiltration range, one strip was in the “ineffective” range, but the median influent was 5.8 µg/L. It is uncertain how these strips would perform at more typical highway concentrations. While there are no removal mechanisms in strips that would support a re-classification, Strips $0.1 < A_S/A_D < 0.2$ are classified as “more effective” for this infiltration range because most of the observed results are in this performance category. Figure 3.7 shows the adjusted value with a red circle and a curved arrow.

Delaware. See commentary on concentration performance groupings (Table 3.1) for an explanation of the reclassification of Delaware in Table 3.9. No adjustments were necessary for the load removal estimates for the higher infiltration ranges because the amount of load reduction with no infiltration exceeded 20 percent.

Ranking

The load rankings for dissolved copper are shown in Table 3.9. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.7.

Table 3.9 Load Rankings for Dissolved Copper

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Copper (dissolved)	**Tier 1 -- More Effective**		
	Strip – HRT<5 (Delaware filter) (MCTT) Strip – HRT>5	(Strip – $A_S/A_D > 0.2$)	Austin filter – earthen EDB Strip – all Swale
	Tier 2 -- Less Effective		
	Wet basin Swale	(Austin filter – earthen) Delaware filter EDB (MCTT) Strip – $0.1 < A_S/A_D < 0.2$ (Strip – $A_S/A_D < 0.1$) Swale Wet basin	Delaware (MCTT) Wet basin
	Tier 3 -- Not Effective		
	EDB – lined Austin filter EDB	Austin filter – concrete EDB – lined	Austin filter – concrete EDB – lined

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.6 Lead, Total

Figure 3.8 shows the overall total lead load removal and infiltration efficiencies for each BMP installation.

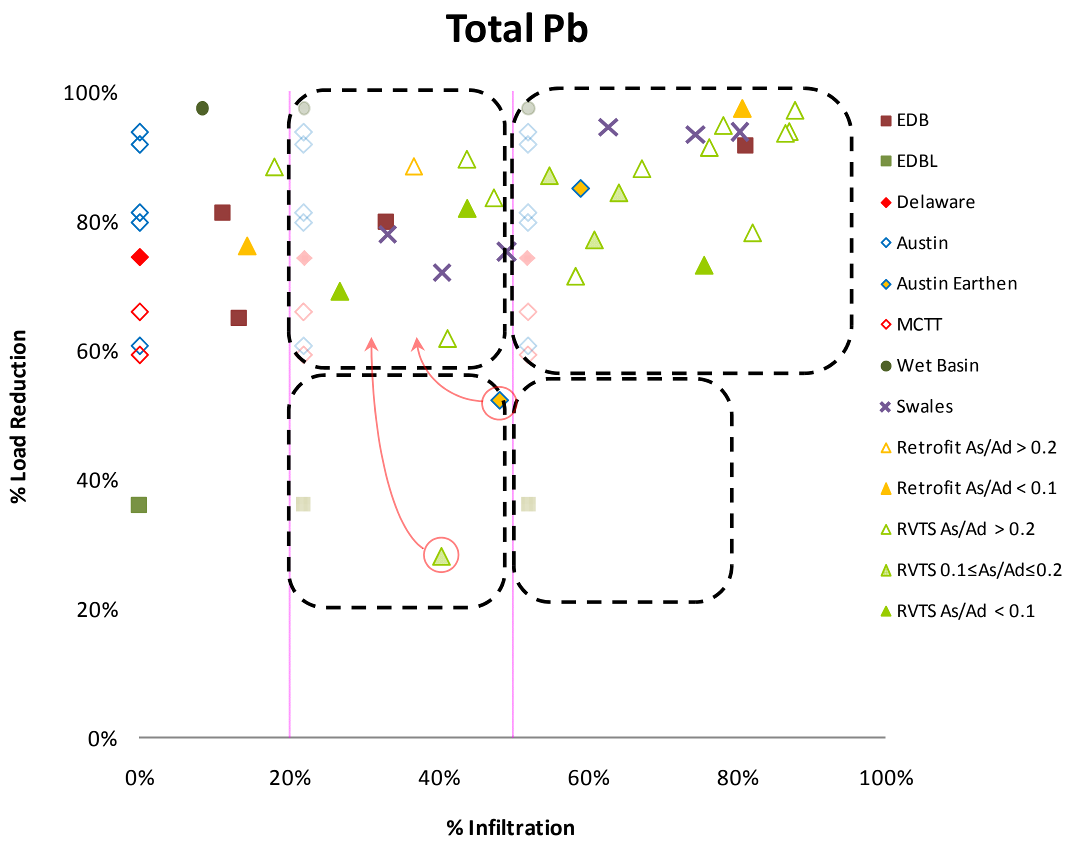


Figure 3.8 Total Lead Removal and Infiltration

<u>Special cases</u>

For reference, the statewide median total lead concentration for highway runoff is 14.3 µg/L (Caltrans, 2009a).

Austin filter – earthen. The Austin sand filter in the 20 to 50 percent infiltration range resulted in total lead removal of less than 60 percent. The median influent concentration was 1 µg/L, compared to the statewide highway median of 14 µg/L. At more typical influent concentrations, the Austin filter is expected to perform better. For this infiltration range, the earthen Austin is reclassified as “more effective,” based on interpolation between the concrete Austin filters and the other earthen Austin filter. The other earthen Austin filter and all the concrete filters had a load removal above 80 percent. The adjusted value in Figure 3.8 is shown with a red circle and curved arrow.

Strip – 0.1 < A_S/A_D < 0.2 (infiltration between 20 and 50 percent). One strip that was 2.2 meters long was ineffective for total Pb. This could be because the median influent was 14 percent of the statewide highway median concentration. Another reason could be that the fire break, which has little vegetation, uses a substantial part of the strip. As discussed with TSS, sediment in the fire break area may be eroding. Erosion of sediment in the un-vegetated section of the strip may be mobilizing particulate lead, which is common in soils from historic use of leaded gasoline. Preventing erosion in these systems is discussed in Section 3.2.1. The performance of this strip is reclassified as "more effective" because all the locations that were tested under influent conditions resulted in load removal above 60 percent.

Ranking

The load rankings for total lead are shown in Table 3.10. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.8.

Table 3.10 BMP Load Rankings for Total Lead

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Lead (total)	**Tier 1 – More Effective**		
	Wet basin Austin filter MCTT Delaware filter Strip – HRT<5 Strip – HRT>5	Austin filter – concrete (Austin filter – earthen) Delaware filter EDB MCTT Strip – $A_S/A_D > 0.2$ (Strip – $0.1 < A_S/A_D < 0.2$) Strip –$A_S/A_D < 0.1$ Swale Wet basin	Austin filter – both Delaware filter EDB MCTT Strip – all Swale Wet basin
	Tier 2 – Less Effective		
	Swale EDB	EDB – lined	EDB – lined
	Tier 3 – Not Effective		
	EDB – lined	---	---

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.7 Lead, Dissolved

Figure 3.9 shows the overall dissolved lead load removal and infiltration efficiencies for each BMP installation.

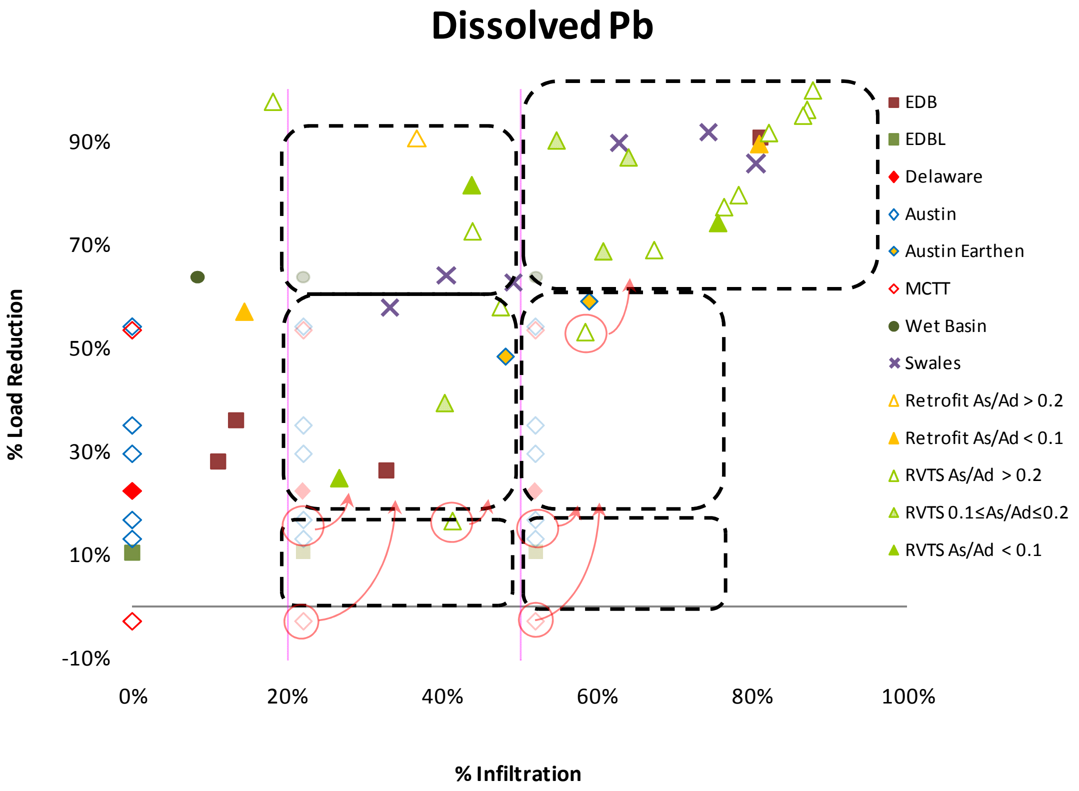


Figure 3.9 Dissolved Lead Removal and Infiltration

<u>*Special cases*</u>

For reference, the statewide median dissolved lead concentration for highway runoff is 1.2 µg/L (Caltrans, 2009a).

Austin filters − concrete. Two of five filters had load removal less than 20 percent. At both locations, more than half of influent concentrations were at or below the reporting limit and even more effluent samples at or below the reporting limit. This obscures the true load reduction, rendering the results at these two locations inconclusive. The load reduction of the other three concrete Austin filter is greater than 20 percent. Since most of the filters had load removal greater than 20 percent and the load removal results less than 20 percent are questionable, Austin filters are classified in the “less effective” group. The adjusted values are shown in Figure 3.9 with a red circle and curved arrow for each infiltration range above 20 percent.

MCTT. See commentary on concentration performance groupings (Table 3.1) for an explanation of the reclassification of performance. The adjusted value is shown with a red circle and curved arrow. The MCTT location with typical influent concentrations demonstrated load removal in the high end of the “less effective” range (the symbol for this location is at 53 percent load reduction and it is partially masked by an Austin filter).

Strip – all. For infiltration from 20 to 50 percent, strip performance was distributed across all groups, with only one of seven strips barely in the “not effective” range. Because the ineffective strip had typical influent concentrations and its performance was fairly close to 20 percent removal, there is not a strong reason to doubt the record of the other six strips. Consequently, all strips are in the “less effective” category. The adjusted value is shown in Figure 3.9 with a red circle and curved arrow. For infiltration above 50 percent, 12 of 13 strips performed in the “more effective” range. The one strip in the less effective range had typical influent concentrations so it is not known why the performance was less. Since the overwhelming majority of strips had higher removal, all strips are classified in the “more effective” group. Once again, the adjusted value is shown in Figure 3.9 with a red circle and curved arrow.

Ranking

The load rankings for dissolved lead are shown in Table 3.11. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.9.

Table 3.11 Load Rankings for Dissolved Lead

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Lead (dissolved)	**Tier 1 -- More Effective**		
	Delaware filter (MCTT) Strip – HRT<5 Austin filter Wet basin EDB Strip – HRT>5	Swale Wet basin	EDB (Strip – $A_S/A_D > 0.2$) Strip – $0.1 < A_S/A_D < 0.2$ Strip –$A_S/A_D < 0.1$ Swale
	Tier 2 -- Less Effective		
	Swale	(Austin filter – concrete) Austin filter – earthen Delaware filter EDB (MCTT) (Strip – $A_S/A_D > 0.2$) Strip – $0.1 < A_S/A_D < 0.2$ Strip –$A_S/A_D < 0.1$	(Austin filter – concrete) Austin filter – earthen Delaware filter (MCTT) Wet basin
	Tier 3 -- Not Effective		
	EDB – lined	EDB – lined	EDB – lined

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.8 Zinc, Total

Figure 3.10 shows the overall total zinc load removal and infiltration efficiencies for each BMP installation.

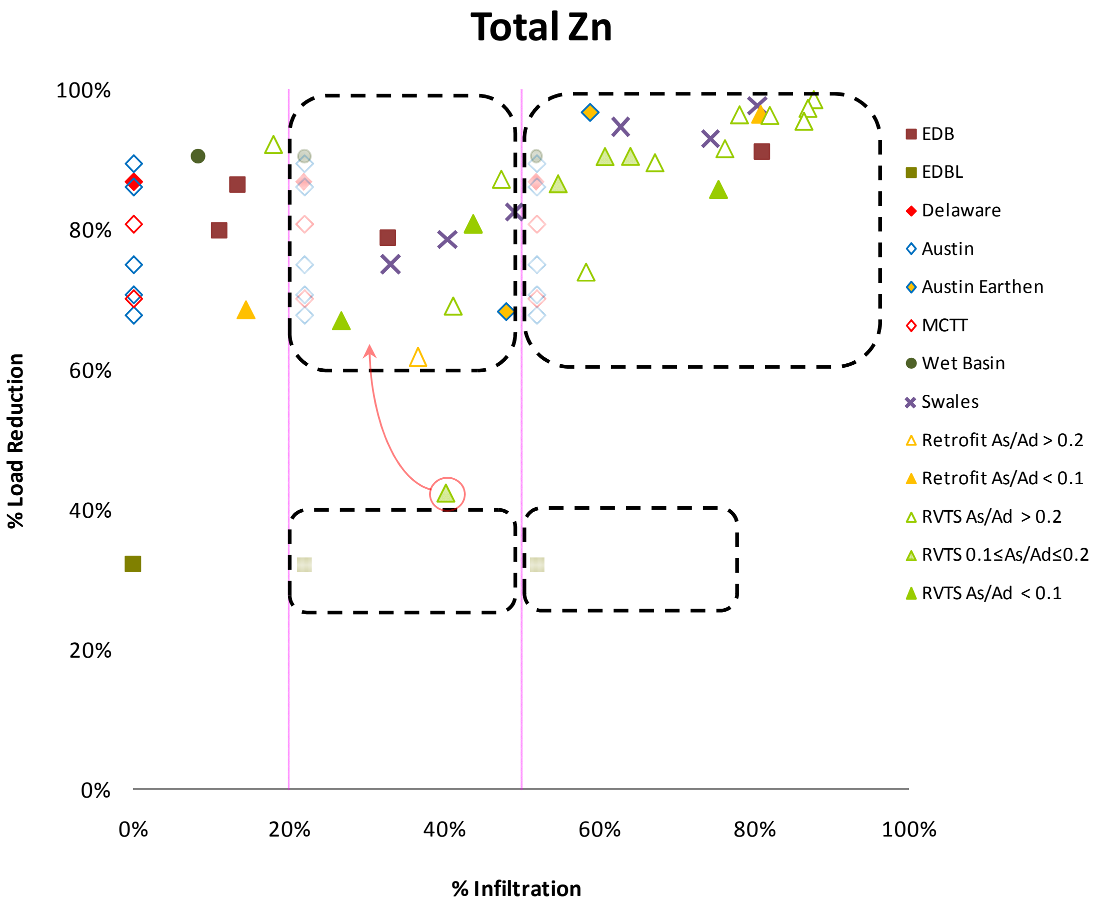


Figure 3.10 Total Zinc Removal and Infiltration

<u>*Special cases*</u>

For reference, the statewide median total zinc concentration for highway runoff is 121 µg/L (Caltrans, 2009a).

Strip – 0.1 < A_S/A_D < 0.2. One strip that was 2.2 meters long had 40 percent load reduction for total Zn. This could be because the median influent was one fifth the statewide highway median concentration. Another reason could be that the fire break, which has little vegetation, may contribute total zinc by erosion. This is discussed in Section 3.2.1. Since five of six strips had load removal greater than 60 percent, this strip is reclassified as "more effective."

Ranking

The load rankings for total zinc are shown in Table 3.12. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.10.

Table 3.12 BMP Load Rankings for Total Zinc

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Zinc (total)	**Tier 1 – More Effective**		
	Delaware filter MCTT Wet basin Strip – HRT<5	Austin filter – both Delaware filter EDB MCTT Strip – $A_S/A_D > 0.2$ (Strip – $0.1 < A_S/A_D < 0.2$) Strip –$A_S/A_D < 0.1$ Swale Wet basin	Austin filter – both Delaware filter EDB MCTT Strip – all Swale Wet basin
	Tier 2 – Less Effective		
	Swale Austin filter Strip – HRT>5 EDB	EDB – lined	EDB – lined
	Tier 3 – Not Effective		
	EDB – lined	---	---

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.9 Zinc, Dissolved

Figure 3.11 shows the overall dissolved zinc load removal and infiltration efficiencies for each BMP installation.

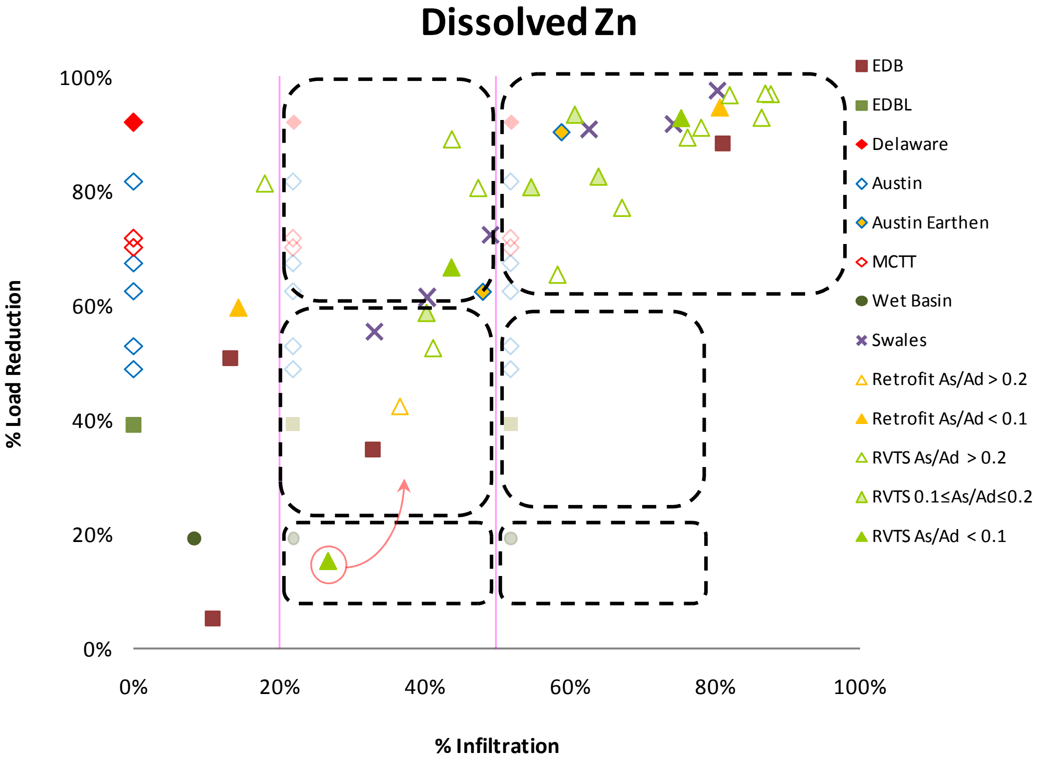


Figure 3.11 Dissolved Zinc Removal and Infiltration

<u>*Special cases*</u>

For reference, the statewide median dissolved zinc concentration for highway runoff is 45 µg/L (Caltrans, 2009a).

EDB and EDB – lined. See commentary on concentration performance groupings (Table 3.1). Unlined EDBs, however, are effective where infiltration is above 20 percent.

Strip – A_S/A_D < 0.1 (infiltration between 20 and 50 percent). One of two of these strips in the moderate infiltration range was ineffective. Its median influent concentration was 12 µg/L, which is 27 percent of the statewide highway median concentration. This may have adversely affected its percent reduction. All other load reduction results from other strips were distributed throughout both effective groups, so to be conservative, strips in this infiltration range are classified as “less effective.”

Swale. Load removals in the infiltration range of 20 to 50 percent are observed in both “effective” performance categories. One of three locations showed reductions less than

60 percent. This could not be explained by influent concentrations, so to be conservative, swales in this infiltration range are classified as "less effective."

Austin filter – concrete. Austin filters are classified in the "less effective" group. Two of the filters had load removal less than 60 percent, and influent conditions did not justify an adjustment.

Ranking

The load rankings for dissolved zinc are shown in Table 3.13. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.11.

Table 3.13 BMP Load Rankings for Dissolved Zinc

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Zinc (dissolved)	**Tier 1 -- More Effective**		
	MCTT Wet basin Austin filter	Austin filter – earthen Delaware filter MCTT	Austin filter – earthen Delaware filter EDB MCTT Strip – all Swale
	Tier 2 -- Less Effective		
	Strip – HRT>5 Swale Strip – HRT<5 Delaware filter	Austin filter – concrete EDB EDB – lined (Strip – all) Swale	Austin filter – concrete EDB – lined
	Tier 3 -- Not Effective		
	EDB – lined EDB	Wet basin	Wet basin

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.10 Cadmium, Total

Figure 3.12 shows the overall total cadmium load removal and infiltration efficiencies for each BMP installation.

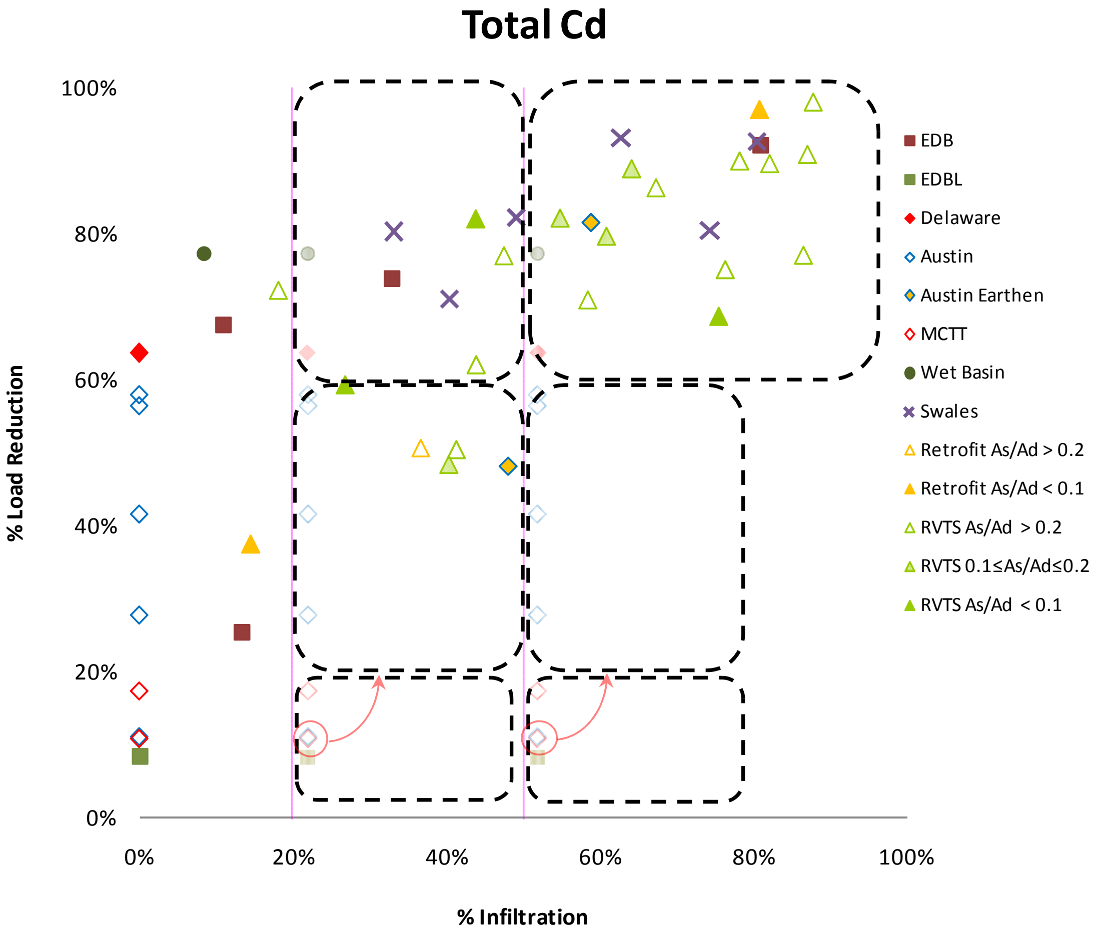


Figure 3.12 Total Cadmium Removal and Infiltration

Special cases

For reference, the statewide median total cadmium concentration for highway runoff is 0.45 μg/L (Caltrans, 2009a).

Strip – all (infiltration between 20 and 50 percent). Contrary to results on concentration, strips consistently demonstrated effectiveness for load removal, probably because of infiltration. For the infiltration range between 20 percent and 50 percent, strip performance was distributed throughout both effective ranges, so to be conservative, strips were classified in the “less effective” group.

Austin filter − concrete. The performance of concrete Austin filters spans two performance groups. Four of five filters had load reductions between 20 and 60 percent. The filter with load reduction below 20 percent had an influent concentration that was less than half the statewide highway median concentration, as did the filter with 28 percent removal. The three filters with the highest load reductions had influent concentrations that were comparable to the statewide highway median concentrations. Based on these observations, concrete Austin filters are reclassified as "less effective." The adjusted value is shown in Figure 3.12 as a red circle and curved arrow. (This value overlaps with the removal for an MCTT, but only the Austin value is adjusted.)

Ranking

The load rankings for total cadmium are shown in Table 3.14. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.12.

Table 3.14 BMP Load Rankings for Total Cadmium

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Cadmium (total)	**Tier 1 -- More Effective**		
	Strip – HRT<5 Wet basin Austin filter Delaware filter Strip – HRT>5 Swale	Delaware filter EDB Swale Wet basin	Austin filter – earthen Delaware filter EDB Strip – all Swale Wet basin
	Tier 2 -- Less Effective		
	EDB	(Austin filter – concrete) Austin filter – earthen Strips – all	(Austin filter – concrete)
	Tier 3 -- Not Effective		
	EDB – lined MCTT	EDB – lined	EDB – lined

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.11 Chromium, Total

Figure 3.13 shows the overall total chromium load removal and infiltration efficiencies for each BMP installation.

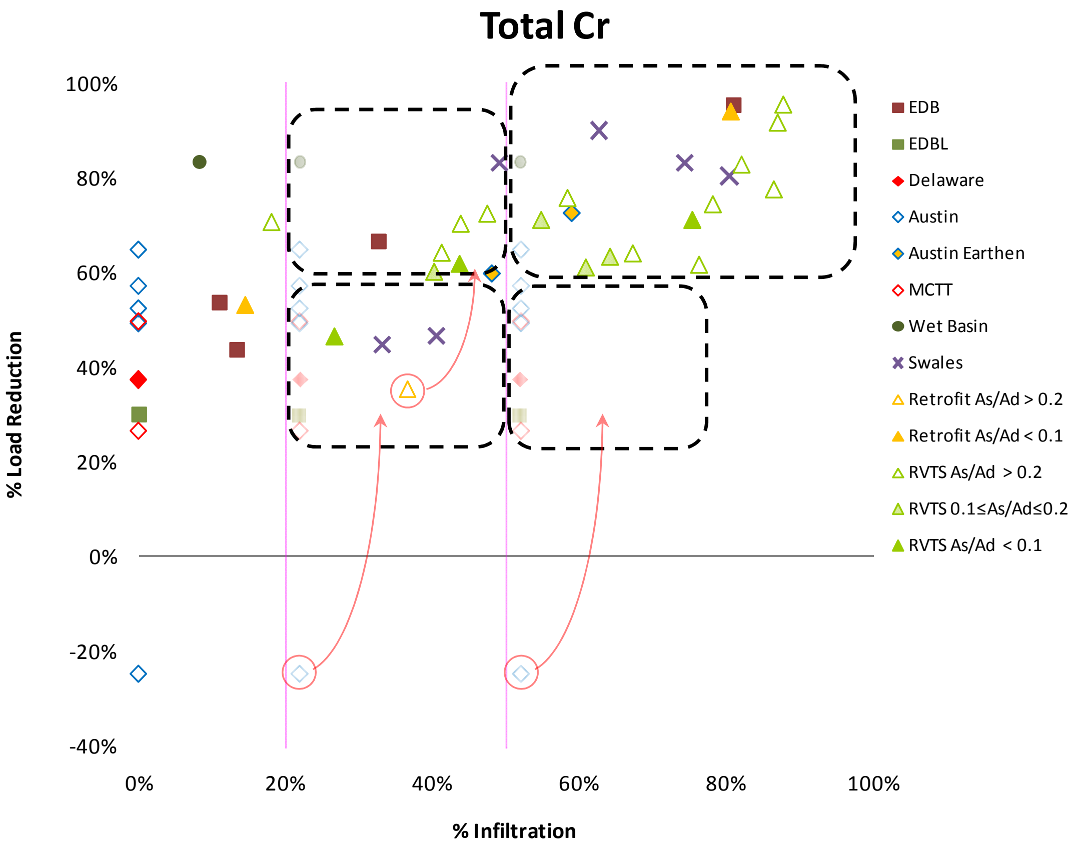


Figure 3.13 Total Chromium Removal and Infiltration

<u>*Special cases*</u>

For reference, the statewide median total chromium concentration for highway runoff is 5.89 µg/L (Caltrans, 2009a).

Austin filter – concrete. The load reduction for lined Austin filters load removals spanned both effectiveness groups, so to be conservative, both BMPs are classified as "less effective." This is despite one location that exported total chromium. The median influent concentration, however, was only 24 percent of the statewide highway median concentration. In addition, that location showed concentration reductions in eight of nine storms. The negative removal is the result of a single atypical event in which the concentration increased from 1.1 µg/L to 4.7 µg/L. Still, even though that event increased concentrations by over 300 percent, the export concentration was still below the statewide highway median concentration. Positive load reduction is expected for typical highway concentrations. The adjusted load reduction in Figure 3.13 is shown by a red circle and a curved arrow.

Swales. The load reductions for swales between 20 and 50 percent infiltration span both effective performance categories. Two of the three swales had load reductions less than 60 percent, so swales will remain classified as "less effective."

Strips $A_S/A_D < 0.1$ (infiltration between 20 and 50 percent). These strips span both positive load reduction categories. For moderate infiltration, one strip had load reduction above 60 percent, and one strip had load reduction below 60 percent. Influent was typical in both cases, so to be conservative, strip $A_S/A_D < 0.1$ will remain classified as "less effective."

Strips $A_S/A_D > 0.2$ (infiltration between 20 and 50 percent). One of four of these strips showed removal below 60 percent. The less effective strip had a median influent concentration of 1.8 µg/L, which was 31 percent of the median statewide highway concentration. This could have adversely affected the percent reduction. Because load removal under typical highway conditions was above 60 percent, strip $A_S/A_D > 0.2$ is reclassified as "more effective." The adjusted load reduction in Figure 3.13 is shown by a red circle and a curved arrow.

Ranking

The load rankings for total chromium are shown in Table 3.15. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.13.

Table 3.15 BMP Load Rankings for Total Chromium

Constituent	Infiltration <20% (Concentration)	Infiltration 20 to 50%	Infiltration >50%
Chromium (total)	**Tier 1 – More Effective**		
	Wet basin (MCTT) Delaware filter Austin filter EDB Swale	Austin filter – earthen EDB (Strip – $A_S/A_D > 0.2$) Strip – $0.1 < A_S/A_D < 0.2$ Wet basin	Austin filter – earthen EDB Strip – all Swale Wet basin
	Tier 2 – Less Effective		
	Strip – HRT>5	(Austin filter – concrete) Delaware filter EDB – lined MCTT Strip – $A_S/A_D < 0.1$ Swale	(Austin filter – concrete) Delaware filter EDB – lined MCTT
	Tier 3 – Not Effective		
	EDB – lined Strip – HRT<5	---	---

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

3.2.12 Nickel, Total

Figure 3.14 shows the overall total nickel load removal and infiltration efficiencies for each BMP installation.

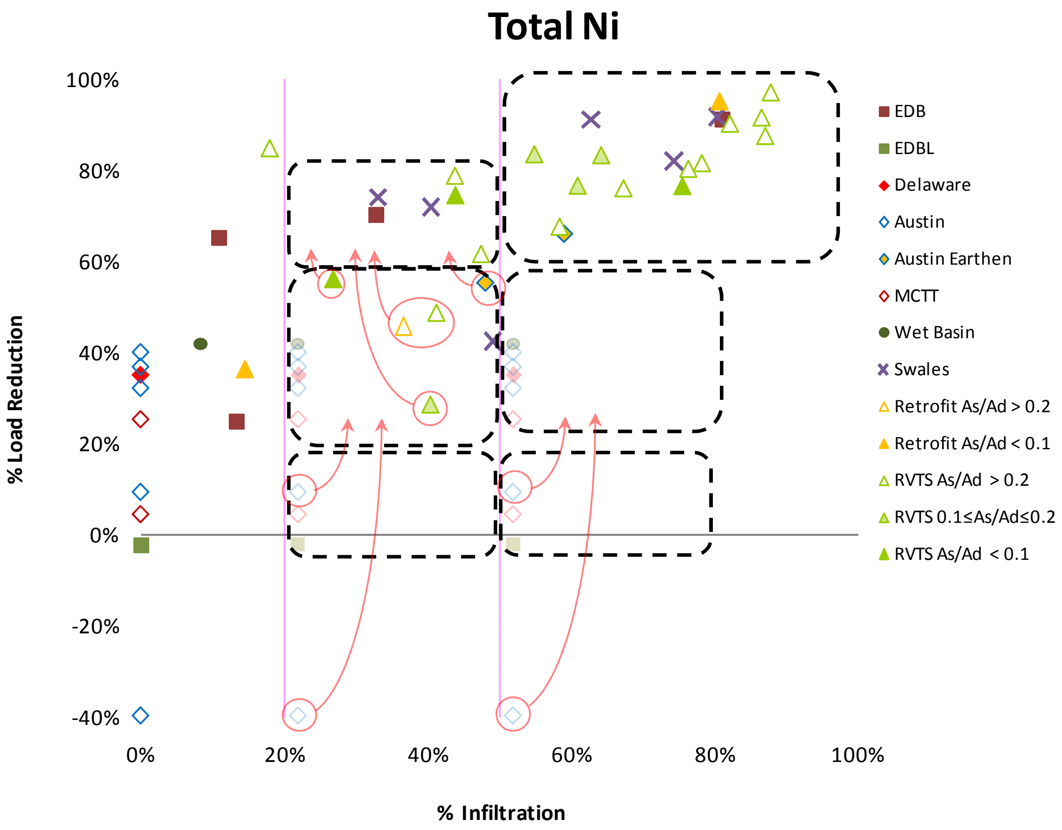


Figure 3.14 Total Nickel Removal and Infiltration

<u>*Special Cases*</u>

For reference, the statewide median total nickel concentration for highway runoff is 7.27 µg/L (Caltrans, 2009a).

MCTT. See commentary on concentration performance groupings (Table 3.1). Though one location demonstrated effective load reduction, this was based on only one positive load reduction out of four storm events. This could be because the other three events had low influent concentrations that ranged from the reporting limit (2 µg/L) to 4.5 µg/L, which all are well below the median statewide highway concentration. However, one data point is insufficient evidence to justify a reclassification. To be conservative, the MCTT remains classified as “not effective.”

Austin filter – concrete. Three of five locations showed significant load reduction. One location had negative load reduction, but the median influent value was 2.3 µg/L, which was only 32 percent of the median statewide highway concentration. This could have adversely affected the percent reduction. Further, the negative reduction is due to a single event in which the concentration increased from the reporting limit (2 µg/L) to 5.2 µg/L, which was still less than the median statewide highway concentration. Load reduction is expected for more typical runoff concentrations. Another location had load reduction of 9 percent and a median influent concentration of 4.2 µg/L. Though substantially lower than the median statewide highway concentration, other filters with similar influent concentrations performed better. But because most of the concrete Austin filters had load reduction above 60 percent, they are reclassified as "less effective."

Austin filter − earthen. The filter in the 20 percent to 50 percent infiltration range had load removal just under 60 percent, but the median influent was 2.2 µg/L, which is only 30 percent of the statewide median concentration. This could have adversely affected the percent reduction. Consequently, the earthen Austin filter for the marginal infiltration range is reclassified in the "more effective" group. The adjusted data point is shown in Figure 3.14 with a red circle and curved arrow.

Strip − all (infiltration between 20 and 50 percent). For marginal infiltration, four of seven strips had performance in the "less effective" range, but their median influent concentrations ranged from 2 µg/L to 4.5 µg/L while the statewide highway median was 7.27 µg/L. The other three strips had median influent concentrations above 5 µg/L, which probably contributed to higher percent load reductions. This concentration is still less than the median statewide highway concentrations. Since strips had load removal above 60 percent for influent conditions below the highway median concentration, strips are reclassified as "more effective," even though the majority of strips had load removal less than 60 percent. The adjusted load reductions are shown in Figure 3.14 with red circles and curved arrows.

Ranking

The load rankings for total nickel are shown in Table 3.16. The rankings for infiltration less than 20 percent are based on the concentration results from the statistical analysis using the mixed-model. The rankings for infiltration ranges between 20 and 50 percent and above 50 percent are based on the groups shown in Figure 3.14.

Table 3.16 BMP Load Rankings for Total Nickel

<table>
<tr><th>Constituent</th><th>Infiltration <20% (Concentration)</th><th>Infiltration 20 to 50%</th><th>Infiltration >50%</th></tr>
<tr><td rowspan="6">Nickel (total)</td><td colspan="3">Tier 1 -- More Effective</td></tr>
<tr><td>Strip – HRT<5
(Delaware filter)
EDB
Wet basin
Swale
Strip – HRT>5</td><td>(Austin filter – earthen)
EDB
(Strip – all)
Swale</td><td>Austin filter – earthen
EDB
Strip – all
Swale</td></tr>
<tr><td colspan="3">Tier 2 -- Less Effective</td></tr>
<tr><td>(Austin filter)</td><td>(Austin filter – concrete)
Delaware filter
Wet basin</td><td>(Austin filter – concrete)
Delaware filter
Wet basin</td></tr>
<tr><td colspan="3">Tier 3 -- Not Effective</td></tr>
<tr><td>EDB – lined
MCTT</td><td>EDB – lined
MCTT</td><td>EDB – lined
MCTT</td></tr>
</table>

Notes:

- Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses are special cases that are discussed in the text.
- Strips are classified two ways. For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used because of its relationship to infiltration. For concentration and load removal where infiltration was small, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- When siting conditions are met, infiltration BMPs (basin and trenches) are considered to have superior performance to all other BMPs that do not infiltrate all of the design volume or flow.

4 Summary and Qualifiers

This chapter contains a summary of the work accomplished and several qualifiers that should be kept in mind when applying these results.

4.1 Summary

The goal of this project was to create a performance-based ranking of BMPs based on field data collected to date. A mixed-model statistical analysis was applied to data obtained from the Retrofit Pilot Program, the District 2 Sand Filter Study, and the RVTS Studies. The statistical analysis was designed to compare the BMPs on an equal basis (i.e., the same influent concentration), and to create a statistically defensible ranking that properly differentiates those BMPs with different performance levels and avoids differentiating those with essentially equivalent performance. Comparing BMPs on an equal basis is difficult since BMPs were not tested under the same conditions. To compare them on an equal basis, the results were extrapolated to more typical runoff conditions (the median loads and concentrations) in the statistical analysis.

The statistical approach was partially successful for concentration rankings but not for load rankings. The data variability caused statistical uncertainties in the extrapolations. The result for concentration analyses was that BMPs were clustered into relatively large groups where performance was indistinguishable. It was nearly impossible to base rankings on statistical differences. The load analysis was worse, with almost no statistical distinction among BMPs.

Post-statistical analysis was needed to develop ranked tiers of BMP performance. The post-statistical analyses assigned all the BMPs into three tiers: more effective, less effective, and not effective. The post-statistical analysis for concentration involved regrouping BMPs into performance categories based on the test conditions, performance variability, and sample size. For load, the post-statistical analysis used a data-based site-by-site assessment of total measured load reduction over the entire monitoring period (sum of loads method).

Through this analysis the critical importance of infiltration in load reduction was highlighted. Accordingly, two different BMP load-based rankings were created, one for marginal infiltration (20 to 50 percent) and another for substantial infiltration (greater than 50 percent). At locations where at least 20 percent infiltration cannot be obtained, the concentration ranking is suggested.

BMPs are ranked according to their performance in reducing concentrations or loads, depending on regulations, for each of the 12 TDCs. Concentration-based rankings are presented in Table 4.1 and should be used when minimizing the average discharge concentration is desired. Load rankings are presented in Table 4.2 and they vary for different levels of BMP infiltration (infiltration 20-50%, and infiltration >50%). The tables are presented at the end of this section.

The designer should consider the feasible BMPs from the highest treatment tier. Ideally, infiltration BMPs are considered first. They are in Tier 0, which is so titled because of the assumption[5] of superior treatment without direct comparison to other BMPs. Treatment Tier 1 would be considered next, if Tier 0 BMPs are not feasible. Only after determining that none of the Tier 1 BMPs are feasible should the designer move to Tier 2. For the TDC in question, Tier 3 BMPs have no reliable or substantial water quality benefit. To emphasize their inadequate level of performance, Tier 3 is separated from the other tiers with a double line and a dark red font is used for the text.

For concentration-based rankings in Table 4.1, the BMPs are ordered within the tiers from lowest predicted effluent to highest, but there is insufficient statistical evidence to base BMP selection on that order. Table 4.1 can also be used for load-based regulations when infiltration from earthen BMPs will not have a substantial impact on load reduction (infiltration < 20 percent).

Within Table 4.2, it is possible that a particular site will result in BMPs that fall within different infiltration categories. The BMPs are listed alphabetically within the treatment tiers. To use Table 4.2, the designer would first identify the level of infiltration for the earthen BMPs according to site conditions and proposed BMP geometries. BMP geometries can affect the level of infiltration by changing the area of the soil-water interface. For example, for the same water quality volume, a shallow basin will infiltrate more than a deep basin. The designer would then choose among BMPs within Tier 1 across both infiltration categories. If no Tier 1 BMPs are feasible, the designer would select from Tier 2 BMPs. An example is presented in Appendix E.

The rankings in Tables 4.1 and 4.2 are specific to each of the 12 TDCs. These tables can be useful for 303(d) situations where the constituent of primary concern is identified. Two approaches to creating an "MEP ranking" that reflects the general treatment capabilities of BMPs for a variety of TDCs are described in Appendix B. Appendix D (on the CD) contains a spreadsheet tool for implementing one of the two MEP approaches.

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[5] Infiltration basins and trenches are in Tier 0 because infiltration of the design storm will comply with surface water standards, whether concentration-based or load-based.

Table 4.1 Concentration-based BMP Ranking for Target Design Constituents

	Concentration-Based Ranking[a]	
	Concentration-Based Regulation[b]	**Load-based Regulation where Infiltration <20%[c]**
TSS		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Wet basin MCTT Delaware filter Austin filter Strip – HRT>5	Wet basin MCTT Delaware filter Austin filter Strip – HRT>5
Tier 2	Strip – HRT<5 EDB Swale	Strip – HRT<5 EDB Swale
Tier 3	EDB – lined	EDB – lined
Phosphorus (total) [f]		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Delaware filter Austin filter EDB Strip – HRT<5	Delaware filter Austin filter EDB Strip – HRT<5
Tier 2	---	---
Tier 3	EDB – lined MCTT Wet basin Strip – HRT>5 Swale	EDB – lined MCTT Wet basin Strip – HRT>5 Swale
Nitrogen (total) [g]		
Tier 0	N.A.	
Tier 1	N.A.	---
Tier 2	N.A.	(Austin filter – both) EDB EDB – lined Wet basin
Tier 3	N.A.	Delaware MCTT Strip – all (Swale)

(Table 4.1 continued)

	Concentration-Based Ranking[a]	
	Concentration-Based Regulation[b]	**Load-based Regulation where Infiltration <20%[c]**
Copper (total)		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Strip – HRT<5 Wet basin (MCTT) Delaware filter	Strip – HRT<5 Wet basin (MCTT) Delaware filter
Tier 2	Austin filter Strip – HRT>5 Swale EDB	Austin filter Strip – HRT>5 Swale EDB
Tier 3	---	---
Copper (dissolved)		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Strip – HRT<5 (Delaware filter) (MCTT) Strip – HRT>5	Strip – HRT<5 (Delaware filter) (MCTT) Strip – HRT>5
Tier 2	Wet basin Swale	Wet basin Swale
Tier 3	EDB – lined Austin filter EDB	EDB – lined Austin filter EDB
Lead (total)		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Wet basin Austin filter MCTT Delaware filter Strip – HRT<5 Strip – HRT>5	Wet basin Austin filter MCTT Delaware filter Strip – HRT<5 Strip – HRT>5
Tier 2	Swale EDB	Swale EDB
Tier 3	EDB – lined	EDB – lined

(Table 4.1 continued)

	Concentration-Based Ranking[a]	
	Concentration-Based Regulation[b]	**Load-based Regulation where Infiltration <20%[c]**
Lead (dissolved)		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Delaware filter (MCTT) Strip – HRT<5 Austin filter Wet basin EDB Strip – HRT>5	Delaware filter (MCTT) Strip – HRT<5 Austin filter Wet basin EDB Strip – HRT>5
Tier 2	Swale	Swale
Tier 3	EDB – lined	EDB – lined
Zinc (total)		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Delaware filter MCTT Wet basin Strip – HRT<5	Delaware filter MCTT Wet basin Strip – HRT<5
Tier 2	Swale Austin filter Strip – HRT>5 EDB	Swale Austin filter Strip – HRT>5 EDB
Tier 3	EDB – lined	EDB – lined
Zinc (dissolved)		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	MCTT Wet basin Austin filter	MCTT Wet basin Austin filter
Tier 2	Strip – HRT>5 Swale Strip – HRT<5 Delaware filter	Strip – HRT>5 Swale Strip – HRT<5 Delaware filter
Tier 3	EDB – lined EDB	EDB – lined EDB

(Table 4.1 continued)

	Concentration-Based Ranking[a]	
	Concentration-Based Regulation[b]	**Load-based Regulation where Infiltration <20%**[c]
Cadmium (total)[h]		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Strip – HRT<5 Wet basin Austin filter Delaware filter Strip – HRT>5 Swale	Strip – HRT<5 Wet basin Austin filter Delaware filter Strip – HRT>5 Swale
Tier 2	EDB	EDB
Tier 3	EDB – lined MCTT	EDB – lined MCTT
Chromium (total)[h]		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Wet basin (MCTT) Delaware filter Austin filter EDB Swale	Wet basin (MCTT) Delaware filter Austin filter EDB Swale
Tier 2	Strip – HRT>5	Strip – HRT>5
Tier 3	EDB – lined Strip – HRT<5	EDB – lined Strip – HRT<5

(Table 4.1 continued)

	Concentration-Based Ranking[a]	
	Concentration-Based Regulation[b]	**Load-based Regulation where Infiltration <20%[c]**
Nickel (total)[d]		
Tier 0	Infiltration basins[d] Infiltration trenches[d,e]	
Tier 1	Strip – HRT<5 (Delaware filter) EDB Wet basin Swale Strip – HRT>5	Strip – HRT<5 (Delaware filter) EDB Wet basin Swale Strip – HRT>5
Tier 2	(Austin filter)	(Austin filter)
Tier 3	EDB – lined MCTT	EDB – lined MCTT

a. Within tiers 1, 2, and 3, BMPs are sorted from lowest to highest average effluent concentration as estimated from the mixed-model statistical analysis.

b. This ranking is intended for concentration-based regulations that require maximum reduction of average discharge (effluent) concentration. If there is a not-to-exceed concentration standard, this analysis is not appropriate and a frequency analysis on exceedances may be more appropriate.

c. When there are no concentration-based standards, these rankings should only be consulted when there are no earthen BMPs that will achieve greater than 20% infiltration.

d. If minimizing average effluent concentrations is a regulatory requirement, infiltration BMPs should be considered first because complete elimination of a discharge will comply with concentration-based requirements.

e. Infiltration trenches often require pre-treatment to reduce the risk of clogging failures, unless site conditions show low sediment loads and large separation from normal high groundwater.

f. Strip classifications for phosphorus assume that salt grass is not planted. Pilot strips and swales planted with salt grass did not effectively reduce phosphorus.

g. For total nitrogen, there is no concentration-based ranking. The ranking shown for Infiltration < 20% is based on the sum of loads method.

h. Proposed New TDCs.

General Notes

- Strips are classified in two ways. For concentration-based rankings, the hydraulic residence time (HRT) was used because of its relationship to surface treatment processes, especially sedimentation. HRT<5 and HRT>5 mean hydraulic residence times less than and greater than 5 minutes.
- BMPs shown in parentheses involved either exceptions to these rules or other judgments that are explained in Table 3.1.

Table 4.2 Load-based BMP Ranking for Target Design Constituents

	Load-Based Ranking[a]	
	Infiltration 20 to 50%	**Infiltration >50%**
TSS		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Austin filter – both[c] Delaware filter[c] EDB MCTT[c] Strip – all Swale Wet basin[c]	Austin filter – both[c] Delaware filter[c] EDB MCTT[c] Strip – $A_S/A_D > 0.2$ Strip $0.1 < A_S/A_D < 0.2$ (Strip – $A_S/A_D < 0.1$) Swale Wet basin[c]
Tier 2	---	---
Tier 3	EDB – lined[c]	EDB – lined[c]
Phosphorus (total)[d]		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Austin filter – earthen EDB	Austin filter – earthen EDB (Strip – $A_S/A_D>0.2$)
Tier 2	Austin filter – concrete[c] Delaware filter[c] Strip – $A_S/A_D>0.2$ Strip – $0.1<A_S/A_D<0.2$ (Strip – $A_S/A_D <0.1$) (Swale) Wet basin[c]	Austin filter – concrete[c] Delaware filter[c] Strip – $A_S/A_D<0.1$ (Strip – $0.1<A_S/A_D<0.2$) (Swale) Wet basin[c]
Tier 3	EDB – lined[c] (MCTT) [c]	EDB – lined[c] (MCTT) [c]
Nitrogen (total)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	---	EDB Strip – all Swale
Tier 2	(Austin filter – concrete)[c] Austin filter – earthen EDB EDB – lined[c] Swale Wet basin[c]	(Austin filter – concrete)[c] Austin filter – earthen EDB – lined[c] Wet basin[c]
Tier 3	Delaware filter[c] MCTT[c] (Strip – all)	Delaware filter[c] MCTT[c]

(Table 4.2 continued)

	Load-Based Ranking[a]	
	Infiltration 20 to 50%	**Infiltration >50%**
Copper (total)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	(Austin filter – earthen) EDB Strip – $A_S/A_D >0.2$ Swale Wet basin[c]	Austin filter – earthen EDB (Strip – $A_S/A_D > 0.2$) Strip – $A_S/A_D < 0.1$ Strip – $0.1<A_S/A_D<0.2$ Swale Wet basin[c]
Tier 2	Austin filter – concrete[c] Delaware filter[c] EDB – lined[c] MCTT[c] Strip – $A_S/A_D <0.1$ Strip – $0.1<A_S/A_D<0.2$	Austin filter – concrete[c] EDB – lined[c] Delaware filter[c] MCTT[c]
Tier 3	---	---
Copper (dissolved)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	(Strip – $A_S/A_D > 0.2$)	Austin filter – earthen EDB Strip – all Swale
Tier 2	(Austin filter – earthen) Delaware filter[c] EDB (MCTT) [c] Strip – $0.1 < A_S/A_D < 0.2$ (Strip – $A_S/A_D < 0.1$) Swale Wet basin[c]	Delaware filter[c] (MCTT) [c] Wet basin[c]
Tier 3	Austin filter – concrete[c] EDB – lined[c]	Austin filter – concrete[c] EDB – lined[c]

(Table 4.2 continued)

	Load-Based Ranking[a]	
	Infiltration 20 to 50%	**Infiltration >50%**
Lead (total)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Austin filter – concrete[c] (Austin filter – earthen) Delaware filter[c] EDB MCTT[c] Strip – $A_S/A_D > 0.2$ (Strip – $0.1 < A_S/A_D < 0.2$) Strip –$A_S/A_D < 0.1$ Swale Wet basin[c]	Austin filter – both[c] Delaware filter[c] EDB MCTT[c] Strip – all Swale Wet basin[c]
Tier 2	EDB – lined[c]	EDB – lined[c]
Tier 3	---	---
Lead (dissolved)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Swale Wet basin[c]	EDB (Strip – $A_S/A_D > 0.2$) Strip – $0.1 < A_S/A_D < 0.2$ Strip –$A_S/A_D < 0.1$ Swale
Tier 2	(Austin filter – concrete) [c] Austin filter – earthen Delaware filter[c] EDB (MCTT) [c] (Strip – $A_S/A_D > 0.2$) Strip – $0.1 < A_S/A_D < 0.2$ Strip –$A_S/A_D < 0.1$	(Austin filter – concrete) [c] Austin filter – earthen Delaware filter[c] (MCTT) [c] Wet basin[c]
Tier 3	EDB – lined[c]	EDB – lined[c]

(Table 4.2 continued)

	Load-Based Ranking[a]	
	Infiltration 20 to 50%	**Infiltration >50%**
Zinc (total)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Austin filter – both[c] Delaware filter[c] EDB MCTT[c] Strip – $A_S/A_D > 0.2$ (Strip – $0.1 < A_S/A_D < 0.2$) Strip –$A_S/A_D < 0.1$ Swale Wet basin[c]	Austin filter – both[c] Delaware filter[c] EDB MCTT[c] Strip – all Swale Wet basin[c]
Tier 2	EDB – lined[c]	EDB – lined[c]
Tier 3	---	---
Zinc (dissolved)		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Austin filter – earthen Delaware filter[c] MCTT[c]	Austin filter – earthen Delaware filter[c] EDB MCTT[c] Strip – all Swale
Tier 2	Austin filter – concrete[c] EDB EDB – lined[c] (Strip – all) Swale	Austin filter – concrete[c] EDB – lined[c]
Tier 3	Wet basin[c]	Wet basin[c]

(Table 4.2 continued)

	Load-Based Ranking[a]	
	Infiltration 20 to 50%	**Infiltration >50%**
Cadmium (total)[e]		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Delaware filter[c] EDB Swale Wet basin[c]	Austin filter – earthen Delaware filter[c] EDB Strip – all Swale Wet basin[c]
Tier 2	(Austin filter – concrete) [c] Austin filter – earthen Strips – all	(Austin filter – concrete) [c]
Tier 3	EDB – lined[c]	EDB – lined[c]
Chromium (total)[e]		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	Austin filter – earthen EDB (Strip – $A_S/A_D > 0.2$) Strip – $0.1 < A_S/A_D < 0.2$ Wet basin	Austin filter – earthen EDB Strip – all Swale Wet basin
Tier 2	(Austin filter – concrete) [c] Delaware filter[c] EDB – lined[c] MCTT[c] Strip – $A_S/A_D < 0.1$ Swale	(Austin filter – concrete) [c] Delaware filter[c] EDB – lined[c] MCTT[c]
Tier 3	---	---

(Table 4.2 continued)

	Load-Based Ranking[a]	
	Infiltration 20 to 50%	**Infiltration >50%**
Nickel (total)[e]		
Tier 0		Infiltration basins Infiltration trenches[b]
Tier 1	(Austin filter – earthen) EDB (Strip – all) Swale	Austin filter – earthen EDB Strip – all Swale
Tier 2	(Austin filter – concrete) [c] Delaware filter[c] Wet basin[c]	(Austin filter – concrete) [c] Delaware filter[c] Wet basin[c]
Tier 3	EDB – lined[c] MCTT[c]	EDB – lined[c] MCTT[c]

a. For load removal, Tier 1 = greater than 60% treatment efficiency; Tier 2 = 20-60% treatment efficiency; Tier 3 = less than 20% treatment efficiency (same as concentration alone). BMPs shown in parentheses involved either exceptions to these rules or other judgments that are explained in Table 3.1. Within tiers, BMPs are sorted alphabetically.

b. Infiltration trenches often requires pre-treatment to reduce the risk of clogging failures, unless site conditions show low sediment loads and large separation from normal high groundwater.

c. Lined BMPs are shown in the columns where substantial infiltration occurs for earthen BMPs. Though these BMPs never infiltrate, regardless of site conditions, they are shown in these columns solely to allow the user to more easily compare the load removal of lined BMPs to those that infiltrate.

d. Strip classifications for phosphorus assume that salt grass is not planted. Pilot strips and swales planted with salt grass did not effectively reduce phosphorus.

e. Proposed New TDCs

General Notes

- For load removal, the ratio of the strip area to the drainage area (A_S/A_D) was used to classify strips because of the relationship of the ratio to infiltration and because it is easy to calculate.

4.2 Qualifiers

4.2.1 BMP Selection Factor

The BMP rankings proposed in this document are based solely on constituent reduction performance. General factors that are not addressed in this analysis include safety, cost, and ease of maintenance.

4.2.2 Limitations in Statewide Interpretation of Water Quality Data

This report draws from the most comprehensive stormwater dataset directly collected by a single agency. Despite an unmatched BMP monitoring program, there is still difficulty in developing standard recommendations that are applicable for all project-specific circumstances in a state as large and diverse as California. The ranking methodologies presented here are based on comparing data collected from different places at different times. The validity of these comparisons is affected by the limited number of representative BMP test locations. For instance, several BMPs were not tested at highway locations as shown in Table 4.3.

Facility type can have a strong influence on whether the test location is relatively cleaner or dirtier than other locations. And even among highway locations, prior work by Caltrans has found that average annual daily traffic (AADT) and ecoregion play a significant role in highway runoff concentrations (Caltrans, 2009a). Besides influent concentrations, there are many other BMP test conditions that could affect performance, such as soil type, vegetation, and antecedent storm conditions.

It is unreasonable to expect that every BMP would be tested under all Caltrans conditions, because of limitations including time, budget, space constraints, safe access, construction conflicts, and space for monitoring equipment. Nevertheless, not testing BMPs for all conditions dictates the use of numeric methods and professional judgment to extrapolate certain observations to typical highway applications. From a statistical perspective, because the important site conditions were not sufficiently controlled among the BMP test locations, statistical tests could not always support these professional judgments. An improved mixed-model could be developed to handle the subjective adjustments needed in the sum of loads method.

Table 4.3 Select Site Characteristics for BMP Studies

	Facility Type[a]			Average Annual Rainfall		
BMP Type	**Hwy**	**P&R**	**MS**	**<15”**	**15 - 30”**	**>30”**
Austin Sand Filters, lined, full-sedimentation	✓			✓	✓	
Austin Sand Filters, unlined, partial-sedimentation	✓					✓
Austin Sand Filters, unlined, full-sedimentation			✓			✓
Delaware Sand Filters			✓	✓		
Detention Basins, lined	✓			✓		
Detention Basins, unlined	✓			✓		
Multi-Chambered Treatment Train (MCTT)		✓		✓	✓	
Strips	✓		✓	✓	✓	✓
Swales	✓			✓		
Wet basins	✓			✓		

[a] Facility Types: MS = maintenance station; P&R = park and ride; Hwy = highway

A factor limiting the precision of these rankings is the natural variability of the data from storm to storm. Because of these variations, the regressions that provided the basis of the performance comparisons are often not very tight, as evidenced by low r^2 values. This isn’t failure to exercise care in collecting the data. It is, however, reflective of the fact that the data sets are inherently “noisy,” and that relationships between influent and effluent values are not always linear.

The data sets used by UCD for the statistical analysis were re-examined in the process of implementing the sum of loads methodology. A number of data problems were found, such as suspicious concentration outliers and flow equipment failures being interpreted as complete infiltration. These problems and how they were corrected are tabulated in Appendix A. Because this happened after the UCD contract expired, these changes were not reflected in the statistical analysis. Consequently, the data sets used in the concentration ranking and in the load ranking are somewhat different.

4.2.3 Not Appropriate for all Concentration Regulations

The concentration rankings are not appropriate for all concentration-based regulations. If there is a specific discharge standard, this analysis should not be used because the frequency of exceedance of a particular concentration cannot be gleaned from the results of the statistical method employed. For example, a concrete-lined sand filter may have an average discharge concentration that is lower than a strip, but the strip will discharge fewer events per year due to infiltration of small storms. Consequently, the frequency with which either BMP exceeds a numeric standard depends on the standard. Therefore the superior BMP cannot be determined unless the numeric standard is known. If, however, the regulations only require the minimization of average discharge concentrations regardless of any particular concentration standard, then the rankings herein are appropriate.

4.2.4 Application of Results to Clean Sites

Since the results in this report are in the context of typical Caltrans concentrations, the results are not applicable to particularly clean sites. Generally, but not without exception, cleaner sites tend to be park-and-ride lots, North Coast facilities, and sites with low AADT per lane (Caltrans, 2004; 2009). For sites with lower runoff concentrations, differences in performance among BMPs will be less noticeable. In the case of very clean runoff, infiltration may be the only reliable pollutant reduction mechanism and BMPs could be ranked solely on infiltration capacity.

4.2.5 BMP Selection, Not Site-Specific Prediction

The rankings in this document arose from estimates of BMP performance based on existing data set. These estimates are thought to be adequate for ranking BMPs in broad categories but they should not be used to make predictions about effluent quality or load removal for a particular project. Site-specific conditions exert a large influence on BMP performance. Infiltration, for instance, greatly affects load reduction. Likewise, effluent concentration is affected by influent concentration, which varies from site to site. Variations in BMP design also influence performance. For example, hydraulic loading on filters affects treatment efficiency as shown in the Tahoe small-scale testing program (Caltrans, 2009b). An associated issue is that some standard design methods and parameters have evolved since the pilot studies were conducted. A case in point is the allowable drainage time for EDBs, which can range from 24 to 72 hours (Caltrans, 2007). The EDB data in this report came from facilities designed for 72-hour drain times only

(Caltrans, 2004). So the existing data set might not be a good predictor of future BMP installations.

All of these factors contribute to the decision to place BMPs into few but broad rankings (i.e., more effective, less effective, not effective). The existing data set is thought to be adequate to support these groupings. Nevertheless, the rankings shown here are not predictive of effluent quality, particularly effluent quality at any particular site.

Further, the performance tiers for concentration and load are not equivalent. For the concentration rankings, the tiers are defined by relative differences in effluent quality, independent of any set level of removal efficiency. Tier 1 BMPs are expected to have lower effluent concentrations than Tier 2 BMPs. For the load-based rankings, the tiers correspond to specific levels of load reduction (below 20%, 20 to 60%, and above 60%).

4.2.6 Needed: Infiltration Estimation

This report does not describe how to estimate infiltration capacity. Infiltration is dependent on many factors, but soil, climate, and BMP design are certainly key factors. There are hydrologic models available for such estimates.

4.2.7 The Affects of BMP Design on Using the Load-based Ranking

Different types of BMPs at a given site location will often have differing levels of infiltration. The performance tiers for a single infiltration category (arranged in columns in Table 4.2) can only be applied where all BMPs at a given site fit that infiltration category. A more careful look at the performance categories is needed when BMPs fall into different infiltration categories for a given site. An example of this condition is presented in Appendix E.

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Appendix A is available on the enclosed CD

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APPENDIX B

Approaches to an MEP Ranking

In practice, the choice of BMPs based on ranking of treatments of individual TDCs will be somewhat unusual. Where a TMDL regulation is in place or impending, the ability of a BMP to remove a particular constituent is important. In most cases, however, MEP will be the design criterion. This section presents two approaches to ranking BMPs for MEP uses.

MEP Based on TSS Reduction

One approach to sorting through the multiple TDC rankings is to choose one constituent to serve as a surrogate measure of treatment effectiveness. The obvious candidate constituent is TSS because many of the other constituents have significant particulate fractions. The theory is that a BMP that effectively removes TSS will also effectively remove other constituents. The data sets support this approach to a greater or lesser degree, depending on the constituent. An example of a good correlation is phosphorus, seen in Figure B.1. Another example is shown in Figure B.2 where the removal of both total and dissolved copper are shown as a function of TSS removed.

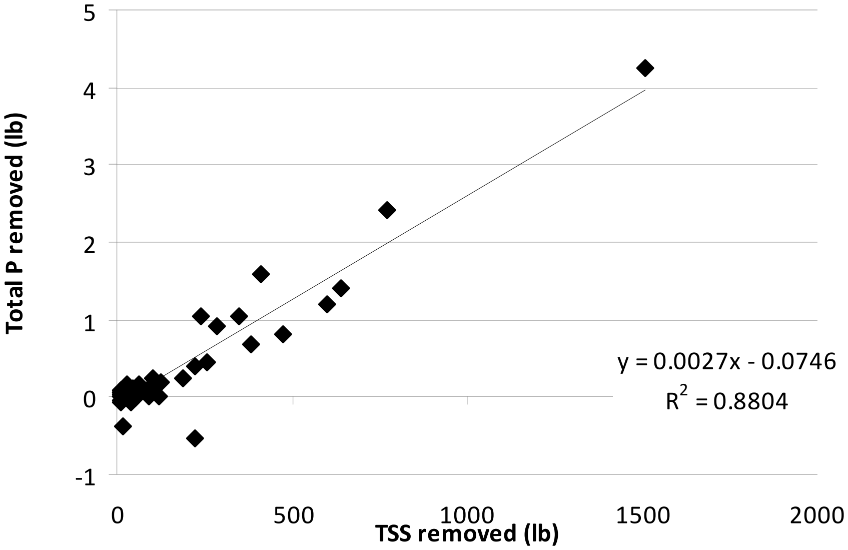

Figure B.1 Linear regression between TSS removed and total-P removed by all BMPs

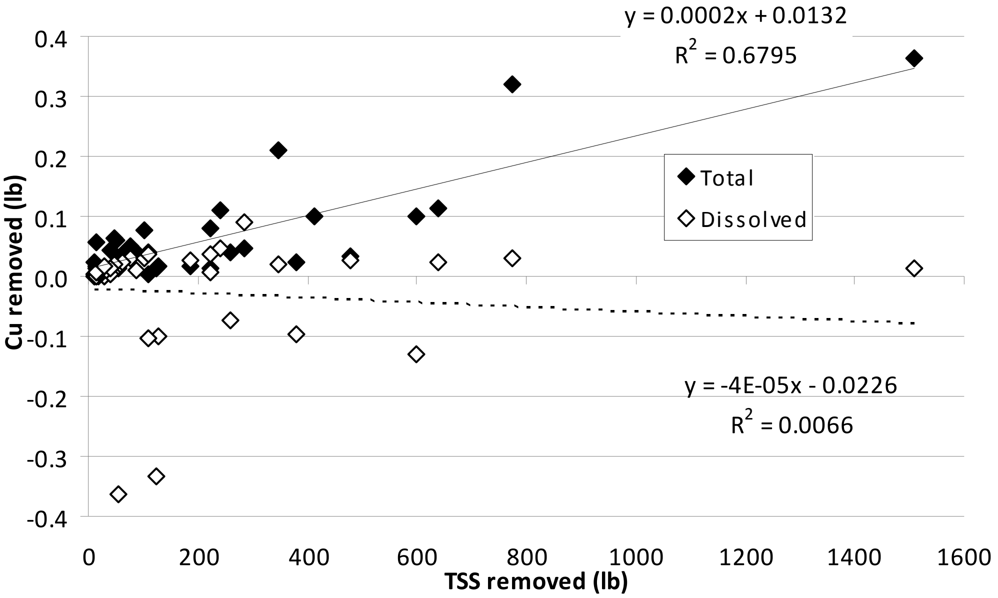

Figure B.2 Linear regressions between TSS removed and total and dissolved copper removed by all BMPs

Regressions were performed for all the TDCs. Results are summarized in Table B.1. The key result is the coefficient of determination (r^2) which is the square of the correlation coefficient between the observed and modeled (predicted) data values. As expected, the correlations between TSS and dissolved constituents were very poor. For the "total" constituents, however, the correlations were quite reasonable, ranging from 0.325 to 0.880 with a mean of 0.61. Moreover, all of the slopes were positive. Thus, improving TSS treatment would also improve the treatment of other constituents. From this point of view, an argument can be made that TSS is a reasonable surrogate parameter for general treatment effectiveness.

Table B.1 Parameters of Linear Regressions Between TSS Removed and Other Constituents Removed by all BMPs

Constituent	Slope (lb/lbTSS)	Intercept	r^2
Existing TDCs			
Phosphorus (total)	0.0027	0.0746	0.880
Nitrogen (total)	0.0069	0.8765	0.597
Copper (total)	0.0002	0.0132	0.680
Copper (dissolved)	$-4x10^{-5}$	0.0226	0.007
Lead (total)	0.005	0.0066	0.568
Lead (dissolved)	$-6x10^{-6}$	0.0147	0.006
Zinc (total)	0.0024	0.1039	0.727
Zinc (dissolved)	0.0001	0.1058	0.046
Proposed TDCs			
Cadmium (total)	$4x10^{-6}$	0.0002	0.602
Chromium (total)	$1x10^{-5}$	0.0028	0.325
Nickel (total)	$2x10^{-5}$	0.0027	0.488

MEP Based on Treatment Scores

An alternative approach is to develop a more general metric that reflects the treatment performances of a BMP for all TDCs. The BMPs could then be ranked by this metric. A simple, but effective metric, a so-called "treatment score," can be created by assigning points to BMPs according to their place in the treatment tiers and then summing the points. A straight summing may not be appropriate because it would weight all TDCs equally. Weights should reflect the relative environmental impact or regulatory importance of each TDC. Metals are potential toxicants and allowable discharge concentrations are specified in the California Toxics Rule (CTR) (Caltrans, 2006b). Violating the CTR could be a cause for regulatory action. Nutrients are potential contributors to eutrophication, but there are no concentration limits that are generally enforced. TSS can cause a variety of environmental effects, but like nutrients, are generally not the subject of numerical limits. Both TSS and nutrients would be governed by narrative water quality objectives written to avoid the creation of nuisance conditions, but except for extreme cases, regulatory actions would probably only accompany a TMDL process.

An example MEP ranking is presented below. To reflect how different BMPs operate in different site conditions, three rankings – one for each of the infiltration categories presented in Section 3 – were created. The procedure for creating each ranking is the same. In this example, 2 points are assigned for Tier 1 treatment, 1 point for Tier 2, and 0 points for Tier 3 (see Table 4.1 for the tiers). The tiers and points for the Delaware filter on an "Infiltration >50%" site are shown in Table B.2.

Table B.2 Example Treatment Score Calculation for Delaware Filter on Infiltration >50% Sites

TDC	Tiers (from Table 4.1)	Points	Weights	Weighted Point Scores
TSS	1	2	0.00	0
P-total	2	1	1.00	1.00
N-total	3	0	1.00	0
Cu-total	2	1	0.75	0.75
Pb-total	1	2	0.75	1.50
Zn-total	1	2	0.75	1.50
Cd-total	1	2	0.25	0.50
Cr-total	2	1	0.25	0.25
Ni-total	2	1	0.25	0.25
Total weights for nutrients = 2.0 Total weights for metals = 3.0				Treatment score = 5.75

As noted earlier, weights should reflect environmental impact or regulatory importance. TSS was given a weight of zero because there are no firm regulatory standards. Also, the zero weight is designed to avoid double-weighting particulates, which occur as part of all the constituents. Metals were weighted as a group higher than nutrients because metals are toxic and because there are firmer regulatory standards in place. Within the metals group, copper, lead, and zinc were weighted higher than cadmium, chromium, and nickel because copper, lead, and zinc concentrations exceeded CTR values in more than 80% of Caltrans samples (Caltrans, 2006b). In contrast, cadmium, chromium, and nickel concentrations exceeded CTR standards in less than 25% of samples. Dissolved metals were not included to avoid double-counting.

The BMP rankings based on treatment scores using the weights shown above are listed in Table B.3. For sites with significant infiltration, BMPs that maximize infiltration, such as strips, swales, detention basins, and earthen filters, are favored. For sites with little infiltration, BMPs that incorporate filtration – the Delaware and Austin filters – are favored. The scores and rankings shown will change somewhat depending on the weighting factors assigned to the various TDCs. For instance, a “general metals” BMP ranking could be created by zeroing out the weights for the nonmetal constituents. A spreadsheet tool to allow exploration of different weighting schemes is included in Appendix D on the CD accompanying this report. Sample rankings based on general metals and on TSS only are included in the spreadsheet.

Table B.3 Example MEP Ranking Based on Treatment Scores

Infiltration <20% (same as concentration alone)		Infiltration 20-50%		Infiltration > 50%	
BMP	**Score**	**BMP**	**Score**	**BMP**	**Score**
Delaware filter	8.00	EDB	9.00	EDB	10.00
Strip – HRT<5	7.50	Austin filter – earthen	8.75	Strip – $A_S/A_D>0.2$	10.00
Austin filter – concrete	7.25	Wet basin	8.00	Austin filter – earthen	9.00
Austin filter – earthen	7.25	Swale	7.75	Strip – $A_S/A_D<0.1$	9.00
Wet basin	6.75	Strip – $A_S/A_D>0.2$	6.75	Strip – $0.1<A_S/A_D<0.2$	9.00
EDB	6.50	Austin filter – concrete	6.50	Swale	9.00
MCTT	5.00	Strip – $0.1<A_S/A_D<0.2$	6.00	Wet basin	7.75
Strip – HRT>5	4.25	Delaware filter	5.75	Austin filter – concrete	6.50
Swale	3.75	Strip – $A_S/A_D<0.1$	5.75	Delaware filter	5.75
EDB – lined	3.00	MCTT	4.25	MCTT	4.25
		EDB – lined	3.50	EDB – lined	3.50

Note: The treatment scores show relative effectiveness within each infiltration category. They should not be compared across categories.

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APPENDIX E

An Example Application of the Load-Based BMP Ranking for Total Phosphorus

This appendix presents a BMP selection scenario for a particular project. It demonstrates how load-based ranking can be used when earthen BMPs fit into more than one infiltration category. Phosphorus is the TDC for this example.

For load-based BMP selection, the designer must estimate how much infiltration is achievable for each earthen (unlined) BMP. Besides soil and climate, different BMP geometries (strip slope, basin depth, etc.) affect infiltration levels.

In this example, assume that shallow earthen basins and shallow earthen Austin sand filters could achieve at least 50 percent infiltration, but site constraints only allow deeper basins and filters that are not estimated to attain 50 percent infiltration. The footprint constraint also eliminates wet basins from consideration. Also assume that there is insufficient space for a wide strip (Strip – $A_S/A_D>0.2$), but moderately sized strips (Strip – $0.1<A_S/A_D<0.2$) can be built to achieve more than 50 percent infiltration. And finally, though there would obviously be the space available for smaller strips, let's say that site conditions dictate only moderate infiltration (between 20 and 50 percent).

Since there are BMPs at different infiltration levels, it is necessary to look across all infiltration categories in Table 4.2 and identify where each BMP belongs. To aid in BMP selection using Table 4.2, the designer could highlight feasible BMPs in the appropriate infiltration categories. Table B.1 is an excerpt from Table 4.2 for total phosphorus. Infiltrating BMPs are highlighted yellow in the highest infiltration category that the designer has estimated as achievable. Feasible non-infiltrating BMPs (lined BMPs) are highlighted gray in all infiltration categories because their load removal performance does not rely on infiltration. Guided by the markup of Table B.1, the designer would first consider the highlighted BMPs within the highest performance tier across both infiltration categories. In this example, the designer could select an earthen Austin sand filter or an EDB. All other BMPs are either infeasible for this site or they are less effective (in a lower performance tier). The BMPs in Tier 3 would never be selected.

Table B.1 Example Use of the BMP Ranking in Table 4.2 for a Particular Site Condition

	Load-based Ranking	
	Infiltration 20 to 50%	**Infiltration >50%**
Phosphorus (total)		
Tier 0		Infiltration basins Infiltration trenches
Tier 1	Austin filter – earthen EDB	Austin filter – earthen EDB (Strip – $A_S/A_D>0.2$)
Tier 2	Austin filter – concrete Delaware filter Strip – $A_S/A_D>0.2$ Strip – $0.1<A_S/A_D<0.2$ (Strip – $A_S/A_D <0.1$) (Swale) Wet basin	Austin filter – concrete Delaware filter Strip – $A_S/A_D<0.1$ (Strip – $0.1<A_S/A_D<0.2$) (Swale) Wet basin
Tier 3	EDB – lined (MCTT)	EDB – lined (MCTT)