Effectiveness of Coanda Screens for Removal of Sediment, Nutrients, and Metals From Urban Runoff

Steve Esmond, PE, COANDA, Inc., Irvine, CA, sesmond@coanda.com

EXECUTIVE SUMMARY

A Coanda-Effect curb inlet BMP was evaluated for approximately two years at a test facility in Rowlett, Texas, between June 2009 and March 2011. During this period, the BMP captured an average of 227 lbs per acre per year (25,500 kg per sq.km. per year) of urban debris and sediment. Of this amount, approximately 40 percent by weight was primarily soil particles in the range of 0.5 mm to 5.0 mm. The 60 percent fraction, being greater than 5 mm, was comprised mostly of leaves, grass, and urban debris. The captured debris had a bulk gross bulk density of 15.2 pcf. The BMP removed significant amounts of nutrients, metals, bacteria, and other water quality pollutants. Removal of these substances from runoff represents a significant benefit to runoff water quality. The unit required no maintenance, captured debris, continuously passed storm water, and most importantly, did not plug or overflow. At no time did debris escape capture, and debris quickly dried, remaining dry and inert within the debris compartment. Periodic debris removal has been accomplished using a vacuum truck which cleans the vault in about 10 minutes.


Figure 1 –Curb Inlet Installation

INTRODUCTION

The technology described in this paper involves a tilted-wire, wedge-wire screen panel to remove thin layers of high-velocity flow from the bottom edge of a supercritical flow. Typical slot openings are 1 mm or less, and the screens are self-cleaning with no moving parts.

There is a growing need on water resources projects to screen sediment and fine debris from delivered flows. Unfortunately, with traditional screen designs, maintenance effort needed to keep screens clean and hydraulic throughput is often dramatically reduced by blockage. One design that offers potential for economically screening fine materials with a minimum of cleaning maintenance is the Coanda-effect screen, also known as the static inclined screen or tilted wedgewire screen. Such devices have been used in the mining industry since about 1955, and have been introduced into water resources by Esmond et.al. (2011). The Coanda curb inlet BMP has been certified as meeting the definition of "full capture" according to the LA Regional Water Quality Control Board. Debris is removed by a stainless steel tilted wedge wire screen designed in such a way as to divert water downward by mechanical shearing and aided by the Coanda effect. Debris is separated by the wires with spacings of 0.5 mm, thus removal efficiencies are 100% for particles equal or greater than 0.5 mm. A detailed discussion of the Coanda effect and its application to tilted-wire screens is provided by the United States Bureau of Reclamation (Wahl 2001).

* *Presented at IECA's 43rd Conference, Las Vegas, Nevada, USA, Session EC12, February 26-29, 2012.*

BMP DESCRIPTION

The BMP was installed in June 2009 and evaluated for two years as a case study. Curb inlet dimensions are 10 ft long by 41 inches deep (vertical) by 26 inches wide. The debris compartment has a volume of 36 cu ft. Debris is retained in the BMP by means of a debris fence constructed of stainless steel perforated plate with small holes, providing a net open area of 46%.

Hydraulic Design

Whenever storm runoff flows into the curb inlet, virtually 100 percent of the storm water passes through the screen. Debris slides down the face of the screen into the debris compartment. A 20" diameter outlet pipe under the screen discharges treated water from the bottom of the vault directly to Lake Ray Hubbard, a water supply reservoir for the City of Dallas, the shoreline being only one block away from the BMP.

The debris fence is a secondary but hydraulically significant element whose purpose is both to retain debris already captured by the screen, and to provide emergency hydraulic bypass. Total open area of the debris fence, including the overflow slots is 6.808 sq ft., which is about 3 times the open area of the 20 inch diameter outlet pipe, which has a total cross section area of 2.18 sq ft. It is typical that all installations provide a greater hydraulic capacity in the Coanda screen and/or the debris fence than either the curb inlet itself or the outlet pipe. The inlet at the curb will be flooded at 11.5 cfs. The outlet pipe will carry 12.1 cfs when the curb inlet is filled with water. By comparison, the Coanda screen has a hydraulic design capacity of 8.5 cfs and the debris fence has a design capacity of over 40 cfs. Thus, the BMP has been designed for significantly greater hydraulic capacity than the curb inlet itself.

Figure 2 – Location of Installation


Figure 3 – Location North of Lake Ray Hubbard

Location

The curb inlet BMP was installed in Rowlett, (a suburb of Dallas) Texas. Refer to red dot shown in Figures 2 and 3. The setting is a single family residential neighborhood adjacent to Lake Ray Hubbard. The contributing drainage area of the curb inlet is 2.16 acres, which is approximately 50% pervious and 50% impervious. The characteristics of drainage area are typical of the surrounding community, being heavily vegetated with large trees and grassy lawns. Thus, runoff can be expected to contain a large amount of leaves and grass.

SAMPLING METHODOLOGY

Debris was removed and tested on nine separate occasions: August 8, 2009, October 5, 2009, December 16, 2009, February 26, 2010, April 2, 2010, June 16, 2010, August 28, 2010, October 22, 2010, and March 14, 2011. Debris was carefully recovered by hand using clean tools and disposable rubber gloves. Debris was taken to a laboratory for quantification, physical characterization, segregation particle size, then tested for analysis of chemical constituents.

DEBRIS AND POLLUTANT CAPTURE RATES

It is a known and well documented fact that certain nutrients, metals and bacteria tend to adsorb onto particulate matter. Even though the BMP is designed primarily to remove sediment and debris, the removal of pollutants can be substantial due to surface adsorption onto particles. The BMP is designed for peak flow conditions, and will remove all debris greater than 0.5 mm. A small fraction of sediment less than 0.5 mm is also removed.

As noted, the debris was collected and classified at each of the nine sampling events. Both the amount and composition of debris varied significantly throughout the year. The season of highest overall debris generation was during fall and winter due to deciduous foliage. Refer to Figure 4 which illustrates the seasonal variation in debris generation and debris characterization. Not surprisingly, most of the debris collected throughout the year was dominated by the presence of grass and leaves. During the fall and winter months the predominant class of debris was tree leaves.

Figure 4A provides a graphical summary of rainfall over the term of the case study. A total of 51.3 inches of rainfall fell at the site between June 6, 2009 and March 14, 2011. Heavy rains fell throughout the fall of 2009, but during 2010 the North Texas area suffered from a lack of rainfall. A decline in debris generated in the watershed seems to be reflected in the declining rainfall, as shown in Figure 4B. It should be noted that the BMP was cleaned by the City in December 2010 and was not tested. Each of the nine bars in Figure 4B represents an individual sampling and testing event.

Figure 4C is a record of the lbs of material collected per acre per year. The units on this graph are annualized values. From June 2009 to March 2011, the net weighted average capture rate is 227 lbs per acre per year. The amount collected appears to be related to both the season and the amount of rainfall. The bulk density averaged 15.2 pcf.

PARTICLE SIZE PARTITIONING AND TESTING

Beginning in May 2010, both the sampling and analytical testing regimes changed. Each bulk sample collected subsequent to that time was screened in order to separate the sample into particle size fractions for analysis. A 5.0 mm sieve was used to separate the bulk sample into two particle size fractions. The fraction smaller than 5.0 mm was comprised mainly of sediment. The other fraction greater than 5.0 mm was comprised of debris. After segregation, the two fractional samples were weighed, characterized, and submitted for instrumental analysis by Aqua-Tech Laboratories, Inc. of Bryan, Texas. This shift in testing accounts for the change in time scale between Figure 4C and Figure 4D. This paper focuses on the last four sampling events which differentiated between sediment and debris.

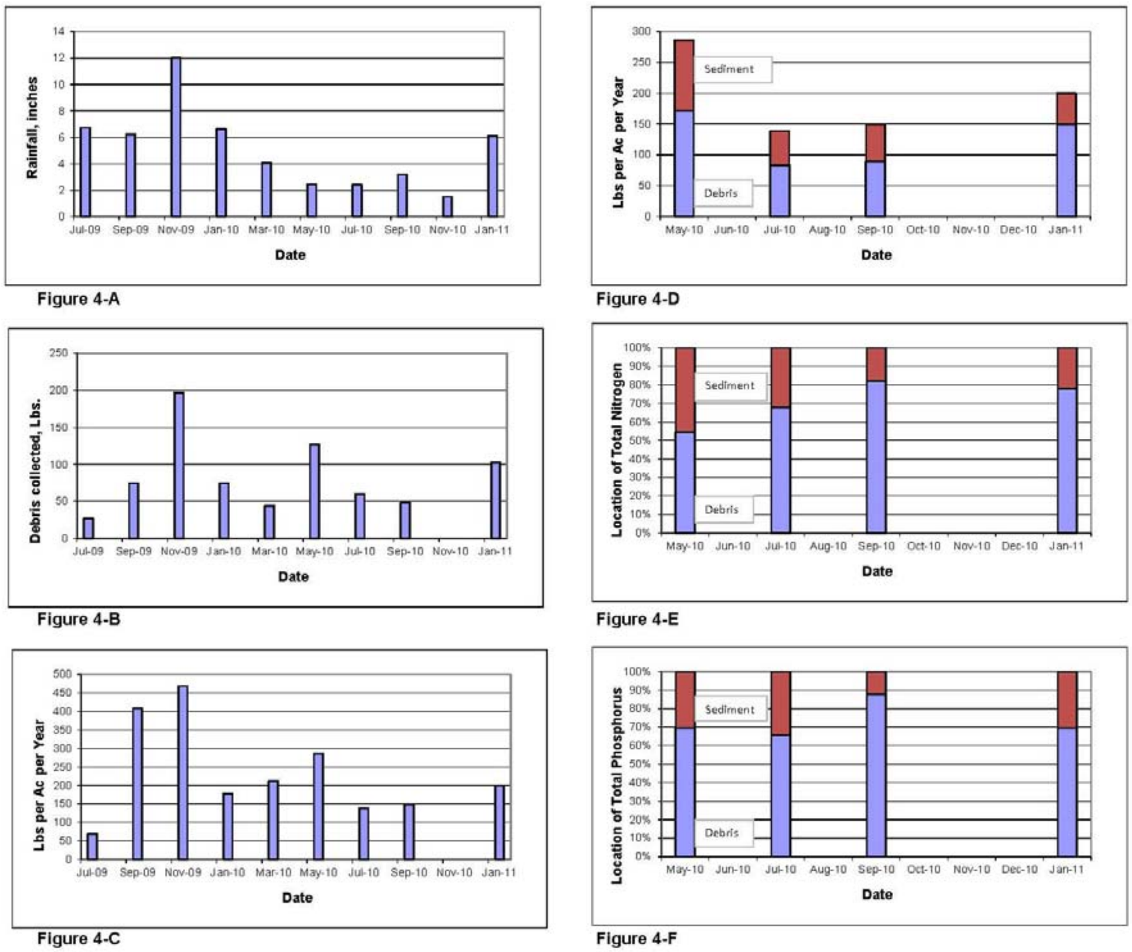

Figure 4 – Seasonal Debris Generation and Characterization

To get a visual comparison between the fractions, refer to Figures 5 and 6. Figure 5 is a photograph of a typical sample with particle size greater than 5.0 mm. Figure 6 is a photograph of a sample with particle size between 0.5 mm and 5.0 mm. For the purposes of this paper, the differentiation between sediment and debris uses the following terminology in this paper. “Sediment” refers to particles greater than 0.5 mm but less than 5.0 mm, and “debris” refers to particles greater than 5.0 mm.

RESULTS AND DISCUSSION

Figure 6D shows the quantity of debris plus sediment collected, which for this particular period averaged 194 lb per acre per year. As a function of weight, the fine debris or sediment (particle size fraction less than 5.0 mm) averaged 35.4 percent of the total gross weight collected. The percentage of fine material or sediment within any batch ranged between about 26 to 40 percent of the total weight.

Figure 6E shows where the nitrogen resided in the bulk sample. On average, 35.1 percent of the total nitrogen was retained on the sediment (<5.0 mm). This partitioning varied seasonally from a low of 17.8 percent in Sep 2010 to a high of 45.5% in May 2010. The higher nitrogen content of the sediment seems to coincide with spring and summer months, which corresponds with the growing season and period in which fertilizers are typically being applied.

	
Figure 5 – Debris (>5.0 mm)	Figure 6 – Sediment (<5.0 mm)

Similarly, in Figure 6F it can be seen that 29.2 percent of the total phosphorus is partitioned off with sediment particulates (<5.0 mm). This percentage varied from a low of 12.2 percent in Sep 2011 to a high of 34.2 percent in Jul 2010. As with nitrogen, phosphorus seems to have increasing affinity for sediment as opposed to debris during the growing season.

In addition to nutrients, this study investigated several heavy metals which may be of concern in storm water runoff. During the period from June 2010 to March 2011, the following metals were tested in addition to nitrogen and phosphorus: As, Cr, Cu, Pb, Ni, and Zn. In each of the four sampling events within those dates, the bulk samples were screened into plus 5.0 mm (debris) and minus 5.0 mm (sediment) fractions. Each fraction was tested for these metals in addition to nutrients. The results are shown on Table 1. All of the units for Table 1 are expressed in mg per kg dry weight, except for total solids (TS), which is in percent by weight.

The data on Table 1 have been developed into a graphical presentation on Figure 7 (A through H). In all eight graphs, the units of the vertical scale is presented as a “capture coefficient” in kg per sq km per year. The nutrients in these graphs represent 290 days of data, and the metals represent 215 days of data. The capture coefficient has been adjusted to a full year.

Table 1 - Nutrients & Metals on Debris				
	Sample Date			
	6/16/2020	8/28/2010	10/22/2010	3/14/2011
Debris (>5.0 mm)				
Total Solids, %	39.2	32.3	54.9	34.2
Ammonia N	1,170	1,220	482	1,300
TKN	8,120	32,200	4,500	2,920
Nitrate-N	45.9	44	96.4	19.6
Nitrite-N	6.37	15.2	9.06	13.3
Total-N	9,342	33,479	5,087	4,253
Total-P	3,000	3,750	1,840	1,910
Ortho-P		731		
As	17.2	4.71	2.56	2.77
Cd		1.95	0.555	0.808
Cu		50.3	24.2	34.4
Pb		11.00	7.57	7.61
Ni		47.8	13.5	18.4
Zn		237	102	162
Sediment (<5.0 mm)				
Total Solids, %	47.6	42.2	64.4	34.8
Ammonia N	769	859	78	1,080
TKN	8,840	17,200	1,310	2,430
Nitrate-N	19.7	27.3	19.7	22.9
Nitrite-N	5.23	11.6	4.85	14.3
Total-N	9,634	18,098	1,412	3,547
Total-P	1,610	2,240	326	2,450
Ortho-P		400		
As	18	8.61	1.65	9.74
Cd		3.69	0.508	2.26
Cu		36.7	5.82	53.6
Pb		14.6	2.96	13.5
Ni		37.7	3.88	37.5
Zn		194	26.9	236

Total nitrogen is presented on Figure 7A. Total N data for the bulk sample extends back to the fall of 2009, which preceded the partitioning by screening to separate the entire sample into particle size fractions. All of the earlier data for nitrogen in the total bulk sample is presented on Table 7A. The data seem to illustrate a strong seasonal variation in nitrogen loading, the bulk of the nitrogen load apparently coming in the spring and summer months. The total nitrogen capture coefficient ranged from a low of 63 to a high of 164 kg/sq km yr, the weighted average being 118. Nitrogen capture associated with only the debris (>5.0 mm) averaged 87. Thus, on an annual loading rate basis, 26 percent of the nitrogen came with the debris (<5.0 mm).

Phosphorus displays a similar trend to nitrogen, with strong seasonal variability, as seen in Figure 7B. The bulk of the phosphorus load also apparently comes in the spring and summer months. The total phosphorus capture coefficient ranges from a low of 7.5 to a high of 33 kg/sq km yr, the weighted average being 25.4. Phosphorus capture from debris (>5.0 mm) averaged 19 kg/sq.km-yr. Thus, on an annual loading rate basis, 23 percent of the phosphorus is associated with sediment (<5.0 mm).

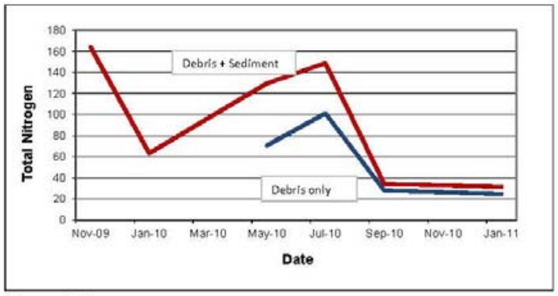

Figure 7-A

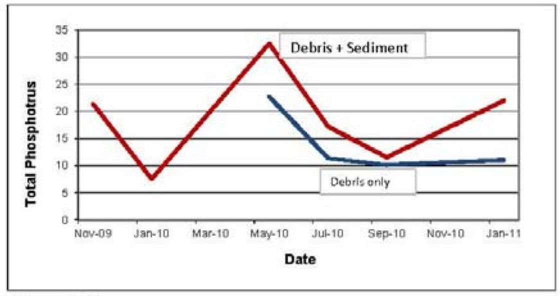

Figure 7-B

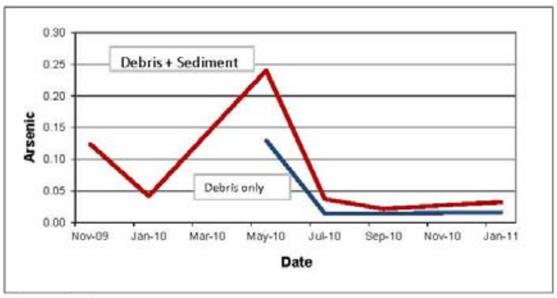

Figure 7-C

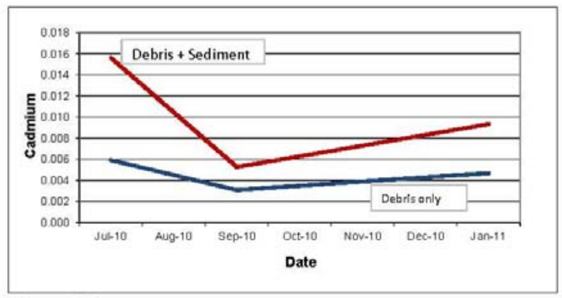

Figure 7-D

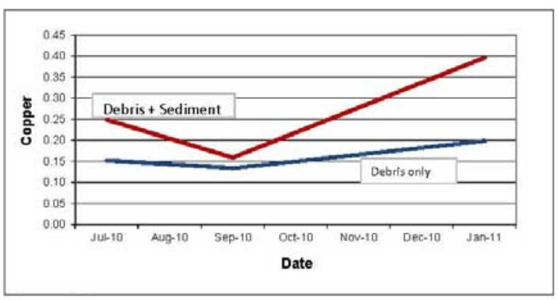

Figure 7-E

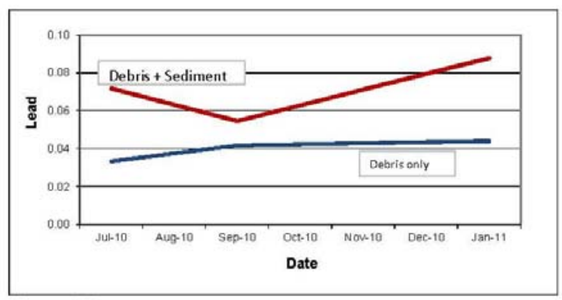

Figure 7-F

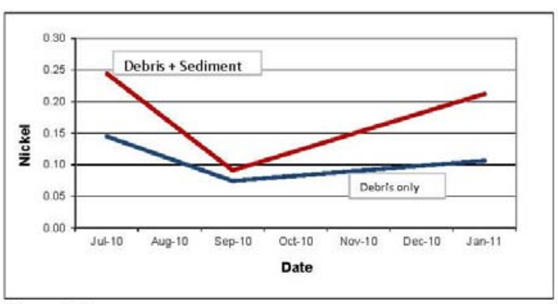

Figure 7-G

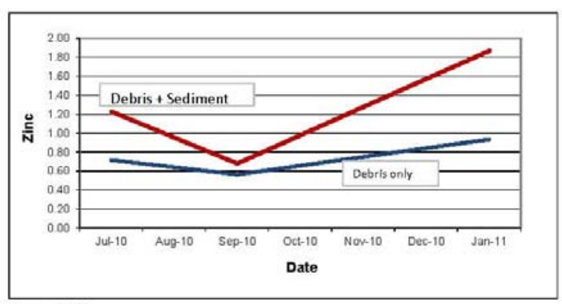

Figure 7-H

Figure 7 – Pollutant Capture Coefficients, kg/sq km-year

Arsenic, in Figure 7C, displays a strikingly similar trend to phosphorus. This is not at all surprising, since As is in the same group as phosphorus (and also nitrogen) in the periodic table. The capture coefficient for As averaged 0.127 kg/sq km yr. Arsenic load from debris (>5.0 mm) averaged 0.086 kg/sq km yr. Thus, on an annual loading rate basis, 32 percentage of arsenic was associated with sediment (<5.0 mm).

Cadmium, shown on Figure 7D, displays a different pattern from the nutrients, in fact, almost a mirror image. The capture coefficient for Cd averaged 0.016 kg/sq km yr. Cadmium capture associated with debris (>5.0 mm) averaged 0.010 kg/sq km yr. Thus, on an annual loading rate basis, 35 percent of the Cd was associated with sediment (<5.0 mm).

Copper is displayed in Figure 7E. The capture coefficient for Cu averaged 0.329 kg/sq km yr. Cu capture associated with debris (>5.0 mm) averaged 0.248 kg/sq km yr. Thus, on an annual loading rate basis, 25 percent of the Cu was associated with sediment (<5.0 mm).

Lead is displayed in Figure 7F. The capture coefficient for Pb averaged 0.094 kg/sq km yr. Lead capture associated with debris (>5.0 mm) averaged 0.067 kg/sq km yr. Thus, on an annual loading rate basis, 29 percent of the Pb was associated with sediment (<5.0 mm).

Nickel is displayed in Figure 7G. The capture coefficient for Ni averaged 0.246 kg/sq km yr. Nickel capture associated with debris (>5.0 mm) averaged 0.179 kg/sq km yr. Thus, on an annual loading rate basis, 27 percent of the Ni was associated with sediment (<5.0 mm).

Zinc is displayed in Figure 7H. The capture coefficient for Zn averaged 1.55 kg/sq km yr. Zinc capture associated with debris (>5.0 mm) averaged 1.15 kg/sq km yr. Thus, on an annual loading rate basis, 25 percent of the Zn was associated with sediment (<5.0 mm).

BACTERIAL TESTING

Fecal coliform testing was performed on the bulk samples which were recovered in March 2011. Sample preparation and testing were performed according to Method SM 9222D. The bulk sample was elutriated in buffered, distilled water, then filtered and incubated on culture media for quantification of fecal coliforms. Results were calculated and reported on a dry weight basis. The coarse bulk sample had a bacterial content of 39,300 CFU per g dry, and the fine bulk sample tested at 42,100 CFU per g dry. Accordingly, the bacterial capture coefficient for the BMP was 898 x 10^9 CFU per sq km year, or in round numbers, approximately 10^{12} CFU per sq km year.

IMPLICATIONS FOR RECEIVING WATER QUALITY

The BMP is designed to remove 100 percent of all debris greater than 0.5 mm. Some regulatory agency jurisdictions have adopted a 5.0 mm standard for debris. The implications in this research demonstrate that significant differences exist between this BMP and a 5.0 mm screen as to their respective removal efficiencies of solids, debris, and pollutants. On the basis on the data in this study, if a 5.0 mm particle size is employed as a regulatory standard for trash, then almost half of the solids and almost one third of the nutrients and metals will pass into the environment, carried by particles ranging of 0.5 mm to 5.0 mm.

It is well known that nutrients, some metals, and a number of other pollutants typically adsorb onto debris and solids transported with urban runoff. When these solids enter a water supply lake such as Lake Ray Hubbard, there is often impairment of water quality and adverse economic impacts associated with treating the water prior to use.

Lake Ray Hubbard receives what has been deemed an excessive amount of nutrients (nitrogen and phosphorus) from its watershed (Archibald, p. 590). The Rowlett Creek watershed is the major source of nutrients to Lake Ray Hubbard, contributing over half of the total nitrogen and three-fourths of the phosphorus (Lee, p. 16). Column 2 of Table 2 references the pollutant loadings obtained by other sources of information outside this paper. The removals in column 3 were measured in the present study, and column 4 provides the percentage capture, which is the removal divided by the loading.

Table 2 – Pollutant Removal Rates Versus Watershed Loadings

	Kg per km^2/year		% Capture
	Loading	**Removal**	
Debris + Sediment [1]	--	25,500	100
Debris Only [1]	--	15,300	100
Sediment Only [1]	--	10,200	100
Total N [2]	415	118	28
Total P [2]	255	25.4	10
Arsenic [3]		0.13	
Cadmium [3]		0.01	
Copper [3]	2.8	0.33	12
Lead [3]	12.6	0.10	1
Nickel [3]		0.25	
Zinc [3]	32.0	1.55	5

Sources for Referenced Loadings (column 2):

1. This study
2. Lee et al
3. "Simple Method" model

The capture coefficient for total nitrogen is equivalent to 28 percent of the total nitrogen loading. If only a 5.0 mm screen were used, the amount captured would have been 21 percent. Likewise, the capture rate for phosphorus is approximately 10% of the total phosphorus loading, but a 5.0 mm screen would remove 7 percent of the phosphorus loading.

MITIGATION OF SEDIMENT BUILDUP IN LAKE

The observed debris plus sediment capture rate in this two year study averaged 25,500 kg per km^2 per year. In this study, it was debris was determined to account for 15,300 kg per km^2 per year and sediment accounts for 10,200 kg per km^2 per year. The next question might be to what extent sediment has been building up in this body of water over its life cycle.

Lake Ray Hubbard was built in the 1960s and began to fill in 1968. From that time until 2005, the State of Texas estimated it had accumulated 37,960 acre feet of sediment (TWDB). Given the lake's drainage area of 1,074 sq. mi., and assuming a sediment density of 80 pcf (Avnimelech), the sediment accumulation rate has been 8,700 kg per km^2 per year.

Given the relatively inorganic chemical composition of sediment, versus the relatively biodegradable organic nature of leafy green waste and debris, one might expect the sediment loading to be a reasonably approximate the sediment accumulation rate. The observed bulk density of the debris ranged from 11 to 15 pcf, and when thoroughly decomposed, would not add much volume to the lake sediment. However, the granular material continuously observed in the sediment samples in this study is relatively more inert and would be captured in the lake. Thus, comparing the sediment buildup of 8,700 kg per km^2 per year with the sediment capture rate observed in this study, which is 10,200 kg per km^2 per year, one observes these are within close proximity.

COST-EFFECTIVENESS

The cost-effectiveness of implementing Coanda-effect technology throughout the Lower Rowlett Creek watershed is presented in this section. Curb inlet retrofit installation costs are approximately $1,500 per acre, which is consistent with current pricing in North Texas. Applying this figure over the entire Lower Rowlett Creek watershed of 44.8 km^2 or 11,000 acres (Lee, p. 18), the total installation cost would be $16.5 million. In other words, this the cost to retrofit the entire Lower Rowlett Creek watershed. Annual O&M cost to clean and dispose of the debris is estimated at $150 per ton. Assuming the watershed generates 250 lbs of debris per acre per year, the debris removal and disposal cost would be about $20 per acre per year. Thus, the total annual debris removal and disposal cost for the watershed would come to about $250,000.

The benefit provided by this investment would be the value of removing virtually 100 percent of the debris and sediment from the lake, 28 percent of the nitrogen loading which is 11,800 lbs per year, and 10 percent of the phosphorus loading which is 2,600 lbs/year, in the Lower Rowlett Creek watershed. Other benefits include a variable percentage of metals and bacteria removed.

Average concentration of total N in the main body of Lake Ray Hubbard ranges between a minimum of 0.5 mg/l to average of around 1.0 mg/l (Lee, p. 67). Using the nitrogen removals observed in this study, annual rainfall of 36 inches per year and runoff coefficient of 0.6, the mitigated total N concentration would be 0.5 mg/l. Thus, there could be a substantial reduction in the concentration of total N within the lake if this technology were implemented in the watershed. Likewise, the total P averages around 0.03 mg/l (Lee, p. 64). The calculated mitigated concentration is 0.1 mg/l. These calculations are made for comparison purposes only. It should be noted that even if mitigated to this extent, this analysis does not take into account the aquatic cycles of N and P in a lake environment, including adsorption and deposition.

If implemented solely as a sediment mitigation strategy, the degree of success could be measured by the amount of sediment captured prior to entering the lake via storm runoff before it reached the shoreline. The initial cost to implement this strategy, as described above, is $1,500 per acre or $370,000 per km^2. Amortizing this figure over 10 years at 5% yields an equivalent annual cost of $30,000 per km^2 per year. Add to that the annual cleaning cost of $20 per acre or $500 per km^2 per year, the total implementation cost comes to $30,500 per km^2 per year.

The observed capture rate in this study was 10,200 kg per km^2 per year. Using 80 pcf as described above to convert this to volume, the mitigated sediment buildup rate in the lake would be 0.41 acre feet per km^2 of drainage area per year. The Region C Water Planning Group, created by the Texas Water Development Board in 2006, estimated the cost per acre-foot of sediment retained to be $435 (2011 Region C Water Plan). This is equivalent to one cent per cubic foot, an incredibly low figure. Nevertheless, applying that value to the sediment buildup rate of 0.41 acre feet per km^2, the cost of sediment in the lake is equal to about $180 per km^2 of drainage area per year.

Thus, the BMP implementation cost of $30,500 per km^2 per year would return a benefit of only $180 per km^2 per year. Clearly, the implementation of sediment controls cannot be justified on the basis of sediment buildup in the lake. The cost per acre-foot of sediment retained would have to be raised from $435 ($0.01 per cu.ft.) to $74,000 ($1.70 per cu.ft.) of sediment retained.

The implementation of sediment control in storm water runoff can be justified on the basis of water quality improvement. A secondary benefit is derived from the mitigation of sediment buildup in the lake.

CONCLUSIONS

Capture efficiencies observed in this study are:

- 100 percent for both debris and sediment,
- 30 percent for nitrogen,
- 10 percent for phosphorus,
- Variable but measureable percentages for metals.

The BMP consistently performed as designed without problems during the two year study period. Significant water quality improvements occur when using these screens as opposed to a 5.0 mm screen. The additional amounts of pollutants removed by the BMP, versus a 5.0 mm screen, are shown on Table 3.

Table 3 - Enhanced (Additional) Removal Provided by Coanda-Effect BMP

Debris and Sediment	67%
Total-N	35%
Total-P	30%
Arsenic	47%
Cadmium	100%
Copper	33%
Lead	41%
Nickel	39%
Zinc	33%
Fecal Coliform	35%

Observed fecal coliform bacteria capture coefficient was 10^{12} CFU per km^2.

If 5.0 mm particle size is established as a regulatory standard for trash, then approximately half of the solids, almost one third of the nutrients and metals, and half of the bacteria will pass into the environment, carried by particles ranging from 0.5 mm to 5.0 mm.

REFERENCES

Archibald, E.M., and G. Fred Lee, "Application of the OECD Eutrophication Modeling Approach to lake Ray Hubbard, Texas," Journal American Water Works Association, 73:590-599, 1981.

Avnimelech, Y., G. Ritvo, L. Meijer, and M. Kochba, "Water Content, Organic Carbon and Dry Bulk Density in Flooded Sediments," Aquacultural Engineering, 25:25-33, 2001.

Esmond, SE, Weir, RK, and Webber, R., "Removal of TMDL Pollutants and Gross Solids in an Urban Environment: BMP Case Study," StormCon 2011, August 2011.

Lee, G. Fred, Abdul-Rahman, Magda, and Meckel, Elaine, "Eutrophication of Lake Ray Hubbard, Dallas, Texas," North Central Texas Council of Governments, 1978.

"2011 Region C Water Plan," Region C Water Planning Group, Texas Water Development Board, 2011, 4C.20.

"Simple Method to Calculate Urban Stormwater Loads," New York State Stormwater Management Design Manual, New York State Department of Environmental Conservation.

"Volumetric Survey of Lake Ray Hubbard, May 2005 Survey" Texas Water Development Board, 2006.

Wahl, Tony L., "Hydraulic Performance of Coanda-Effect Screens," Journal of Hydraulic Engineering, ASCE, June 2001.

Rainfall measured at the following weather stations: Periods 1 and 2, Rowlett Spinnaker Point Weather Station (KTXROWLE8); Periods 3, 4, and 5 Rowlett Springfield Estates Weather Station (KTXROWLE3).

ABOUT THE AUTHOR

Steve Esmond, PE, Chief Engineer, COANDA, Inc., 3943 Irvine Blvd, #327, Irvine, CA 92602, (714) 272-1997, sesmond@coanda.com, web address: www.coanda.com.