MODELED FLOW DURATION VARIATIONS AND COSTS FOR POLLUTANT REMOVAL ASSOCIATED WITH DIFFERENT STORMWATER CONTROL PRACTICES

A. Narayanan[1], C. Bochis[2], and R. Pitt[3]

AUTHORS: Water Resources Engineer II[1], Brown and Caldwell, 990 Hammond Drive, Suite 400. Atlanta, GA 30328
Graduate Research Assistant[2], Professor[3], Department of Civil, Construction and Environmental Engineering, The University of Alabama, 260 H.M. Comer, PO Box 870205, Tuscaloosa, AL 35487-0205.
REFERENCE: *Proceedings of the 2007 Georgia Water Resources Conference*, held March 27-29, 2007, at the University of Georgia.

Abstract. Runoff volume and pollutant discharges increase with development, with associated detrimental receiving water effects. These increases can be partially controlled by installing stormwater control practices, such as wet detention pond at outfalls, using conservation design controls such as grass swales and bioretention devices. The runoff volume and the pollutants associated with the different source areas within a watershed can be used to identify the most likely suitable stormwater control practices for the area. This paper presents the reductions in runoff volume and pollutant discharged, and the costs associated with installing these control practices in an example 228 acre watershed located in Jefferson County, AL with 75% commercial lands and 25% residential lands. The Source Loading and Management Model for Windows (WinSLAMM) was used to calculate the reduction of these pollutants and runoff volume, the associated variations in flow durations, and the costs involved in retrofitting different combinations of a wet detention pond, grass swales, and bioretention devices in the example watershed.

INTRODUCTION

It is well known that the volume of runoff from a watershed increases with development because of the increase in the amount of impervious areas that prevents the infiltration of rainwater. This increased runoff volume, and associated peak flows, is a common cause of increased streambank erosion and other problems in receiving waters. An effective combination of stormwater management and site development practices can be used to reduce peak flows and water volume and pollutant discharges, with subsequent benefits to the receiving waters. Stormwater controls can include wet detention ponds, bioretention facilities, and grass swales, while development characteristics include the amount of impervious cover and how they are connected to the drainage system. The stormwater controls add extra costs to the development costs. Costs must consider their design and construction costs, plus maintenance costs. The magnitude of these costs are dependent on a number of complex factors including local site conditions, site topography, time of year, accessibility to equipment, economies of scale, type of control measure, existing and proposed future land uses, environmental considerations, government regulations, public preferences, and degree of technical assistance available. However, some of the stormwater controls (those that reduce the peak discharge rates during critical design storms) can also reduce the costs of other components of the conventional drainage system. This presentation will discuss how runoff flow-duration, pollutant discharges, and costs, can be compared for different development scenarios using recent modifications made to the Source Loading and Management Model, WinSLAMM (Pitt 1986; Pitt and Voorhees 2002).

JEFFERSON COUNTY NPDES MONITORING WATERSHED CHARACTERISTICS

A number of local watersheds are being monitored by the Storm Water Management Authority (SWMA) of Jefferson County, AL, as part of their NPDES stormwater permit. Table 1 lists five of these sites and their calculated annual average volumetric runoff coefficients, TSS concentrations, percent impervious values, and the expected biological conditions of the receiving waters due to expected hydromodifications of the receiving waters from the land development. The expected biological conditions of the receiving waters were calculated by WinSLAMM to be "poor". It is interesting to note that the highly impervious watersheds (ALJC001 and ALJC012), which have mainly industrial and commercial land use respectively, have higher values of Rv (~0.6) but lower values of TSS concentrations, compared to the watersheds dominated by residential land uses (ALJC009 and ALJC010). The residential watersheds are closer to the threshold between fair and poor biological conditions (an Rv of about 0.25) than the industrial and commercial watersheds. These biological conditions in the nearby receiving waters have been verified by biologists from the Jefferson County Storm Water Management Authority

Table 1. Runoff Quantity and Quality for the Five Jefferson Co., AL Monitoring Sites

Site ID	Major Land Use Category	Area (ac.)	Percent Total Impervious Areas	Percent Directly Connected Impervious Areas	Calculated Volumetric Runoff Coefficient (Rv)	Calculated TSS Concentration (mg/L)	Expected Biological Conditions of Receiving Waters due to Hydromodifications
ALJC001	Industrial	341	74.7	71.9	0.67	89	Poor
ALJC002	Industrial	721	59.9	46.5	0.51	118	Poor
ALJC009	High Density Residential	102	46.0	34.3	0.37	176	Poor
ALJC010	Medium Density Residential	133	35.6	27.7	0.30	218	Poor
ALJC012	Commercial	228	63.9	60.5	0.62	92	Poor

during their stream investigations. It is therefore possible that stormwater controls that reduce the runoff discharges could be effective in improving receiving water biological conditions in these residential areas, but it would be much more difficult in the industrial and commercial watersheds, as expected.

This paper investigated Site ALJC012, a 92 ha (228 ac) watershed located in Hoover, AL. As noted previously, these sites are being monitored by the Storm Water Management Authority as part of their NPDES stormwater permit. These data are also being used to update the validation of WinSLAMM for the region. The sampling location for this watershed is at a large culvert running under Highway 31, just south of where the highway intersects Highway 150, in Hoover, AL. The drainage basin is composed mostly of commercial areas (70%) made up of strip shopping centers mixed with offices and banks, and a portion of the very large Riverchase Galleria shopping mall. Apartments make up about 25% of the drainage area along, with some undeveloped woodland (about 5%). Table 2 shows the source areas for the two major land use for the ALJ012 (commercial mall/apartments) watershed located in Jefferson County, AL.

The drainage system serving this area is concrete curbs and gutters in good conditions and not very steep. All the houses in the apartment complexes have pitched roofs of composite shingles that are disconnected, with the water directed onto the surrounding grass (silty loam soil). A large part of this apartment land use (60%) is woodland ("other pervious area").

The commercial area is a mixture of shopping centers with business offices and banks having flat and pitched roofs entirely connected to the drainage system. Paved parking lots and roofs are a large part of this land use (49%). However, there are also some landscaped areas (also having a silty loam soil) that comprise about 28% out of the commercial land use area.

ANALYSES OF SOURCE AREA RUNOFF AND POLLUTANT CONTRIBUTIONS

Particulate solids and zinc contributions from different source areas in this commercial/apartment watershed were analyzed for various rain depths for this paper. Analyses using WinSLAMM with one year of rainfall data (1976 was used as that is a representative rain year for this area) showed that the site produced a runoff volume of about 120,000 ft^3 /ac-yr (8,500 m^3/ha-yr), or approximately 61% of the annual rain (Rv = 0.61). This runoff quantity is expected to result in poor biological conditions in the receiving water due to hydromodifications. The concentration of total suspended solids was 67 mg/L (annual mass discharges of about 53,000 kg).

Table 2. Jefferson County AL, Commercial Mall/Apartments Watershed: Average Source Areas by Land Use (Acres, Unless Otherwise Noted)

Land Use	Curb Miles	Street with Curbs and Gutters	Parking, Paved and Connected	Storage, Paved	Pitched Roof Drained to Impervious	Pitched Roofs Drained to Pervious Areas	Flat roof drained to impervious areas	Large Turf	Other Pervious	Total
Apartments	3.03	6.8	8.5	0	0	7.8	0	0	34	57.4
Commercial	8.03	27	61	9.7	0	0	23.9	48	0	171
Total area	11.06	34.6	69.5	9.7	0	7.8	23.9	48	34	228.4

Table 3. Summary of Source Area Percentage Contribution of Runoff Volume

Land Use	Street with curbs and gutters	Parking, paved and connected	Storage, Paved	Pitched Roof drained to impervious	Pitched Roof drained to pervious	Flat Roof drained to impervious	Large Turf	Other pervious	Total	Rv
Apartments	3.8	5.8	0	0	5.2	0	0	3.6	18.4	0.46
Commercial	14.5	41.8	6.6	0	0	13.8	5	0	81.7	0.68
Total area:	18.3	47.6	6.6	0	5.2	13.8	5	3.6	100	0.61

Table 3 is a summary of the source area contributions to the total runoff volume discharges (in percent). As expected, almost all (>85%) of the annual runoff volume is expected to come from the directly connected impervious areas, such as the parking lots, streets and roofs.

Tables 4 and 5 are summaries of the particulate solids and zinc contributions (in percent) from each of the source areas for this site. The directly connected impervious areas are the largest contributors, but the landscaped areas are also expected to contribute large portions (34%) of the total particulate solids. The parking areas and streets contribute about 43% of the total area zinc discharges. The roofs also contribute a large portion of the zinc (37.6%), even though they only are expected to contribute about 5% of the runoff volume.

The most suitable stormwater controls for this area are those that would affect the major sources of the pollutants and flows of interest. As noted above, the greatest quantity of runoff is likely to originate from directly connected impervious areas, as expected. The source areas that first contribute runoff are directly connected parking lots and pitched roofs, which start to produce flow during very small rains (0.01 inches). The streets start contributing runoff at 0.02 inches of rain, followed by flat connected roofs (0.09 inches), and then landscape and disconnected roofs at 0.12 inches of rain.

In the residential area, paved parking and streets contribute the most particulate solids discharges for rains up to about 0.15 inches in depth. For higher rain depths, the landscaped areas contribute the majority of the particulate solids (at least 60%). The roofs started contributing the majority of zinc at 0.09 inches of rain, and greater.

Based on these source area contribution findings, the source area controls of most potential use will be those that can treat runoff from parking areas and directly connected roofs. Drainage system and outfall controls may also be useful as these source areas contribute the majority of the pollutants and flows for many rains.

Table 4. Summary of Source Area Percentage Contribution of Particulate Solids

Land Use	Street with curbs and gutters	Parking, paved and connected	Storage, Paved	Pitched Roof drained to impervious	Pitched Roof drained to pervious	Flat Roof drained to impervious	Large Turf	Other pervious	Total
Apartments	3.4	3.3	0	0	0.2	0	0	9	16
Commercial	15.8	36.2	5.7	0	0	1.3	25	0	84
Total area:	19.2	39.5	5.7	0	0.2	1.3	25	9	100

Table 5. Summary of Source Area Percentage Contribution of Zinc

Land Use	Street with curbs and gutters	Parking, paved and connected	Storage, Paved	Pitched Roof drained to impervious	Pitched Roof drained to pervious	Flat Roof drained to impervious	Large Turf	Other pervious	Total
Apartments	1.6	2.3	0	0	10.2	0	0	6.1	20.2
Commercial	10.3	25	3.9	0	0	27.4	13.3	0	79.9
Total area:	11.9	27.3	3.9	0	10.2	27.4	13.3	6.1	100

CONTROL PRACTICES CHARACTERISTICS

Wet detention ponds, grass swales, and bioretention devices were designed for this watershed to reduce the pollutant loadings and runoff. Since this watershed is highly urbanized, retrofitting control practices will be difficult. As in most areas, the most cost-effective stormwater controls need to be installed at the time of development. The aerial photograph of this watershed (Figure 1) was examined to locate potential stormwater controls. A wet detention pond can be located at the 5.6 acre landscaped area at the junction of highway 31 and highway 150. This pond was designed to be 9 ft deep, with 3 acres maximum pool area and will serve the entire 228 acres of the watershed. This pond is only about 1.3% of the watershed, smaller than what would normally be used for such a highly impervious drainage area. However, the available location precluded using a larger pond, and upland controls to reduce the volume of water flowing to the pond were also used.

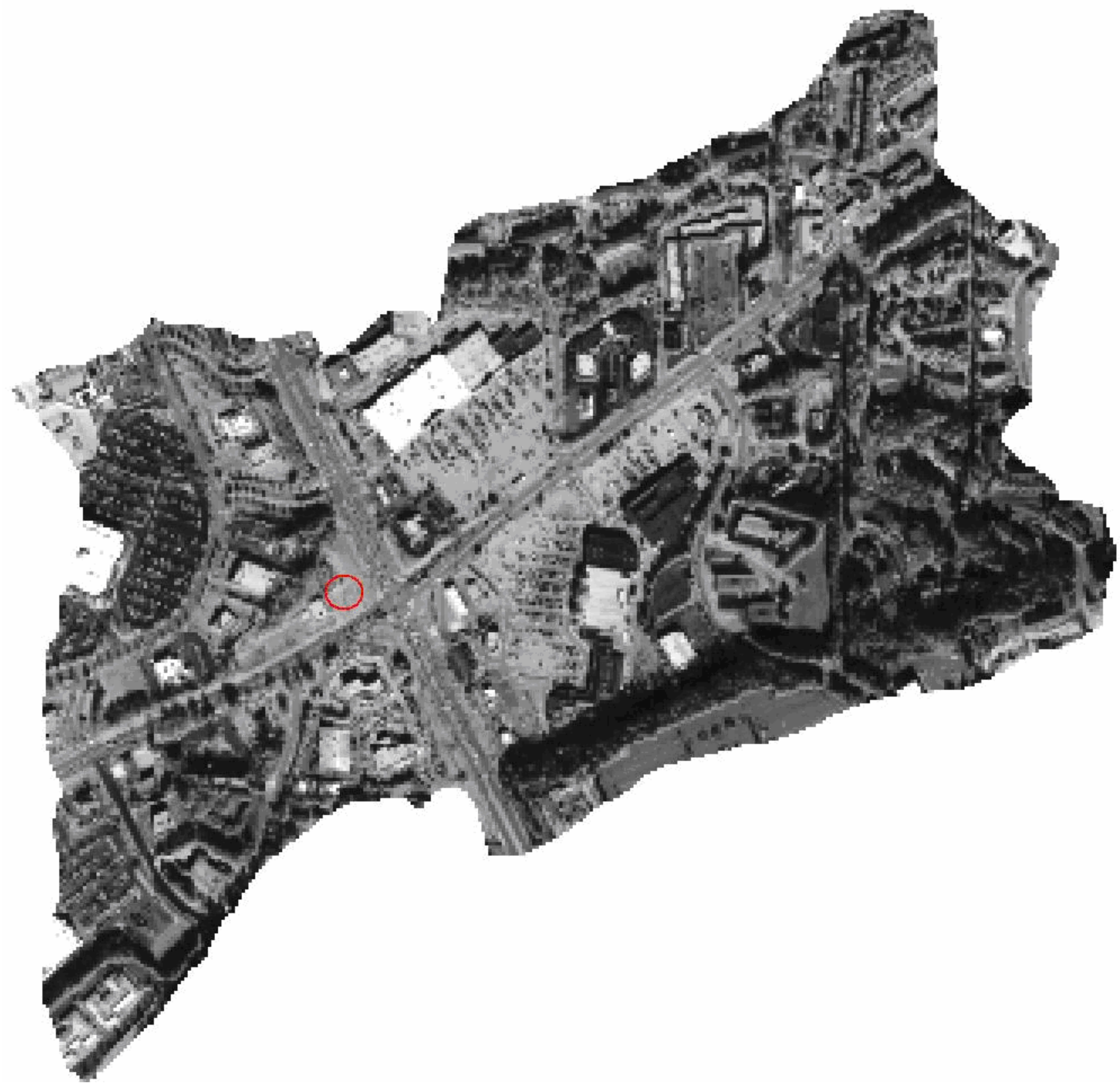

Figure 1. Aerial Photograph of Commercial/Apartment Watershed, also Showing Location of Wet Detention Pond (aerial photograph courtesy of SWMA)

Grassed swales can be used along some of the roads in the watershed. Swales having a 5 ft bottom width, 22 ft top width, 2.8 ft deep and 3:1 side slope were designed for this site. The infiltration rates in the soils were assumed to be 0.15 inches per hour). These swales could be used to replace about half of the conventional curb and gutter drainage system. Bioretention devices can also be retrofitted at landscaped areas to treat roof runoff and as parking lots islands to treat the parking area runoff in both the land uses. A total of 126 bioretention devices can be used in the residential area. Each was designed to have surface areas of 81 ft^2, with soil infiltration rates of 0.3 inches per hour . A total of 105 bioretention devices can be used in commercial areas. Each was designed to have 225 ft^2 surface areas. In the residential area, 61 bioretention devices can be used at parking areas, while in the commercial areas, 50 bioretention devices can be used in the parking areas. Construction of the bioretention devices would result in the loss of about 56 parking spots in the residential are and 127 parking spots in the commercial area, if used in areas of existing parking. The actual loss would be less, as some landscaped islands currently exist that could be converted to bioretention facilities. The bioretention device areas total about 1.3 percent of the total paved parking areas in the residential area, and about 4.3 percent of total paved parking areas in the commercial area.

The stormwater controls, in various combinations, were then evaluated by WinSLAMM to calculate the expected reductions in runoff volume, particulate solids and zinc discharges, and the costs.

RESULTS AND DISCUSSION

Seven site situations were examined that included (i) no controls, (ii) detention pond only, (iii) grass swale only, (iv) site bioretention only, (v) detention pond and swale, (vi) detention pond and site bioretention, and (vii) detention pond, site bioretention and swale. Table 6 summarizes the costs, total particulate solids, and runoff volume discharges after implementing these different control combinations. The runoff reductions are substantial with the swales and bioretention devices, but the expected resulting hydromodifications and biological receiving water impacts are still expected to be significant, with resulting poor conditions. Additional reductions in runoff volumes are likely needed to improve the expected receiving water conditions to at least a fair condition. This site contains one of the largest shopping malls in the southeast, and the watershed has a very large amount of impervious surfaces. Although these expected runoff volume reductions are large and the amount of controls and the associated costs are also large, further effort in runoff reductions are still needed to protect the receiving waters.

Figure 2 is a plot showing flow-duration curves calculated by WinSLAMM for the watershed discharges that occur for different percentages of time for each control option. The options that contain the wet pond have the greatest benefit on reducing the peak flow rates, reducing the peak discharges by up to about 35 to 40%. The infiltration devices in turn, reduce the total volumes of the discharges.

Figure 3 and 4 plot the cost per unit mass of particulate solids and zinc reduced compared to their maximum percentage reduced for the control practices. Pond and bioretention devices in combination are expected to reduce particulate solids by about 90%. The combination of the wet detention pond, swales, and bioretention reduce the particulate solids by about 92%, but at a unit cost that is nearly three times as high. However, in the case of zinc reductions, swales play a vital role: the combination of the wet detention pond and swales results in the most cost effective reduction in zinc concentration at the outfall for large targeted reductions.

A combination of the wet detention pond, grass swales, and bioretention devices is expected to provide the best reductions in runoff, particulate solids, and zinc in this watershed. The installation of the bioretention devices and replacing half of the curb and gutter with grass swales not only reduces the runoff volume and pollutant discharges, but also decreases the costs of the conventional drainage system. Since, the grass swales serves to convey stormwater instead of the usual curb and gutter and pipe systems and the upland bioretention devices provide some reduction in the runoff volume during critical drainage design storms. Therefore, any decrease in pipe diameter or length of pipe needed results in a significant decrease in the cost of the system. These additional cost savings are not included in these analyses. Of course, if these practices are retrofitted at this site, these capital cost savings would not be realized, and additional costs associated with their removal must be added to these calculated costs.

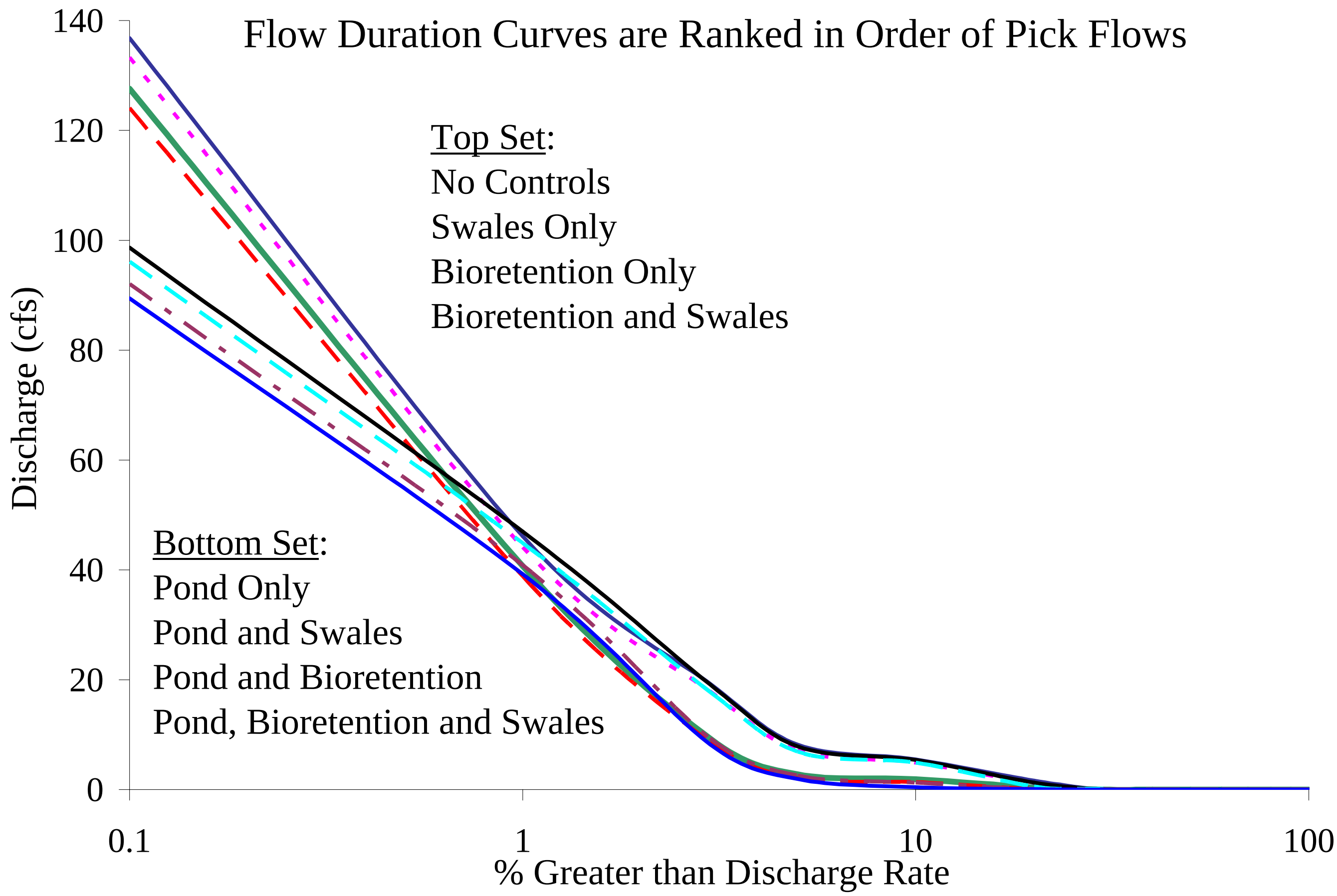

Figure 2. Flow-duration Curves for Different Stormwater Conservation Design Practices

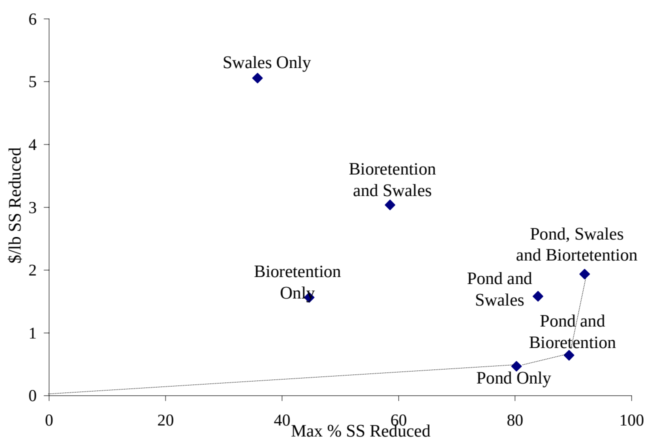

Figure 3. Cost Effectiveness of Control Practice(s) in Particulate Solids Reduction

Figure 4. Cost Effectiveness of Control Practice(s) in Zinc Reduction

Table 6. Various Control Practice Costs and Total Particulate Solids Concentration Before and After Implementing Controls

	No controls	Pond Only	Swale Only	Site Bioretention only	Pond, Site Bioretention and Swale
Capital Cost, $	0	310,100	803,100	387,400	1,438,600
Land Cost, $	0	0	0	0	0
Annual Maintenance Cost, $/year	0	7,900	26,400	13,200	46,200
Present Value of All Costs, $	0	408,200	1,132,000	552,400	2,014,400
Annualized Total Costs of Stormwater Controls, $/year	0	32,800	90,800	44,300	161,700
Total Particulate Solids Conc. before Drainage System (mg/L)	65	65	65	86	86
Total Particulate Solids Conc. after Drainage System (mg/L) (considers source area and drainage system controls)	52	52	46	77	69
Total Particulate Solids Conc. at outfall (mg/L) (considers source area, drainage system, and outfall controls)	52	13	46	77	14
Total Particulate discharges (lbs/year) at outfall	92,900	23,100	74,900	64,600	9,400
Percent reduction of total particulates discharges, compared to no controls	n/a	75%	19%	30%	90%
Unit removal costs for total particulates ($/lb)	n/a	0.47	5.04	1.57	1.94
Total Runoff Volume after Controls (ft^3 per year)	28,700,000	28,200,000	25,800,000	13,410,000	10,680,000
Percent reduction of total runoff volume discharges, compared to no controls	n/a	2%	10%	53%	63%
Unit removal costs for runoff volume ($\$/ft^3$)	n/a	0.07	0.03	0.003	0.007
Runoff Coefficient after Controls, Rv	0.63	0.62	0.56	0.29	0.23
Expected biological conditions in receiving waters, if complete watershed developed in this manner (based on runoff volume)	poor	poor	poor	poor	poor

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Center for Economic Development and Resource Stewardship (CEDARS) of Nashville, TN, for their funding which has allowed us to develop additional extensions to WinSLAMM. The Stormwater Authority of Jefferson County, AL, is also acknowledged for their support in providing us with the ALJC012 watershed data.

LITERATURE CITED

Burton, G.A. Jr., and R. Pitt. *Stormwater Effects Handbook: A Tool Box for Watershed Managers, Scientists, and Engineers*. ISBN 0-87371-924-7. CRC Press, Inc., Boca Raton, FL. 2002. 911 pages.

Maestre, A. and R. Pitt (2005). *The National Stormwater Quality Database, Version 1.1, A Compilation and Analysis of NPDES Stormwater Monitoring Information.* U.S. EPA, Office of Water, Washington, D.C. (final draft report) August 2005.

Pitt, R. "The Incorporation of Urban Runoff Controls in the Wisconsin Priority Watershed Program." In: *Advanced Topics in Urban Runoff Research*, (Edited by B. Urbonas and L.A. Roesner). Engineering Foundation and ASCE, New York. pp. 290-313. 1986.

Pitt, R. and J. Voorhees. "SLAMM, the Source Loading and Management Model." In: *Wet-Weather Flow in the Urban Watershed* (Edited by Richard Field and Daniel Sullivan). CRC Press, Boca Raton. pp 103 – 139. 2002.

Schueler, T. "The importance of imperviousness." *Watershed Protection Techniques.* Center for Watershed Protection. 1(3): 100-111. 1994.

Southeastern Wisconsin Regional Planning Commission (SEWRPC). *Costs of Urban Nonpoint Source Water Pollution Control Measure.* Waukesha, WI.. 1991.