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THE ECONOMICS OF STRUCTURAL STORMWATER BMPs IN NORTH CAROLINA

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Abstract

Urban stormwater runoff and the associated negative quantitative and qualitative effects can be controlled by various best management practices (BMPs). These innovations run along the continuum of small, or site specific, to large, or regional, scale practices. This publication focuses on which BMPs work best at removing selected pollutants and their relative costs for NC conditions.

The costs of BMPs include both installment (construction and land) and annual operating costs (inspection and maintenance). Construction costs and annual operating costs are statistically analyzed for effects of scale by means of the estimation of BMP specific non-linear equations relating the costs to watershed size. Structural stormwater BMPs require initial capital investments and then annual operating costs. To estimate total economic impacts the Present Value of Costs approach was used. Annual costs were related to the area treated and to the removal effectiveness of the specific BMP for a proper economic evaluation.

All BMPs, except for bioretention not in sandy soil, displayed economies of scale and large differences were found in the annual costs per acres treated between the BMPs analyzed. Based on these cost differences, the installation of bio-retention areas is to be preferred over sandfilters or wet ponds in smaller watershed where sandy soil prevails (less than 10 acres). A stormwater wetland is the least expensive BMP for larger watersheds and sandy soils (over 10 acres). For watersheds on non sandy soil, bioretention is the most economical option up to about about 6 acres followed by wet ponds for mid size watersheds and stormwater wetland for watersheds over 10 acres.

No significant relationship could be assessed between removal efficiency and watershed size for the four BMPs analyzed and removal rates for stormwater wetlands were lower than expected. Based on the cost per percent of TP, TN and Zn removed, the conclusion are similar to those based on cost per acre treated. Based on nitrate the conclusion is more mixed. Where the opportunity cost of land is very high (commercial use), a wet pond is preferable over a bio-retention area for small watersheds (2 acres or less). A comparison of BMPs by cost per percent of TSS removed was not possible because of lack of data.

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Summary and Conclusions

Based on the analysis presented in this report, the following conclusions can be reached with respect to structural stormwater BMPs in North Carolina:

Costs per acre treated

- All BMPs, except for bioretention not in sandy soil, display economies of scale within the practice — the construction cost and the maintenance cost per acre treated decrease as the size of the watershed increases.
- There are large differences in the annual costs per acres treated between the BMPs analyzed.
- Based on the cost per acre treated, the installation of bio-retention areas is to be preferred over sandfilters or wet ponds in smaller watersheds where sandy soil prevails (less than 10 acres).
- A stormwater wetland is the least expensive BMP for larger watersheds and sandy soils (over 10 acres), assuming a stormwater wetland can be reasonably installed (i.e., access to dependable water sources is not an issue).
- For watersheds on non-sandy soil, bioretention is the most economical option up to about 6 acres followed by wet ponds for mid-size watersheds and stormwater wetland for watersheds over 10 acres.
- Bio-retention areas are substantially less expensive than sand filters except in extremely high land cost situations. Similarly, stormwater wetlands are substantially less expensive than wet ponds except in extremely high land cost situations.

Removal Efficiency

- No significant relationship could be assessed between removal efficiency and watershed size for the four BMPs analyzed.
- Pollutant removal rates for stormwater wetlands were lower than expected. In North Carolina it has been assumed that stormwater wetlands work substantially better than wet ponds in removing most types of pollutants. However, for TSS, TP, and NO_3^-, wet ponds and stormwater wetland function was found to be comparable.

Costs per percent pollutant removed

- Based on the cost per percent of TP, TN and Zn removed, the conclusions are similar to those based on cost per acre treated.
- Based on nitrate the conclusion is more mixed. Where the opportunity cost of land is very high (commercial use), a wet pond is preferable over a bio-retention area for small watersheds (10 acres or less).
- A comparison of BMPs by cost per percent of TSS removed was not possible because of lack of data.

Management

- All BMPs need to be maintained, and money should be set aside for maintenance up front. Approximate amounts can be determined from this study.
- Watershed administrators should expect to see more bio-retention areas designed and installed if small-scale practices are mandated.

Recommendations

Stormwater best management practices (BMPs) are becoming commonly used throughout the United States. One of the questions facing design engineers and developers is what is the optimum practice to select for a particular watershed size, land cost, and target pollutant. In this report we present an *economic* decision making tool as to what is the *best* BMP to choose for North Carolina conditions given a particular size of watershed, type of watershed as described by curve number range, soil type, and pollutant type. The resulting information should be valuable to design engineers and developers involved in stormwater management.

1. Introduction

The construction of pavement and buildings, and the clearing of land, increase the volume and speed of stormwater runoff. When impervious or disturbed areas are created by urban construction activities, and stormwater is not adequately managed, the environment may be adversely affected by: (1) changes in volume, timing, and location of the stormwater discharges, and (2) the movement of pollutants from the site to waterbodies. This contributes to flooding, and damage to property and habitat (stormwater quantity impacts). It also contributes to lowering of water quality, by increasing the flow of human pollutants such as oil, fertilizers and pesticides, and the flow of natural elements such as nitrogen, phosphorus and sediment into the water (stormwater quality impacts). Degradation of lakes, streams and wetlands due to urban stormwater reduces property values, raises bills from public water utilities and reduces tourism and related business income.

Urban stormwater runoff and the associated negative quantitative and qualitative effects can be controlled by various best management practices (BMPs). These innovations run along the continuum of small, or site specific, to large, or regional, scale practices. This publication focuses on which BMPs work best at removing selected pollutants and their relative costs for NC conditions.

The goal of this report is to present decision makers with a general *economic* decision making tool as to what is the *best* BMP to choose for a particular size of watershed, curve number range, and pollutant type.

1.1 Structural Stormwater BMPs

An urban stormwater BMP is believed to be a 'best' way of treating or limiting pollutants in stormwater runoff. Certain BMPs are better under certain conditions than others. The size of the watershed, the imperviousness of the watershed, and the amount of available land for the structure all influence the selection of a BMP. The stormwater treatment practices to be investigated in this study include structural devices and include wet ponds, stormwater wetlands, bio-retention areas and sand filters.

Wet Ponds also called wet detention ponds or facilities, have been used in North Carolina longer than any other stormwater BMP. Wet Ponds are runoff-holding facilities that have standing water in them constantly. Storm flows are held in the pond temporarily and then released to minimize large scale flooding. Wet ponds are characterized by larger excavation volumes and have forebays located where the inflow enters the BMP. The primary removal mechanism is settling while stormwater runoff resides in the pool. Nutrient uptake also occurs through biological activity in the pond. Wet ponds can be designed to be vegetated, and the plant roots hold sediment and use the nutrients that are often contained in urban runoff. Developers can design the wet ponds to look like natural lakes and enhance the value of surrounding property. Mosquito larvae-eating fish live in the pond to keep mosquito problems to a minimum. Wet ponds can be used for any size of drainage area. In North Carolina, wet ponds treat watersheds as small as 0.75 acres and as large as several hundred acres. Wet ponds may cause community concerns regarding safety; there is an increased liability due to drowning risk because of their relative depth. Additionally, wet pond effluent is often warmer than base stream water, causing thermal pollution and potentially damaging downstream aquatic habitats.

Stormwater Wetlands,[1] also called constructed wetlands, are comparable to wet ponds but are much shallower and more heavily vegetated with wetland plants. In many stormwater wetlands the average depth of water is approximately 1-1.5 feet. They serve as a natural filter for urban runoff and also help to slow the flow of water to the receiving waters and replenish ground water. As stormwater runoff flows through the wetland, pollutant removal is achieved by settling, adsorption and biological uptake within the practice. Wetlands are effective stormwater practices in terms of pollutant removal and also offer aesthetic value. When properly designed, stormwater wetlands have excellent wildlife habitat potential (MWCOG, 1992). In North Carolina, constructed stormwater wetlands have been located on watersheds as small as four to five acres, but they are most commonly used for larger drainage areas and typically serve watersheds ranging from 15 acres to over 100 acres. Thanks to its vegetative cover, wetland effluent is typically cooler than that of wet ponds, minimizing the impacts of thermal pollution.

There are also some limitations to stormwater wetlands. Wetlands consume a relatively large amount of space making them an impractical option on sites where surface land area is constrained or land prices are high. They have, therefore, limited applicability in highly urbanized settings. There can also be a public perception that wetlands are a mosquito source, although design features can minimize the potential of wetlands becoming a breeding area for mosquitoes (McLean, 2000).

Sand filters are usually two-chambered stormwater treatment practices; the first chamber is for settling, and the second is a filter bed filled with sand or another filtering media. As stormwater flows into the first chamber, large particles settle out, and the finer particles and other pollutants are removed as stormwater flows through filtering media. At the bottom of the sand layer, an underdrain pipe typically connects the treated water with the existing drainage network. Sand filters, in general, are good options for relatively small drainage areas in ultra-urban environments where space is limited and original soils have been disturbed. Moreover, sand filters are particularly well suited to treat runoff from stormwater hotspots[2] common in ultra urban areas because stormwater treated by sand filters has no interaction with, and thus no potential to contaminate groundwater.

Sand filters are best applied on small sites and can be used on sites with up to about 6% slopes. It is difficult to use sand filters in extremely flat terrain, as they require a significant drop in elevation (ranging from two to five feet) to allow runoff flow through the filter. There are several modifications of the basic sand filter design, including the surface sand filter, underground sand filter and the perimeter sand filter. All of these filtering practices operate

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[1] For regulatory purposes under the Clean Water Act, the term wetlands means "those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions.

[2] Stormwater hotspots are land uses or activities that generate highly contaminated runoff and include: commercial parking lots, fueling stations, industrial rooftops, outdoor container storage of liquids and loading/unloading facilities and vehicle/equipment service, maintenance/washing/steam cleaning areas.

on the same basic principle. Underground and perimeter sand filters are particularly well suited for ultra-urban watersheds as they consume no surface space. The perimeter sand filter can be applied with as little as 2 feet of drop in elevation. In this report we address the economics of the latter type of sand filter specifically. The first sand filter in North Carolina was installed in the early mid-1990's . Their use is currently not widespread due to the costs of construction. Sand filters are designed for impervious watershed in particular, and typically one sandfilter treats a drainage catchment of less than a few acres.

Bioretention/rain gardens in many respects are landscaped and vegetated filters for storm water runoff. Surface runoff is directed into shallow, landscaped depressions. These depressions are designed to incorporate many of the pollutant removal mechanisms that operate in forested ecosystems. Trees and shrubs are planted in bedding material consisting of a high percentage of sand, and lesser amounts of silt, clay and organic matter. During rain events, stormwater ponds above the mulch and soil in the system. Runoff from larger storms is generally diverted past the facility to the storm drain system. The remaining runoff filters through the mulch and prepared soil mix. Typically, the filtered runoff is collected in a perforated underdrain and returned to the storm drain system. Bioretention systems are generally applied to small sites and in a highly urbanized setting. Bioretention facilities are ideally suited to many ultra-urban areas as they can be fit into existing parking lot islands or other landscaped areas.

Because bioretention can potentially fulfill two purposes: water quality control and landscaping requirements their use is expected to increase. For example, in 1997 there were no bioretention areas in North Carolina, whereas today it is the secondly most common planned practice in Greensboro, the state's third largest city (Bryant, 2001). Bio-retention areas typically serve small watersheds such as (portions of) parking lots, or residential run off areas. In North Carolina, the majority of bioretention areas served watersheds ranging from one to two acres.

Table 1 summarizes the four structural stormwater BMPs discussed above, by relative size of the associated drainage area.

Table 1. Structural Stormwater BMPs by relative size of commercial/residential drainage area

BMP	Relative size of commercial/residential drainage area	
	Large	Small
Wet Pond	X	X
Stormwater Wetland	X	
Sandfilter*		X
Bioretention/Raingarden**		X

*Only effective with a significant drop in elevation (for perimeter sandfilter at least two feet).
** In clay soils a significant drop in elevation (4 feet) is typically required.

1.2 Objectives

Section 1.1 has described several options for achieving water quality improvements in stormwater runoff, all of which have various technical characteristics (design requirements and site constraints[3]), ecological characteristics (i.e. capabilities regarding pollution control) and economic characteristics (maintenance requirements and construction costs). Economics is an important consideration in the selection of BMPs to achieve water quality goals at least costs.

The *first* objective of this study is the assessment of the costs by BMP. To properly compare alternatives, all costs for the design life of a BMP should be included The cost calculation will include land cost, construction cost, and operations/maintenance costs to relate the calculated costs to practice type. The economic evaluation assumes that all BMPs are optimally sized and designed from an engineering point of view. Next the cost will be related to the ecological characteristics of the BMPs in order to assess which practices are most cost effective in terms of total cost per % of pollutant removed. Regarding the pollutant removed the assessment will be performed for total suspended solids (TSS), total phosphorus TP, total nitrogen (TN), nitrate NO_3^- and zinc (Zn).

The *second* examination in this study elaborates on the economic evaluation by BMP above. The installation of one structural BMP is rarely sufficient to control both stormwater quantity impacts and the various pollutants that make up stormwater quality impacts. Would an engineer choose to use twenty sand filters in a watershed, one large stormwater wetland, or two wet ponds? Treatment 'trains', or systems, of BMPs are to be specifically tailored for particular environmental conditions as well as for particular stormwater quantity and quality impacts.

The economic methods to address each of the two research objectives employed and data used are discussed in section 3. Sections 4 and 5 present results, and conclusions and management implications, respectively.

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[3] BMPs should only be used in areas where the physical site characteristics are suitable. Some of the important physical site characteristics are soil type, watershed area, water table, depth to bedrock, site size and topography. If these conditions are not suitable, a BMP can loose effectiveness, require excessive maintenance or stop working.

2. Methodology

The costs of BMPs include both installment (construction and land) and annual operating costs (inspection and maintenance). The first category of costs will only occur in the year when the BMP is installed. The other costs may occur yearly through the life of the BMP to maintain it. In this section we discuss in detail the survey that was conducted to collect data to assess the different costs categories for North Carolina conditions.

Construction costs and annual operating costs are statistically analyzed for effects of scale by means of the estimation of BMP specific non-linear equations relating the costs to watershed size.

Given that structural stormwater BMPs require initial capital investments and then annual operating, the costs of these practices will often vary considerably over time. To estimate total economic impacts the stream of costs was discounted and annualized so that the various BMPs can be compared. The Present Value of Costs approach is used for this purpose.

Annual costs are to be related to the removal effectiveness of the specific BMP for a proper economic evaluation. This last part of this section, therefore includes a description of the sources and methods used for the assessment of the removal figures.

2.1 Cost Data

2.1.1 Construction Costs

Data on construction costs were collected by means of a phone survey and site contacts with designers and property owners in 1999-2001 and included a total of over 40 BMPs throughout eastern and central North Carolina. Consequently, the population of practices that were sampled spanned a range of local design criteria and storm water permitting requirements. The major structural stormwater BMPs that were analyzed included twelve wet ponds, twelve storm water wetlands, eight sand filters and eleven raingardens (Table 2).

The cost of construction collected was either the bid price or the known amount that was spent by granting agencies, such as the North Carolina Department of Transportation. If an agency or community supplied labor, such as with plant installation, the number of person-hours was estimated and an hourly labor rate of $20 per person-hour was applied. This wage rate was chosen to reflect the average wage of laborer ($15/ hour) and a 30% overhead cost. Construction costs do not include any piping or storm water conveyance that is external to the storm water BMP.

Construction and maintenance costs were set to those in Raleigh-Durham, North Carolina. This was done using the standard estimation guide used by many engineers, the R.S. Means Building Construction Cost Data (2001) handbook. The Means book provides a comparison of installation, material, and total costs for construction for cities across the United States to facilitate cost estimation of construction projects. Construction costs for several communities across North North Carolina, Virginia and Delaware could be related to those in Raleigh-Durham by using the Means conversion factors for total costs as listed in Table 3.

Maintenance costs were slightly more problematic. It was decided to relate maintenance costs by only using the installation conversion factor, which necessarily omits material costs. This was done because the vast majority of maintenance is only human labor. Because factors were not available for every community from which cost data was collected, certain cities were assigned conversion factors of a geographically adjacent city. These, too, are noted in Table 3. Costs data from 1999 and 2000 were converted to 2001 dollars by means of a 3 % inflation rate per year.

Table 2. BMPs surveyed to collect cost data for cities in North Carolina, Delaware, and Virginia

BMP Type	Number of Sites	Locations in North Carolina
Stormwater Wetlands	15	Banner Elk, Brevard, Cary, Durham, Edenton, Gastonia, New Bern, Smithfield, Taylorsville, Raleigh, Wilson, Wilmington
Wet Ponds	13	Cary, Fayetteville, Garner, Greensboro, Greenville, Raleigh, Rocky Mount, Wilmington, Wilson
Sand Filters	12	North Carolina: Charlotte, Durham, Greensboro, Raleigh, Wilson *Delaware*: Dover, Newark, Rehobeth Beach *Virginia*: Alexandria
Bio-retention	18	Aberdeen, Cary, Gastonia, Goldsboro, Greensboro, High Point, Kinston, Raleigh, Southern Pines

Table 3. Conversion Factors for estimating construction and maintenance costs

Location(s)	Means "Match"	Total Factor	Installation/ Maintenance Factor
Raleigh-Durham, Garner, Cary, Smithfield	Raleigh-Durham	76.5	55.1
Greensboro, High Point	Greensboro	76.3	54.9
Banner Elk, Brevard	Asheville	75.0	53.1
Taylorsville	Hickory	67.4	39.4
Gastonia	Gastonia	75.0	52.0
Charlotte	Charlotte	75.2	52.4
Fayetteville, Moore County	Fayetteville	75.6	55.1
Greenville, Rocky Mount, Wilson	Rocky Mount	68.7	40.8
Wilmington	Wilmington	75.2	54.1
Kinston, New Bern	Kinston	67.8	67.8
Edenton	Elizabeth City	70.3	43.4
Rehobeth Beach, DE, Dover, DE	Dover, DE	100.9	102.7
Newark, DE	Newark, DE	100.9	102.7
Alexandria, VA	Washington, DC	94.8	90.1

Source: Waier (2001)

2.1.2 Maintenance and Inspection Costs

All structural stormwater BMPs require inspection and periodic maintenance to prevent or overcome problems such as odor, insects, weeds, turbicity, trash and sediment. In fact inspection and maintenance are an important part in the operation of any BMP.

Some BMPs may require far more time for control and inspection to function effectively than other BMPs. For managers with high opportunity costs of their time (i.e., the return to time spent in other activities is large), management of intensive BMPs will hold a relative disadvantage. This cost is important to include even though it is often more difficult to measure than other input costs. There are also differences in relative maintenance efforts needed in terms of the frequency of scheduled maintenance, such as sediment clean outs, and chronic maintenance problems (such as clogging).

Estimates for the maintenance costs and inspection of the practices were obtained from the survey mentioned above (Table 2). For each practice the maintenance situation was evaluated. In a limited number of the observations the maintenance situation was considered inadequate and an upward correction of the maintenance costs was made.

The property manager was asked whether he or she knew what was spent on BMP upkeep on annual bases and if there were any special one-time maintenance costs, such as dredging, that occurred. If bid prices were not known, then the property owner estimated the number of person-hours and the $ 20 per person-hour labor rate as was mentioned above, was applied. There was ample information on wet pond upkeep and a reasonable amount of cost information for sand filter maintenance, however, far less reliable information was available for North Carolina, or surrounding states for that matter, on the maintenance costs associated with either bio-retention areas or stormwater wetlands. This was expected due to the fact that the use of these practices is essentially new to the region.

Table 4. Maintenance activities and rates per BMP.

BMP Type	Maintenance performed (rate/frequency)
Wet Pond	Mowing banks (monthly, seasonal). Outlet/inlet inspection (after large events). Removing vegetation from outlet (varies). Forebay dredging (0-3 times over life of pond).
Stormwater Wetland	Harvest and replanting of wetland vegetation (0-1 times over life of wetland). Outlet/inlet inspection (after large events). Removing vegetation from outlet (varies). Forebay dredging (0-3 times over life of pond).
Bio-retention Area	Pruning shrubs and trees (0-2 times per year). Mowing (monthly, seasonal). Weeding (monthly, seasonal). Re-mulching (1-2 times per year). Replanting shrubs (0-1 times over life of bio-retention area). Removing sediment accumulation (1-2 times over initial life of practice). Underdrain inspection (1 time per year).
Sand Filter	Dredging sedimentation chamber (1 time annually to 1 time every three years). Removing built up debris from sand chamber (2-3 times per year initially, 1 time per year thereafter). Outlet inspection (1 time per year). Underdrain inspection (1 time per year).

A list of maintenance activities appropriate for each practice is given in Table 4. Time per each activity varied by BMP size and the level of upkeep deemed appropriate by the owner. There were several BMPs which received very limited maintenance. Maintenance figures from these sites were omitted from the study, provided the practices did not appear to be functioning appropriately or were not meeting the aesthetic requirements the practice was required to meet. Not all the maintenance activities were performed for each BMP type listed. For example, a bio-retention device comprised of a mulch bottom with trees and shrubs would not need to be mowed.

2.1.3 Land Opportunity Costs

A continuous tradeoff exists between building stormwater BMPs and other land commitments. BMP construction may reduce the availability or the size of a (re-) development site, and this is a frequent concern of real-estate interests. Land opportunity costs recognize the foregone opportunity of using the land for other commitments. In highly urbanized areas dedicating land to stormwater BMPs involves a loss of development profit, and this loss is likely to be the most important cost item of a BMP.

The size of stormwater best management practices is dependent upon watershed composition and precipitation (Hunt and Doll, 2000). An important indicator is the runoff (typically runoff from the first inch of rainfall) which is determined by precipitation and curve number (CN). The CN reflects the ability of a watershed to store water through initial storage and subsequent infiltration. A high curve number suggests a very impervious area, such as a parking lot that sheds nearly all rainfall. Curve numbers for land that includes open space vary by soil types. The runoff value calculated by the curve number indicates how much water will run off per given area. To calculate total runoff volume for the stormwater practice to treat, the runoff value must be multiplied by the watershed area. With the storage volume known, it is then possible to calculate the surface area needed.

Table 5. Ratio of surface area to watershed size (in %) for stormwater BMPs.

	Wet Pond	Stormwater Wetland	Sandfilter	Bio-retention
State guidelines for NC				
• 50 % impervious		1.50		
• 70 % (70% or less for wet ponds)	0.75	1.96		N/A
• 80 %	0.91			
• 100 %	1.12		1.7	
NCSU- BAE guidelines				
Residential dev.				
• Piedmont	1.50	2.00		2.5
• Coastal Plain	0.75	1.00		1.5
Highly imp. area. (CN 90)				
• Piedmont and Coastal Plain	2.00	3.00		3.0
100 % impervious	5.00	6.50	1.7	7.0

From the survey (Table 2) minimal data was available on the actual surface area of the practices. Instead a couple of rules of thumb were applied to estimate the surface area. Sandfilters are commonly used for small impervious areas. Based on these watershed characteristics sand filters can be assumed to dedicate about 720 sf of surface area per drainage acre (1.7 %). Estimating the surface area for ponds, wetlands and bio-retention areas is more complicated due to the larger variation in watershed composition and conflicting opinions. Table 5 summarizes both State guidelines for NC and location specific sizing rules developed by Biological & Agricultural Engineering at NCSU. In the costs calculations the latter rules were used.

Prices of land vary to a large extent. In the calculations we distinguish three situations: (1) undeveloped land for commercial use with an average opportunity costs of $ 5 per square ft ($ 217,800/a), (2) undeveloped land for residential use with an average opportunity cost of $ 50,000 per acre, and (3) undeveloped land with zero opportunity cost because of the requirement for open space.

2.2 Cost Equations and Present Value of Costs (PVC) approach

As follows from the above, total costs (TC) of a stormwater BMP is made up of the following three components:

Construction costs + Maintenance & Inspection Costs + Land Opportunity Costs

First, to capture potential scale effects, regression equations relating construction and maintenance costs and watershed size are developed for the four types of BMPs (Wiegand *et al.*, 1986). The cost curves are specified as $C = ax^b e^u$, where C denotes costs of the BMP; x is the size of the watershed in acre, and e^u is the error term. For estimation purposes the costs curves are reformulated as $\ln Y = a + b \ln x + u$; parameters can then be estimated by conventional linear egression. The associated correlation coefficients (R^2) can then be examined to determined the validity of size effects on construction and maintenance costs. Scale effects exist if b is unequal to 0 and this implies that R^2 is unequal to zero.

Second, the differences in cost components over the lifetime of the BMPs need to be accounted for. Costs will vary considerably over time. BMPs require initial capital investments and then annual operating costs. Due to this time element, simply summing all costs over the lifetime of a BMP is inappropriate.

To estimate the correct economic impacts the stream of costs is discounted to provide a Present Value of Costs (PVC). Two ingredients are needed to calculate this value: the cash outflows, C_t, for each year $t = 1, \ldots, T$ of the duration of the BMP, and the discount rate i : $PVC = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t}$. The discount rate is a critical factor for determining the net value costs of a BMP. The discount rate reflects the time value of money and the risks associated with the specific industry. This study uses a discount rate of 10 % for the private developer.

The PVC values are then converted to **annualized costs per acre treated and annualized costs per percent of pollutant removed**, to enable BMPs of different duration, treatment area and removal effectiveness to be compared. For the PVC calculations presented in this report, a spreadsheet model was developed in Excel. Details are available upon request.

Taxes: Developers may be able to use the costs of structural stormwater BMPs as a deductible for tax purposes. Operating costs are generally fully deductible as expenses in the year incurred. Capital investments associated with compliance must generally be depreciated over some number of years. Tax advantages are highly dependent on the marginal tax rate and were not accounted for in the calculations.

2.3 Pollutant Removal Effectiveness

A large body of national research data was available on the removal effectiveness of the four types of BMPs. Particularly there was a considerable amount of data for areas surrounding the following cities: Austin TX; Baltimore, MD; Chicago, IL; Minneapolis, MN; Seattle, WA and Tampa, FL. However, North Carolina's climate is substantially different from many other parts of the U.S. with respect to temperature and precipitation. Because of this, a screening procedure was used to decide which data to use.

The out-of-state cities' weather was compared to the weather of three cities in North Carolina: Charlotte, Raleigh-Durham and Wilmington. These three cities represent the weather conditions found in eastern and central North Carolina, the locations of the BMP surveyed (Table 2).

Temperature and rainfall data over the period of 1990 -2000 was collected for the six out-of state and the three in-state cities using both the Midwestern Climate Information System (MICIS, 2000) and the Southeastern Regional Climate Center's CIRRUS system (CIRRUSweb, 2000). Average monthly mean temperature and average monthly precipitation level were assessed for each city and statistically analyzed for significant differences. Six comparisons are graphically shown in Appendix I.

The temperatures and precipitation levels of the remaining three cities: Austin TX, Baltimore, MD, and Tampa, FL, where similar to the climate of at least one of the three cities in North Carolina[4]. Therefore, pollutant removal information collected from research in the Austin, TX, region, the Baltimore-Washington metropolitan area, and the northern two-thirds of Florida were all included in the analysis and were added to what had been collected in North Carolina and Virginia.

Appendix II provides an overview of all the data sources used to assess the pollutant removal efficiencies. The two principal sources of best management practice effectiveness were the ASCE/EPA joint venture National BMP pollutant removal database (found at http://www.bmpdatabase.com), and The Center for Watershed Protection's National Pollutant Removal Performance Database (2000 version). Other sources were used as noted.

Pollutant loads (mass removals) were the efficiencies of choice for the study. Mass loads were chosen because they are a better measure of impact to downstream water bodies. In studies where both concentrations and mass removal percentages were given, the latter was chosen for use in this study. In systems where it was apparent that water inflow was equal or nearly equal to water outflow, concentration data was deemed reasonable to use in lieu of mass removal, were the latter data type not given.

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[4] Austin and Charlotte had similar temperatures, though Charlotte was somewhat cooler in the winter. Except for the month of June, the difference in the average monthly rainfall in Charlotte and Austin, TX was less than 1". Raleigh-Durham and Baltimore, MD were quite similar both with respect to temperature and rainfall, with Raleigh-Durham being slightly wetter and warmer. Again differences in rainfall were within 1" on a per-month basis. Finally, Wilmington, NC and Tampa, FL, were surprisingly similar. Precipitation levels for each city were high in late summer and early fall, reflecting tropical activity at both locations. The rainfall amounts for July-September were 7-8" for both cities. Tampa was warmer in the winter but the difference with Wilmington was within 10°F.

3. Results

3.1 Costs of individual BMPs per acre treated

Based on the cost data collected by the survey (Table 2) cost curves were estimated for construction and annual maintenance for each of the four BMPs. Also the surface area of the practices was assessed. The results are summarized in Table 5. The cost curves relate size of watershed area to expenditure. The relationships for the construction costs are also visualized in Appendix III.

Table 6 shows that all BMPs, except for bioretention not in sandy soil, displays large economies of scale within the practice. More specifically, the construction cost per acre treated decrease with the increase in the size of the watershed[5]. The same applies for the maintenance cost per acre. Recall that it is assumed that the BMPs analyzed were all optimally sized and designed from an engineering point of view (introduction).

Table 6. Summary of Construction Cost Curves, Annual Maintenance Cost Curves and Surface Area for five Stormwater BMPs in North Carolina, C = Cost in \$, x = Size of watershed in acre, SA = Surface Area in acre

	Wet Ponds	Stormwater Wetlands	Sand Filters	Bio-retention in clay soils	Bio-retention in sandy soils
Range of BMP size	0.75 – 67	4 – 200	0.5 – 9	0.3 – 9.2	0.3 – 9.2
Construction	$C=13{,}909x^{0.672}$	$C=3{,}852x^{0.484}$	$C=47{,}888\ x^{0.882}$	$C=10{,}162x^{1.088}$	$C=2{,}861x^{0.438}$
20-year Maintenance	$C=9{,}202\ x^{0.269}$	$C=4{,}502\ x^{0.153}$	$C=10{,}556\ x^{0.534}$	$C= 3{,}437\ x^{0.152}$	$C=3{,}437\ x^{0.152}$
Surface Area					
Residential Dev.:					
•Piedmont	SA=0.015x	SA=0.020x		SA=0.025x	SA=0.025x
•Coastal Plain	SA=0.0075x	SA=0.01x		SA=0.015 x	SA=0.015 x
Highly imp. area CN80					
•Piedmont and Coastal Plain	SA=0.02x	SA=0.03x		SA=0.03x	SA=0.03x
100 % impervious	SA=0.05x	SA=0.065x	SA=0.017x	SA=0.070x	SA=0.070x

Stormwater wetlands and Wet Ponds can be used for the same size of drainage area (Table 1). When comparing these two practices, it is apparent that per acre treated, stormwater wetlands are substantially cheaper in terms of construction costs than wet ponds (Table 6). This is not too surprising considering that wet ponds tend to have substantially higher excavation costs than stormwater wetlands. There is a similar difference in the annual maintenance cost per acre. On the other hand, stormwater wetlands tend have a 30 % larger surface area than wet ponds. For a 50 acre watershed in a residential development in the NC Piedmont, this would imply that 1 acre of land would have to be dedicated to a stormwater wetland and 0.75 acre for a wet pond.

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[5] More formally, taking the derivative, $\partial C / \partial x$, can assess this. For example, for wet ponds marginal construction costs per extra acre of watershed are $9{,}346\ x^{-0.328}$. This is a downward sloping curve.

Wet Ponds and Bio-retention areas both can be used for smaller watersheds but show large differences in both construction costs and operation costs with raingardens being least expensive, particularly in sandy soil. Raingardens, however, tend to take up more land.

A proper economic evaluation requires all three cost components (construction, maintenance & inspection, land) to be integrated into one cost figure and also to take account of the differences in cost components over the lifetime. For this purpose annualized costs per acre treated were calculated using the net value of costs approach. The surface area of the practices varies by location. In the calculation of the annualized costs per acre treated, we therefore distinguish between residential development in Piedmont and Coastal Plain, highly impervious areas (CN 80) and areas that are 100 % impervious. In addition three situations for the price of land were accounted for: (1) undeveloped land for commercial use @ $ 5 per square ft ($ 217,800/a), (2) undeveloped land for residential use @ $ 50,000 per acre, and (3) undeveloped land with zero opportunity cost because of the requirement for open space.

A detailed analysis of the annualized costs for each BMP per acre treated in relation to size of watershed, location and cost of land is given in Appendix IV. It is obvious that there are large differences. For a more specific analysis we compared the BMPs by location and the range of watershed size for which they overlap The results of the annual costs per acres treated for each of the five BMPs are given in (Tables 7-13). Notice that the economic assessment in Tables 7-13 does not take into account any differences in the removal effectiveness of the BMPs. This issue is addressed in section 3.2.

Bio-retention offers the least expensive option for smaller sized watersheds (0.75 - 4 acre) in residential or commercial areas in the North Carolina Piedmont and Coastal Plain. In the Coastal plain where sand is prevalent, bio-retention areas constructed in sandy soil are preferable to those installed in clay or other non-sandy soil. In the Piedmont it appears the wet ponds become optimal for mid size watersheds (9 acre), while bio-retention remains an option through 9 acre watershed sizes in the coastal plain, provided the soil is sandy. For larger watersheds, wetlands are to be preferred (Tables 7 and 8). If bioretention has to be installed in other soil types than sand, its cost per acre treated will be considerably higher[6]. However, bioretention will still be the most economical option for small watersheds up to about 6 acres followed by wet ponds for mid size watersheds and stormwater wetland for larger watershed. It is important to note that stormwater wetlands do need to have relatively sure supplies of water. This is often difficult to achieve on watersheds less that 15 acres. Sand filters are not considered in this analysis because they would nearly never be employed in residential development.

Tables 9-10 show that the same conclusion holds for watersheds in highly impervious areas with commercial or residential use as well as for areas that are 100 % impervious. When requirements for open space apply, again the installation of bio-retention areas is preferred over sand filters or wet ponds in smaller watershed and wetlands are the least expensive BMP for larger watersheds (Table 13).

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[6] Notice that bioretention for non-sandy soil shows an increase in the cost per acre between 4 and 9 acres. This increase is due to the construction costs not exhibiting economies of scale for this practice (see Table 6 and the figure in Appendix II).

Table 7. Piedmont, residential areas[1]: Comparison of the annualized cost of BMPs ($/a)

	Watershed size (acre)[2]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,121	2,826	2,457	2,227	1,761	**1,343**	1,112	963	774
Stormwater Wetlands									**276**	**238**	**197**
Bio-retention in clay	**2,333**	**1,981**	**1,807**	**1,723**	**1,646**	**1,615**	**1,593**	1,630			

1) Opportunity costs of land $ 50,000 per acre.
2) Not all sizes apply to each BMP.

Table 8. Coastal Plain, residential areas[3]: Comparison of the annualized cost of BMPs ($/a)

	Watershed size (acre)[4]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,077	2,782	2,413	2,183	1,717	1,299	1,068	919	730
Stormwater Wetlands									**218**	**179**	**138**
Bio-retention in clay	2,274	1,922	1,748	1,664	1,588	1,556	1,535	1,571			
Bio-retention in sand	**1,863**	**1,296**	**979**	**806**	**618**	**515**	**340**	**220**			

3) Opportunity costs of land $ 50,000 per acre.
4) Not all sizes apply to each BMP.

Table 9. Moderately impervious areas (CN=80), commercial use[5]: Comparison of the annualized cost of BMPs ($/a)

	Watershed size (acre)[6]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,545	3,250	2,881	2,651	2,184	1,767	1,536	1,387	1,197
Stormwater Wetlands									**927**	**888**	**847**
Bio-retention in clay											
Bio-retention in sand	**2,572**	**2,005**	**1,688**	**1,515**	**1,327**	**1,224**	**1,049**	**929**			

5) Opportunity costs of land $ 5 per square ft.
6) Not all sizes apply to each BMP.

Table 10. Moderately impervious areas (CN=80), residential use[7]: Comparison of the annualized cost of optional BMPs ($ per acre treated)

	Watershed size (acre)[8]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,151	2,855	2,487	2,257	1,790	1,373	1,142	993	803
Stormwater Wetlands									**335**	**297**	**256**
Bio-retention in clay	2,983	2,631	2,457	2,373	2,297	2,265	2,244	2,280			
Bio-retention in sand	**1,980**	**1,413**	**1,096**	**924**	**735**	**632**	**457**	**338**			

7) Opportunity costs of land $ 50,000 per acre.
8) Not all sizes apply to each BMP.

Table 11. Impervious 100%, commercial use[9]: Comparison of the annualized cost of BMPs ($/a)											
	Watershed size (acre)[12]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,327	3,031	2,663	2,433	1,966	1,549	1,318	1,169	979
Stormwater Wetlands									**541**	**502**	**461**
Sandfilters	8,760	7,920	7,339	6,967	6,491	6,183	5,528	4,887			
Bio-retention in clay	3,879	3,527	3,353	3,269	3,192	3,161	3,139	3,176			
Bio-retention in sand	**2,186**	**1,619**	**1,302**	**1,129**	**941**	**838**	**663**	**543**			
9) Opportunity costs of land $ 5 per square ft. 10) Not all sizes apply to each BMP.											

Table 12. Impervious 100%, residential use[11]: Comparison of the annualized cost of BMPs ($/a)											
	Watershed size (acre)[12]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,327	3,031	2,663	2,433	1,966	1,549	1,318	1,169	979
Stormwater Wetlands									**541**	**502**	**461**
Sandfilters	8,760	7,920	7,339	6,967	6,491	6,183	5,528	4,887			
Bio-retention in clay	2,97	2,245	2,071	1,987	1,911	1,879	1,858	1,894			
Bio-retention in sand	**2,186**	**1,619**	**1,302**	**1,129**	**941**	**838**	**663**	**543**			
11) Opportunity costs of land $ 50,000 per acre. 12) Not all sizes apply to each BMP.											

Table 13. Open space [13]: Comparison of the annualized cost of optional BMPs ($ per acre)											
	Watershed size (acre)[14]										
BMP type	*0.3*	*0.5*	*0.75*	*1.0*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds			3,033	2,738	2,369	2,139	1,673	1,255	1,024	875	686
Stormwater Wetlands									**159**	**121**	**79**
Sandfilters[15]	8,660	7,820	7,239	6,867	6,391	6,083	5,428	4,787			
Bio-retention in clay	2,215	1,863	1,689	1,605	1,529	1,498	1,476	1,513			
Bio-retention in sand	**1,804**	**1,237**	**920**	**747**	**559**	**456**	**281**	**161**			
13) Opportunity costs of land $ 0. 14) Not all sizes apply to each BMP. 15) Open space sand filters assumes 100% commercial use with required dedication of land to green space. Sand filters could technically be used in this situation.											

3.2 Removal effectiveness and cost per percent pollutant removed

Based on the data sources described in section 2.3, the effectiveness of each of the four BMPs n the Southeast and Mid-Atlantic was determined. For each BMP the data on removal of Total Suspended Solids (TSS), Total Phosphorus (TP), total nitrogen (TN), nitrate (NO_3^-) and zinc (Zn) was analyzed for scale effects by relating the removal effectiveness to the size of the watershed. While additional data was collected for other pollutants, there were too little to use for making BMP determinations. Linear regression was used for this purpose. Based on the results of this statistical analysis, each practice was assigned a single removal rate (the median removal efficiency) in the cost-effectiveness analysis. That is, assuming the practice is designed properly, it will work comparably well whether it serves a 10-acre watershed or a 50-acre watershed. The median pollutant removal efficiencies for each of the practices are reported in Table 14.

There was a wide range of scatter in the data with respect to pollutant removal efficiencies. No significant relationship could be assessed between removal efficiency and watershed size (note Figures 1 and 2) and therefore median pollutant removal efficiencies were used for this report. This is certainly an area for future research and adaptation. Median efficiencies were chosen in lieu of mean efficiencies because the former allows more skewing of data. Outliers, such as negative pollutant removal efficiencies have a more pronounced effect on the results. As such, median removal rates better represent the pollutant removal to expect.

Pollutant removal rates for stormwater wetlands were lower than expected (Table 14). Previous reviews of literature had shown the median stormwater wetland TSS removal rate to be similar to sand filters (around 80%). In North Carolina it has been assumed that stormwater wetlands work substantially better than wet ponds in removing most types of pollutants. However, for TSS, TP, and NO_3, wet ponds and stormwater wetland function is quite comparable.

The negative and low removal efficiencies (Table 14) for nitrate-nitrogen found for sand filter and bio-retention are due in great part to the design configuration. Bio-retention areas and sand filters are designed to drain freely, and the lack of an anaerobic zone is held responsible for low to negative removal rates of nitrate-nitrogen (Davis *et al.*, 2001); Bell *et al.*, 1995). Two biological processes for nitrogen conversion occur within the soils of sand filters and bio-retention areas: ammonification and nitrification (Kadlec and Knight, 1996). These microbial-led transformations are most apt to occur in aerobic zones of the soil layer. See Figure 3 for a simple illustration. Ammonification is the conversion of organic nitrogen to ammonia-nitrogen by bacteria. This process occurs at a much faster rate in aerobic environments, though, it can occur at a slower rate in anaerobic or anoxic zones. Ammonia-nitrogen is then converted to nitrate-nitrogen via the process of nitrification. Nitrification necessarily occurs in aerobic environments. The bacteria *nitrosomanus* and *nitrobacter* convert ammonia-nitrogen to nitrite and nitrate-nitrogen, respectively. The nitrification process can occur in as few as 0.75 days (Ingersoll and Baker, 1998). Typically, this is the end of the nitrogen transformations within a sand filter or bio-retention area, meaning a net export of nitrate-nitrogen should be expected from bio-retention areas and sand filters. The only reason a positive removal was noticed with bio-retention areas is that an anaerobic zone was inadvertently created in a few of the study sites (Davis, 2002).

Figure 1. TSS Removal Efficiency - Stormwater Wetlands

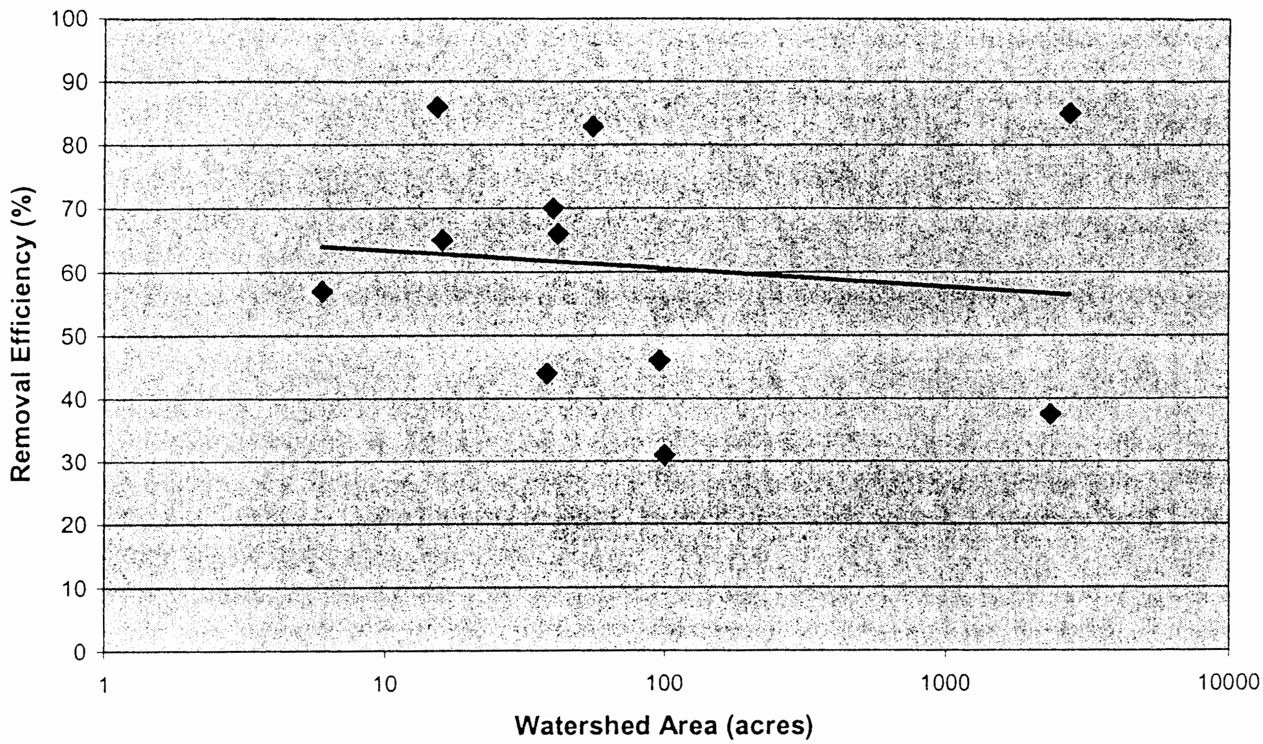


Figure 2. TP Removal Efficiency - Wet Ponds

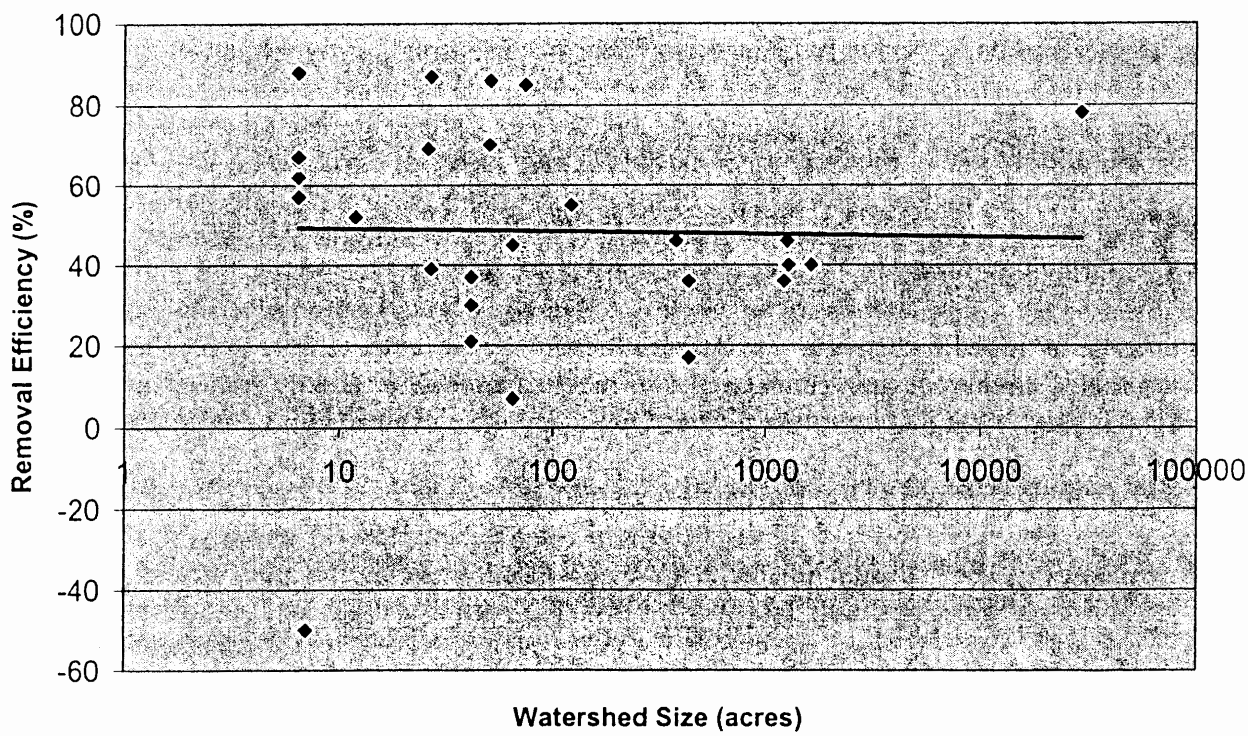
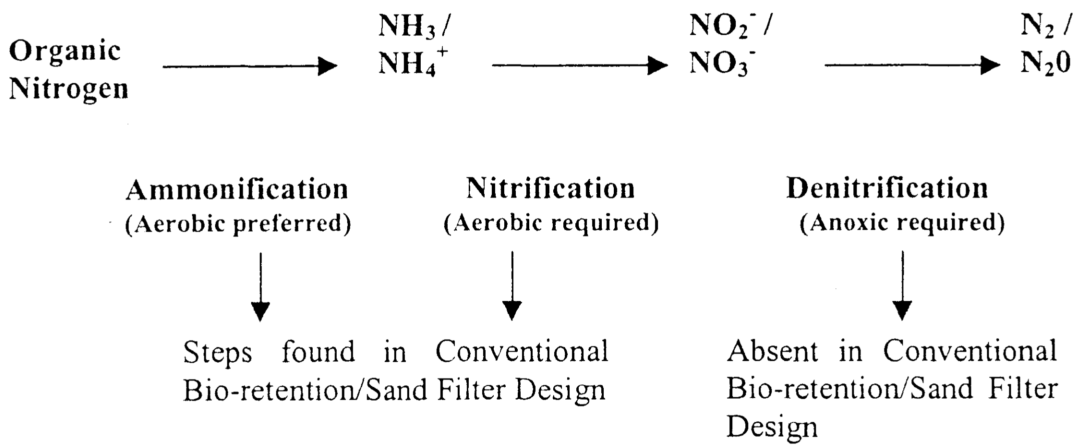


Figure 3. Schematic of Biological Transformations of Nitrogen (adapted from Kadlec and Knight, 1996)



Tables 15-20 relate the information on removal effectiveness (Table 14) to the cost of per acre treatment of the BMPs by location as presented in Tables 6-12. The economic dominant BMP for each type of pollutant and watershed size is highlighted in **bold** in Tables 14-19.

For TP and Zn, the conclusion are very similar to those based on cost per acre treated (section 3.1). For smaller watersheds, bioretention is the most cost-effective option whereas wetlands are preferable for larger wetlands. Based on nitrate the conclusion is more mixed. Where the opportunity cost of land is very high (commercial use), a wet ponds is preferable over a bioretention area for small watersheds. Data on TSS and TN removal effectiveness for bio-retention was not available and no comparison of BMPs was made for the cost of removing these pollutants. Note that literature values are highly variable, which is caused in part by (1) the different methods used to calculate efficiency and (2) the fact that efficiencies are often dependent on hydraulic residence time.

Table 14. Median Removal Effectiveness and number of sites analyzed for four BMPs from studies in the Southeast and Mid-Atlantic

BMP Type	**TSS**		**TP**		**NO_3**		**TN**		**Zn**	
	Rmvl Effic. (%)	No. Sites	Rmvl Effic. (%)	No. Sites	Rmvl Effic. (%)	No. Sites	Rmvl Effic. (%)	No. Sites	Rmvl Effic. (%)	No. Sites
Wet Ponds	65	27	46	28	42.5	16	28	27	51	24
Stormwater Wetlands	61	14	32.5	14	55	8	22	14	49	6
Sand Filters	79	12	59	11	(56.5)	11	41	12	64	11
Bio-retention	N/A	-	71	5	16	4	45	4	89	4

Table 15. Residential areas[15]: annualized cost in $ per % pollutant removed of optional BMPs										
	Watershed size (acre)[16]									
BMP type		*0.5*	*0.75*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds:										
$ per % TSS			48	38	34	27	21	17	15	12
$ per % TP			68	53	48	38	29	24	21	17
$ per % NO_3			73	58	52	41	32	26	23	18
$ per % TN			111	88	80	63	48	40	34	28
$ per % Zn			61	48	44	35	26	22	19	15
Wetlands:										
$ per % TSS								4	4	3
$ per % TP								**6**	**5**	**4**
$ per % NO_3								**7**	**6**	**5**
$ per % TN								13	11	9
$ per % Zn								**6**	**5**	**4**
Bio-retention:										
$ per % TP	33	28	25	23	23	22	23			
$ per % NO_3	142-146	120-124	109-113	99-103	97-101	96-100	98-102			
$ per % TN	52	44	40	35	36	35	36			
$ per % Zn	26	22	20	18	18	18	18			
Bio-retention sand:										
$ per % TP	**27**	**19**	**15**	**10**	**8**	**6**	**4**			
$ per % NO_3	**116-120**	**81-85**	**61-65**	**39-42**	**32-36**	**21-25**	**14-17**			
$ per % TN	**43**	**30**	**23**	**15**	**13**	**9**	**6**			
$ per % Zn	**22**	**15**	**12**	**8**	**6**	**4**	**3**			

15) Opportunity costs of land $ 50,000 per acre. The first figure indicates the cost for the Coastal Plain and the second figure for the Piedmont. Only the Piedmont figure is reported when the difference between both regions is $1 or less. 16) Not all sizes apply to each BMP.

Table 16. Moderately impervious areas, commercial use[17] (CN80), annualized cost in $ per % pollutant removed of optional BMPs										
	Watershed size (acre)[18]									
BMP type	*0.3*	*0.5*	*0.75*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds:										
$ per % TSS			55	44	41	34	27	24	21	18
$ per % TP			77	63	58	47	38	33	30	26
$ per % NO_3			**83**	**68**	**62**	**51**	**42**	36	33	28
$ per % TN			127	103	95	78	63	55	50	43
$ per % Zn			70	57	52	43	35	30	27	23
Wetlands:										
$ per % TSS								14	14	13
$ per % TP								**20**	**19**	**18**
$ per % NO_3								**22**	**21**	**20**
$ per % TN								42	40	39
$ per % Zn								19	18	17
Bio-retention:										
$ per % TP	42	37	35	32	32	32	32			
$ per % NO_3	186	164	154	144	142	140	143			
$ per % TN	66	58	55	51	50	50	51			
$ per % Zn	34	30	28	26	25	25	26			
Bio-retention sand:										
$ per % TP	**36**	**28**	**24**	**19**	**17**	**15**	**13**			
$ per % NO_3	**161**	**125**	105	83	76	66	58			
$ per % TN	**57**	**45**	**38**	**29**	**27**	**23**	**21**			
$ per % Zn	**29**	**23**	**19**	**15**	**14**	**12**	**10**			

17) Opp. cost land $ 217,800, 18) Not all sizes apply to each BMP.

Table 17. Moderately impervious areas, residential use[19] (CN80), annualized cost in $ per % pollutant removed by optional BMP										
	Watershed size (acre)[20]									
BMP type	*0.3*	*0.5*	*0.75*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds:										
$ per % TSS			48	38	35	28	21	18	15	12
$ per % TP			68	54	49	39	30	25	22	17
$ per % NO_3			74	59	53	42	32	27	23	19
$ per % TN			113	89	81	64	49	41	35	29
$ per % Zn			62	49	44	35	27	22	19	16
Wetlands:										
$ per % TSS								5	5	4
$ per % TP								**7**	**6**	**6**
$ per % NO_3								**8**	**7**	**6**
$ per % TN								15	13	12
$ per % Zn								**7**	**6**	**5**
Bio-retention:										
$ per % TP	34	29	26	24	24	23	24			
$ per % NO_3	149	127	117	107	105	103	106			
$ per % TN	53	45	41	38	37	37	38			
$ per % Zn	27	23	21	19	19	19	19			
Bio-retention sand:										
$ per % TP	**28**	**20**	**15**	**10**	**9**	**6**	**5**			
$ per % NO_3	**124**	**88**	**69**	**46**	**40**	**29**	**21**			
$ per % TN	**44**	**31**	**24**	**16**	**14**	**10**	**8**			
$ per % Zn	**22**	**16**	**12**	**8**	**7**	**5**	**4**			
16) 19) Opp. cost land $ 50,000, 20) Not all sizes apply to each BMP.										

Table 18. Imperviousness 100%, commercial use[21], annualized cost in $ per % pollutant removed by optional BMP

	Watershed size (acre)[22]									
BMP type	*0.3*	*0.5*	*0.75*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds:										
$ per % TSS			66	56	53	45	39	35	33	30
$ per % TP			94	79	74	64	55	50	47	43
$ per % NO_3			**101**	**86**	**80**	**69**	**60**	54	51	46
$ per % TN			154	130	122	105	91	82	77	70
$ per % Zn			85	72	67	58	50	45	42	39
Wetlands:										
$ per % TSS								28	27	27
$ per % TP								**40**	**39**	**38**
$ per % NO_3								**43**	**42**	**41**
$ per % TN								83	81	79
$ per % Zn								**37**	**36**	**36**
Sandfilters:										
$ per % TSS	140	127	118	105	100	90	80			
$ per % TP	198	179	167	148	142	127	114			
$ per % NO_3	**214**	194	181	161	153	138	123			
$ per % TN	222	201	187	166	159	143	127			
$ per % Zn	142	129	120	107	102	92	82			
Bio-retention:										
$ per % TP	55	50	47	45	45	44	45			
$ per % NO_3	242	220	210	200	198	196	198			
$ per % TN	86	78	75	71	70	70	71			
$ per % Zn	44	40	38	36	36	35	36			
Bio-retention sand:										
$ per % TP	**49**	**41**	**36**	**31**	**30**	**27**	**26**			
$ per % NO_3	217	**181**	161	139	132	122	114			
$ per % TN	**77**	**64**	**57**	**49**	**47**	**43**	**41**			
$ per % Zn	**39**	**33**	**29**	**25**	**24**	**22**	**21**			

17) 21) Opp. cost land $ 217,800, 22) Not all sizes apply to each BMP.

Table 19. Imperviousness 100%, residential use[23], annualized cost in $ per % pollutant removed by optional BMP										
	Watershed size (acre)[24]									
BMP type	*0.3*	*0.5*	*0.75*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds:										
$ per % TSS			51	41	37	30	24	20	18	15
$ per % TP			72	58	53	43	34	29	25	21
$ pe % NO_3			78	63	57	46	36	31	28	23
$ per % TN			119	95	87	70	55	47	42	35
$ per % Zn			65	52	48	39	30	26	23	19
Wetlands:										
$ per % TSS								8	8	7
$ per % TP								**12**	**11**	**10**
$ per % NO_3								**13**	**12**	**11**
$ per % TN								25	23	21
$ per % Zn								**11**	**10**	**9**
Sandfilters:										
$ per % TSS	135	122	113	100	95	85	75			
$ per % TP	190	172	160	141	134	120	106			
$ per % NO_3	206	186	173	153	145	130	115			
$ per % TN	214	193	179	158	151	135	119			
$ per % Zn	137	124	115	101	97	86	76			
Bio-retention:										
$ per % TP	37	32	29	27	26	26	27			
$ per % NO_3	162	140	129	119	117	116	118			
$ per % TN	58	50	46	42	42	41	42			
$ per % Zn	29	25	23	21	21	21	21			
Bio-retention sand:										
$ per % TP	**31**	**23**	**18**	**13**	**12**	**9**	**8**			
$ per % NO_3	**137**	**101**	**81**	**59**	**52**	**41**	**34**			
$ per % TN	**49**	**36**	**29**	**21**	**19**	**15**	**12**			
$ per % Zn	**25**	**18**	**15**	**11**	**9**	**7**	**6**			
23) Opp. cost land $ 50,000, 24) Not all sizes apply to each BMP.										

Table 20. Any area when requirement of open space apllies[25], annualized cost in $ per % pollutant removed by optional BMP

	Watershed size (acre)[26]									
BMP type	*0.3*	*0.5*	*0.75*	*1.5*	*2*	*4*	*9*	*16*	*25*	*50*
Wet Ponds:										
$ per % TSS			47	36	33	26	19	16	13	11
$ per % TP			66	52	47	36	27	22	19	15
$ per % NO_3			71	56	50	39	30	24	21	16
$ per % TN			108	85	76	60	45	37	31	24
$ per % Zn			59	46	42	33	25	20	17	13
Wetlands:										
$ per % TSS								2	2	1
$ per % TP								**3**	**3**	**2**
$ per % NO_3								**4**	**3**	**2**
$ per % TN								**7**	**5**	4
$ per % Zn								**3**	**2**	**2**
Sandfilters:										
$ per % TSS	133	120	111	98	94	84	74			
$ per % TP	188	170	157	139	132	118	104			
$ per % NO_3	204	184	170	150	143	128	113			
$ per % TN	211	191	177	156	148	132	117			
$ per % Zn	135	122	113	100	95	85	75			
Bio-retention:										
$ per % TP	31	26	24	22	21	21	21			
$ per % NO_3	138	116	106	96	94	92	95			
$ per % TN	49	41	38	34	33	33	34			
$ per % Zn	25	21	19	17	17	17	17			
Bio-retention sand:										
$ per % TP	**25**	**17**	**13**	**8**	**6**	**4**	**2**			
$ per % NO_3	**113**	**77**	**58**	**35**	**28**	**18**	**10**			
$ per % TN	**40**	**27**	**20**	**12**	**10**	**6**	**4**			
$ per % Zn	**20**	**14**	**10**	**6**	**5**	**3**	**2**			

25) Opp. cost land $ 0, 26) Not all sizes apply to each BMP.

3.3 BMP systems

The issue of systems of BMPs is illustrated by way of two case studies:

Case study A

For a 10-acre watershed with CN 80 we compare the installation of a bioretention area (clay soil) plus a wet pond to the installation of a wetland. The bioretention area and wet pond each treat ½ of the 10-acre watershed. The wetland would treat the entire watershed. The comparison is made both for a commercial and a residential area.

Tables 21 and 22 show that in both cases, the cost per acre treated or per % pollutant removed are significantly lower when installing the stormwater wetland.

Case Study B

For a 10 acre watershed we compare 4 bio-retention areas (clay soil) treating 1.25 acres each in front of a wetland that treats all 10 acres with a wet pond that treats the whole watershed. The comparison is made both for a commercial and a residential area with CN 80.

Table 23 shows that for commercial areas, the single practice is to be preferred when cost per acre is the criteria. However, the combined practice is more cost efficient based on the cost per percent of pollutant removed. For residential areas (Table 24) cost of land is considerably less than for commercial areas and this makes the combined practice more competitive in terms of cost per acre. Consequently, the combined practice is to be preferred based on either cost per acre or cost per percent pollutant removed. The example in Tables 23 and 24 shows that placing the bio-retention areas in line with the wetland enhances the removal efficiency of the practices and that this reduces the cost per percent pollutant removed considerably.

Table 21. Commercial area: comparison of bioretention area + wet pond with a wetland, 10 acre watershed with CN 80.

Practice and acreage treated	Bioretention 5 acre	Wet pond 5 acre	Wetland 10 acre
Construction Cost	58,541 + 41,021 =	99,562	11,740
Annual Maintenance Cost	525 + 2,906 =	3,431	752
Opportunity cost of land	32,670 + 21,780 =	54,450	65,340
Present Value of Total Costs	95,680 + 87,544 =	183,224	83,486
Annualized cost /acre watershed	(2,248+ 2,057)/2 =	2,152	981
Annualized cost per % pollutant removed:			
• TSS	N/A		15
• TP	38		21
• NO3	99		23
• TN	62		45
• Zn	33		20

Table 22. Residential area: comparison of bioretention area + wet pond with a wetland, 10 acre watershed with CN 80.		
Practice and acreage treated	Bioretention 5 acre / Wet pond 5 acre	Wetland 10 acre
Construction Cost	58,541 + 41,021 = 99,562	11,740
Annual Maintenance Cost	525 + 2,906 = 3,431	752
Opportunity cost of land	7,500 + 5,000 = 12,500	15,000
Present Value of Total Costs	70,510 + 70,764 = 141,274	33,146
Annualized cost /acre watershed	(1,657 + 1,663)/2 = 1,660	389
Annualized cost per % pollutant removed:		
• TSS	N/A	6
• TP	30	8
• NO3	72	9
• TN	48	18
• Zn	26	8

Table 23. Commercial area: comparison of 4 bioretention areas treating 1.25 ac in line with wetland treating 10 ac with a wet pond, 10 acre watershed with CN 80.		
Practice and acreage treated	4 Bioretention areas of 1.25 acre / Wet land 10 acre	Wet pond 10 acre
Construction Cost	5,180 + 11,740 = 16,920	65,357
Annual Maintenance Cost	1,700 + 752 = 2,452	4,411
Opportunity cost of land	32,670 + 65,340 = 98,010	43,560
Present Value of Total Costs	98,967 + 83,486 = 182,453	146,474
Annualized cost /acre watershed	1,162 + 981 = 2,143	1,721
Annualized cost per % pollutant removed:		
• TSS	N/A	26
• TP	27	37
• NO3	34	40
• TN	33	61
• Zn	23	34

Table 24. Residential area: comparison of 4 bioretention areas treating 1.25 ac in line with wetland treating 10 ac with a wet pond, 10 acre watershed with CN 80.		
Practice and acreage treated	4 Bioretention areas of 1.25 acre / Wet land 10 acre	Wet pond 10 acre
Construction Cost	51,816 + 11,740 = 63,556	65,357
Annual Maintenance Cost	1,700 + 752 = 2,452	4,411
Opportunity cost of land	7,500 + 15,000 = 22,500	10,000
Present Value of Total Costs	73,797 + 33,146 = 106,943	112,914
Annualized cost /acre watershed	867 + 389 = 1,256	1,327
Annualized cost per % pollutant removed:		
• TSS	N/A	20
• TP	16	29
• NO3	21	31
• TN	20	47
• Zn	13	26

References

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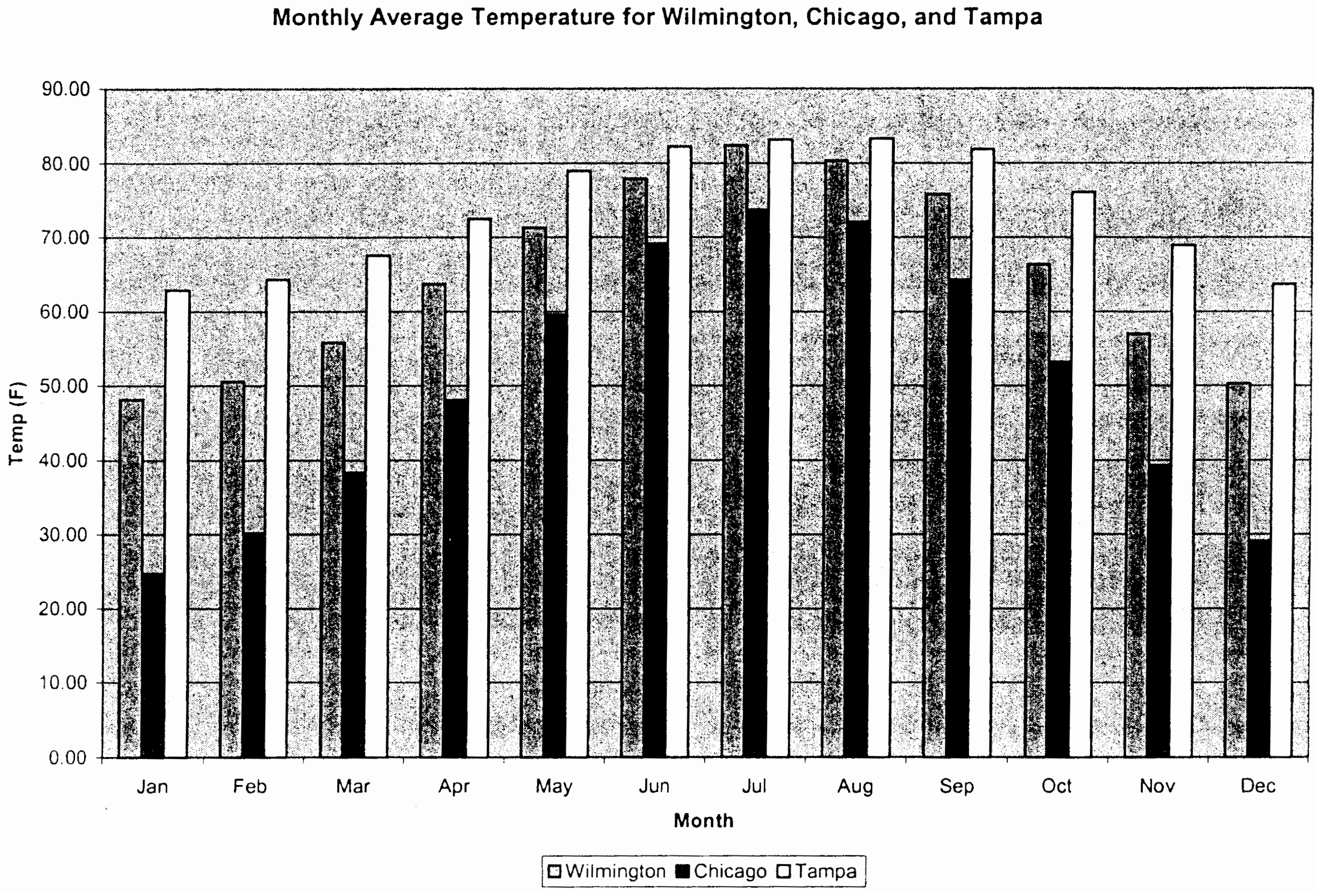
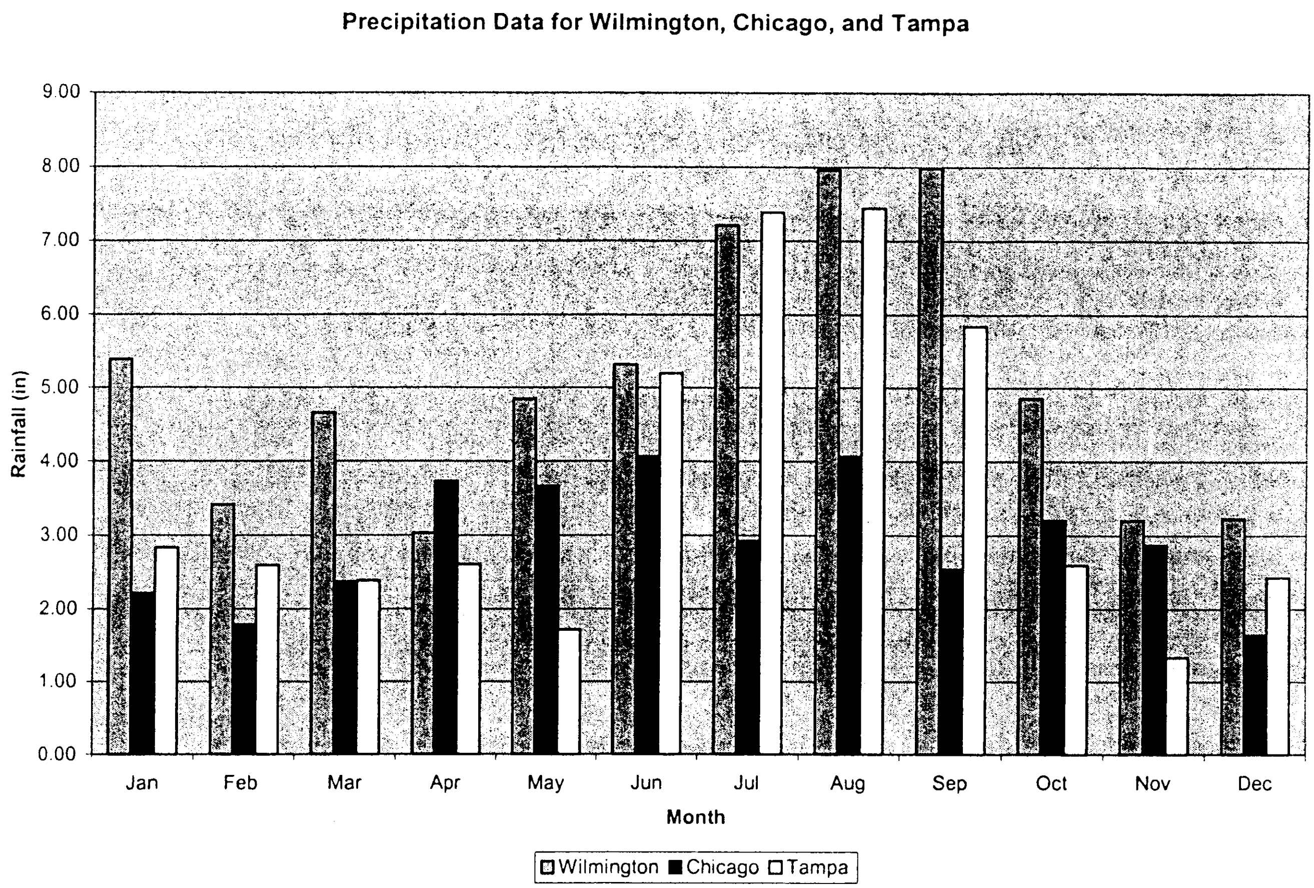
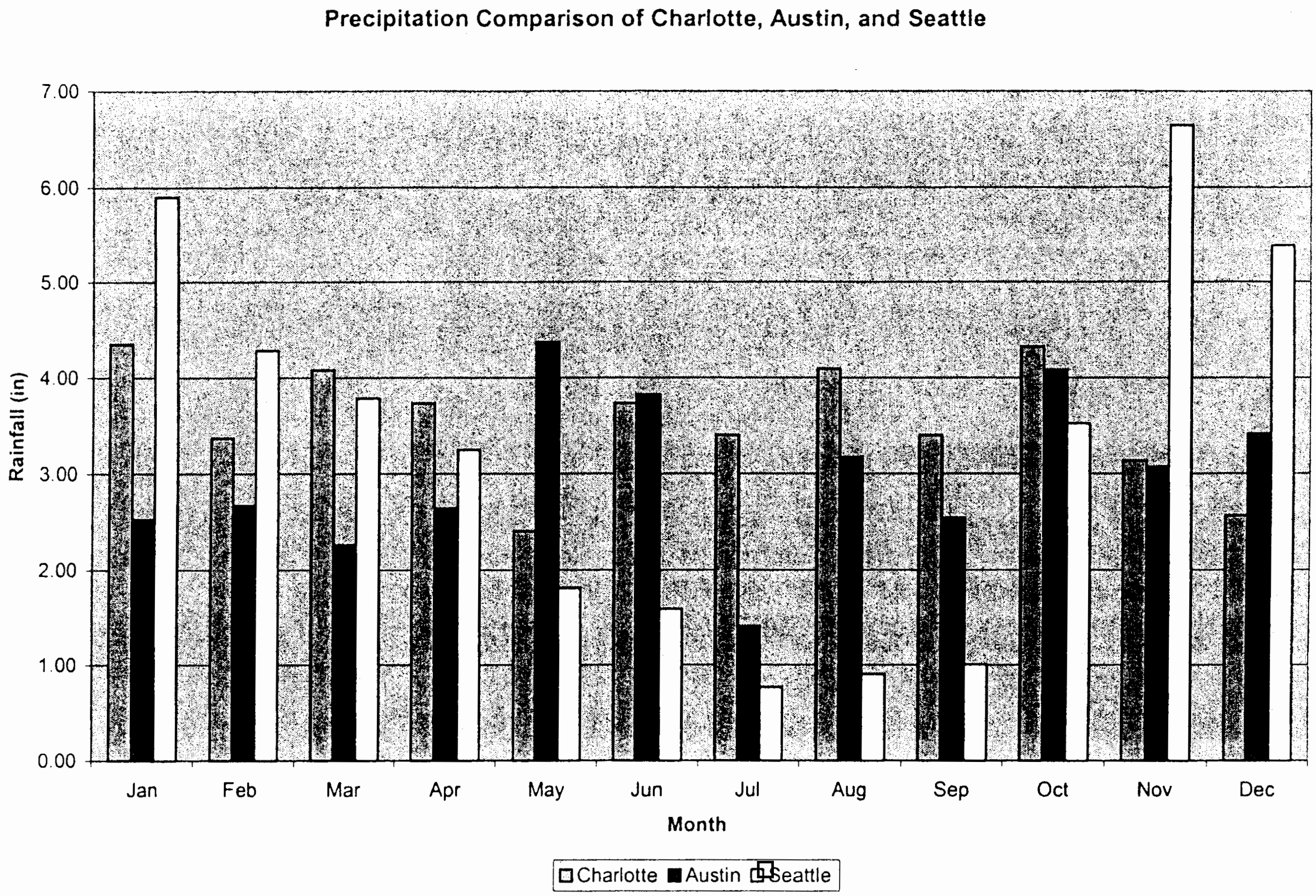
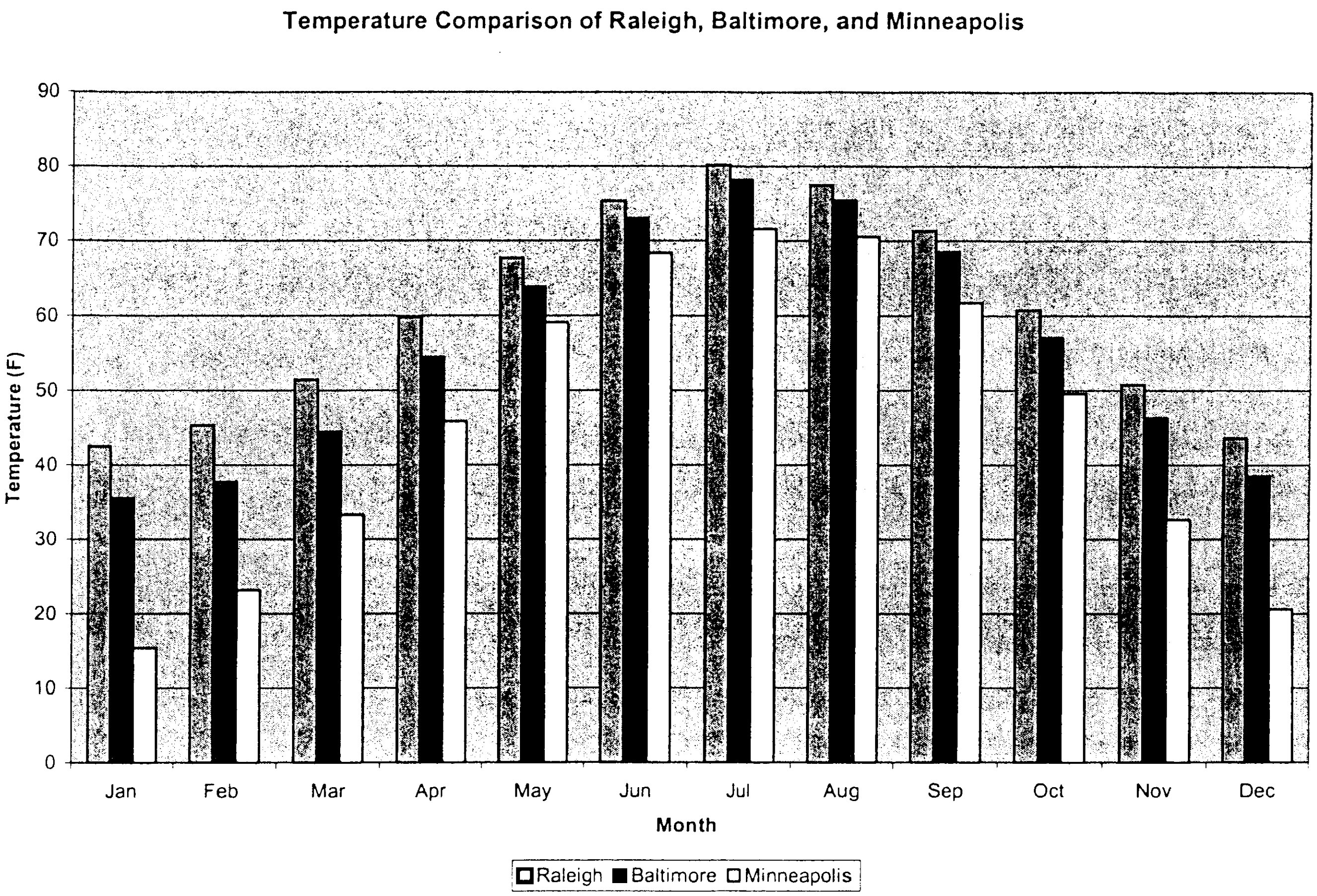
Appendix I. Precipitation and Temperature Comparison of Six U.S. Cities with locations in North Carolina.

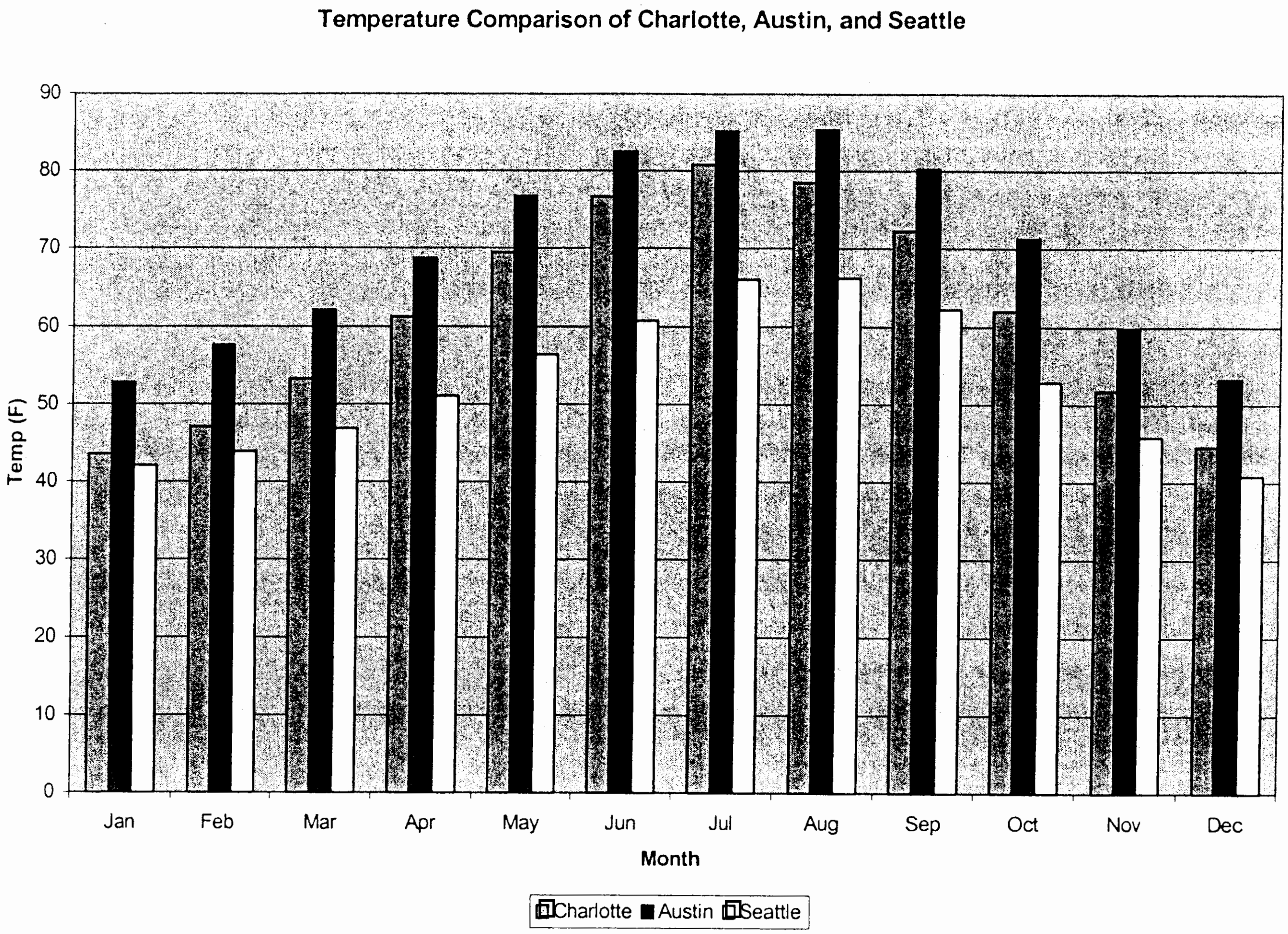



Precipitation Data for Wilmington, Chicago, and Tampa
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Rainfall (in)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Wilmington
Chicago
Tampa

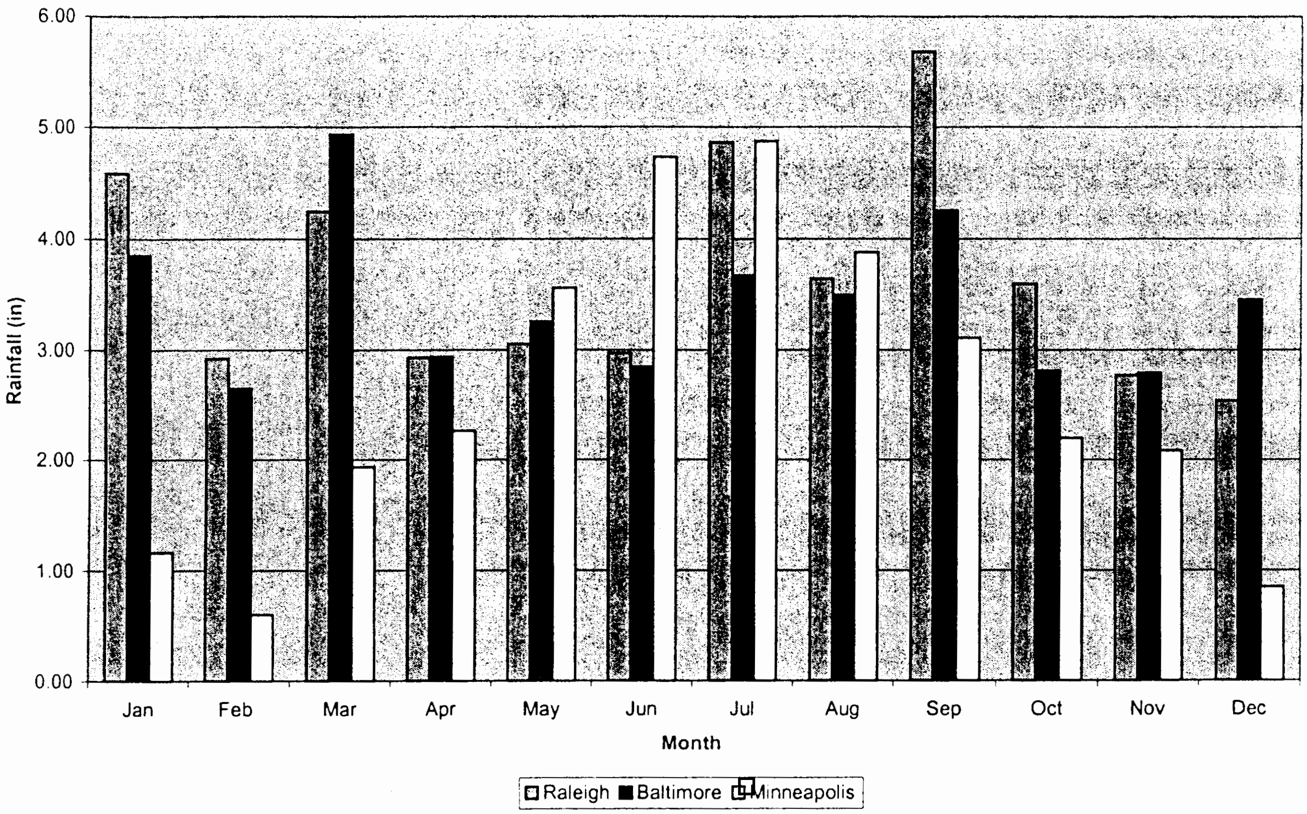

Precipitation Comparison of Charlotte, Austin, and Seattle
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Rainfall (in)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Charlotte
Austin
Seattle



Temperature Comparison of Raleigh, Baltimore, and Minneapolis
Temperature (F)
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Raleigh
Baltimore
Minneapolis


Temperature Comparison of Charlotte, Austin, and Seattle
90
80
70
60
50
40
30
20
10
0
Temp (F)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Charlotte
Austin
Seattle

Precipitation Comparison of Raleigh, Baltimore, and Minneapolis



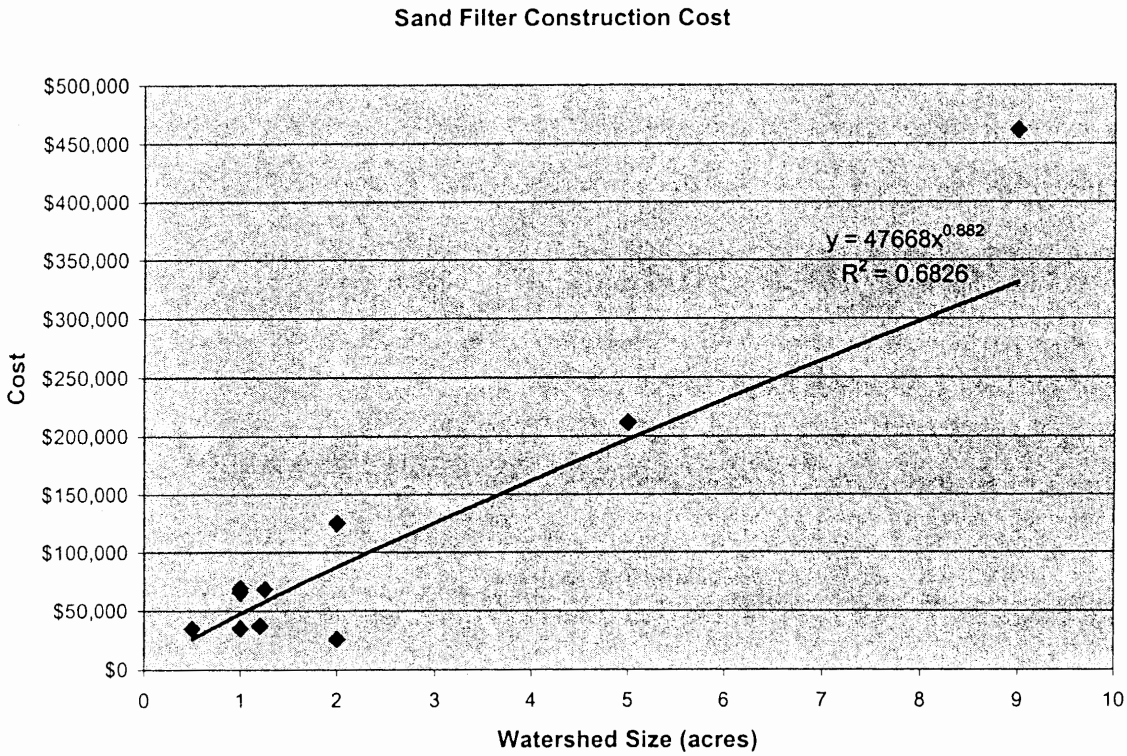
Appendix II. Sources of Information for BMP Pollutant Removal Effectiveness

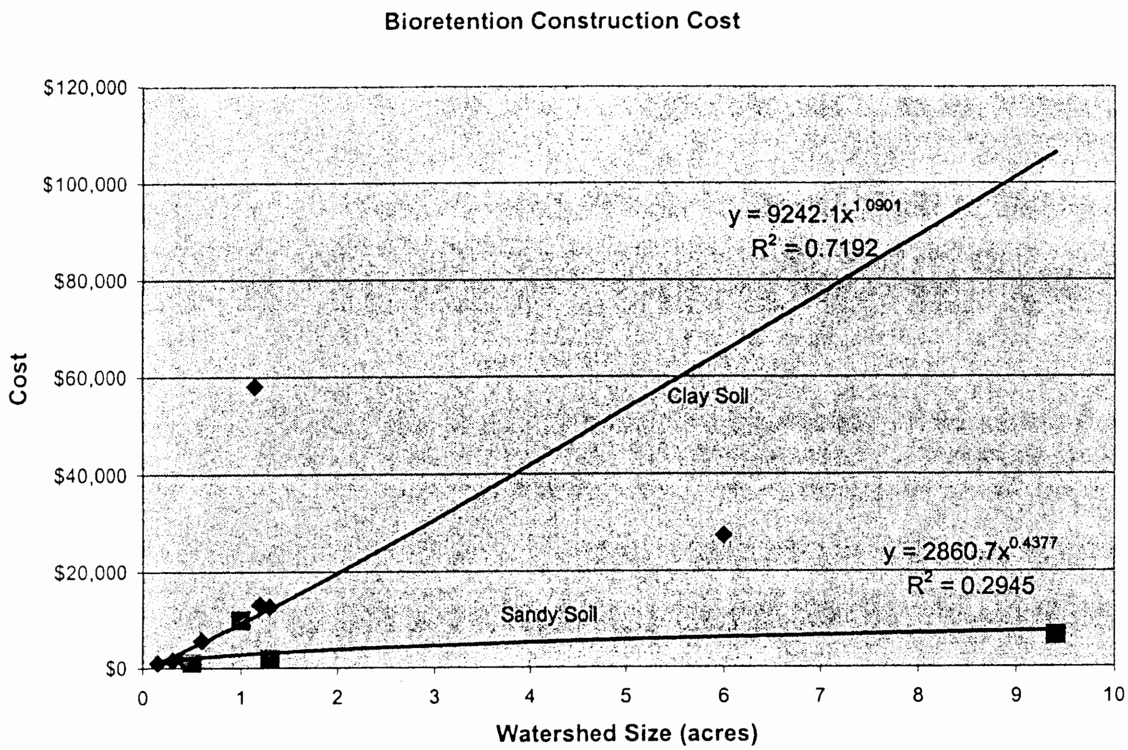
Practice Type	State	Researcher(s) or Agency	Reference
Stormwater Wetlands	FL	Rushton and Dye	CWP
Stormwater Wetlands	NC	Tweedy and Broome	Personal Communication
Stormwater Wetlands	VA	Northern VA Soil & Water District	NBMPD
Stormwater Wetlands	FL	FL DOT/ USGS	NBMPD
Stormwater Wetlands	MD	Baltimore City Water Quality Management Offic	NBMPD
Stormwater Wetlands	FL	EPA/ Florida DER	NBMPD
Stormwater Wetlands	VA	Yu	Personal Communication
Stormwater Wetlands	MD	Althanus and Stevenson	CWP
Stormwater Wetlands	MD	MD Center for Environment & Estuarine Studies	NBMPD
Stormwater Wetlands	VA	Yu	Personal Communication
Stormwater Wetlands	VA	Yu	Personal Communication
Stormwater Wetlands	FL	Carr and Rushton	CWP
Stormwater Wetlands	FL	Harper, Wanileista, Fries, and Baker	CWP
Stormwater Wetlands	NC	Bass	Personal Communication
Stormwater Wetlands	FL	Blackburn, Pimentel, and French	CWP
Stormwater Wetlands	VA	Yu	Personal Communication
Sand Filter	TX	City of Austin	CWP
Sand Filter	TX	Barton Springs/ Edwards Aquifer Conservation District	CWP
Sand Filter	TX	Tenney, Barrett, Malina, Charbeneau, Ward	CWP
Sand Filter	TX	City of Austin	CWP
Sand Filter	VA	Bell, Stokes, Gavin, and Nguyen	CWP
Sand Filter	NC	Hunt	Unpublished Data
Sand Filter	TX	City of Austin	CWP
Sand Filter	TX	City of Austin	CWP
Sand Filter	TX	City of Austin	CWP
Sand Filter	TX	Welborn and Veenhuis	CWP
Sand Filter	TX	Barrett, Keblin, Malina, Charbeneau	CWP
Sand Filter	FL	EPA/ Florida DER	NBMPD
Bio-Retention	MD	Davis	Personal Communication
Bio-Retention	MD	Davis	Personal Communication
Bio-Retention	MD	Davis, Shokouhian, Sharma, Miniami	Water Environment Research
Bio-Retention	MD	Davis, Shokouhian, Sharma, Miniami	Water Environment Research
Bio-Retention	VA	Yu	Personal Communication
Wet Detention Pond	FL	FL DOT/ USGS	NBMPD
Wet Detention Pond	FL	Dormman, Hartigan, Steg, Quasebarth	CWP
Wet Detention Pond	VA	Occoquan Watershed Monitoring Laboratory	CWP
Wet Detention Pond	FL	Gain	CWP
Wet Detention Pond	FL	Martin	CWP
Wet Detention Pond	FL	Florida DOT / USGS	NBMPD
Wet Detention Pond	NC	Wu	CWP
Wet Detention Pond	NC	WRRI / UNCC	NBMPD
Wet Detention Pond	TX	City of Austin	CWP

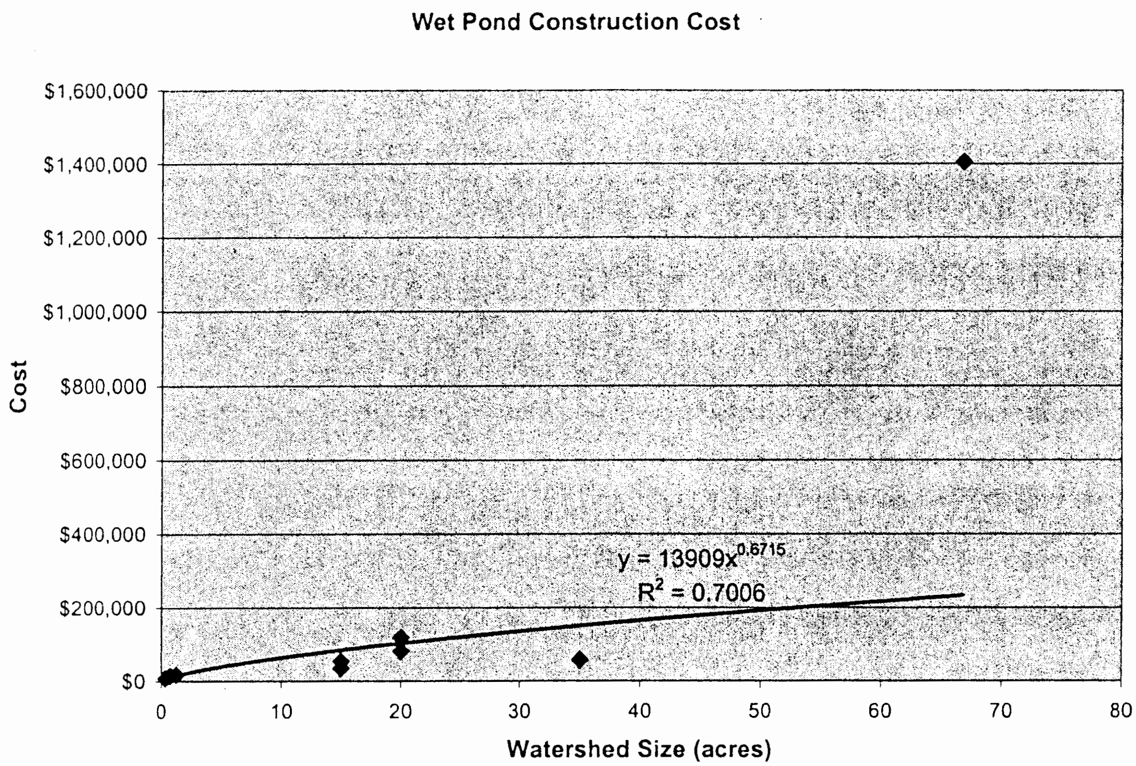
Wet Detention Pond	NC	Wu	CWP
Wet Detention Pond	NC	Borden, Dorn, Stillman, Liehr	CWP
Wet Detention Pond	FL	USGS	NBMPD
Wet Detention Pond	TX	Lower Colorado River Authority	CWP
Wet Detention Pond	TX	City of Austin	CWP
Wet Detention Pond	FL	Environmental Research and Design, Inc / St. John's River Water Mngmt. District	NBMPD
Wet Detention Pond	VA	Yu	Personal Communication
Wet Detention Pond	FL	Holler	CWP
Wet Detention Pond	VA	Yu	Personal Communication
Wet Detention Pond	FL	Rushton, Miller, Hull	CWP
Wet Detention Pond	FL	Rushton, Miller, Hull	CWP
Wet Detention Pond	VA	Occoquan Watershed Monitoring Laboratory	CWP
Wet Detention Pond	FL	Cullum	CWP
Wet Detention Pond	NC	Borden, Dorn, Stillman, Liehr	CWP
Wet Detention Pond	FL	Kantrowitz and Woodham	CWP
Wet Detention Pond	FL	Northwest FL Water Management District	NBMPD

References noted:
CWP – Center for Watershed Protection's National Pollutant Removal Performance Database. 2000
NBMPD – National Best Management Practice Database (http://www.bmpdatabase.com)
Much of Dr. Shaw Yu's data (from the University of Virginia) is going to be described in the National BMP pollutant database.

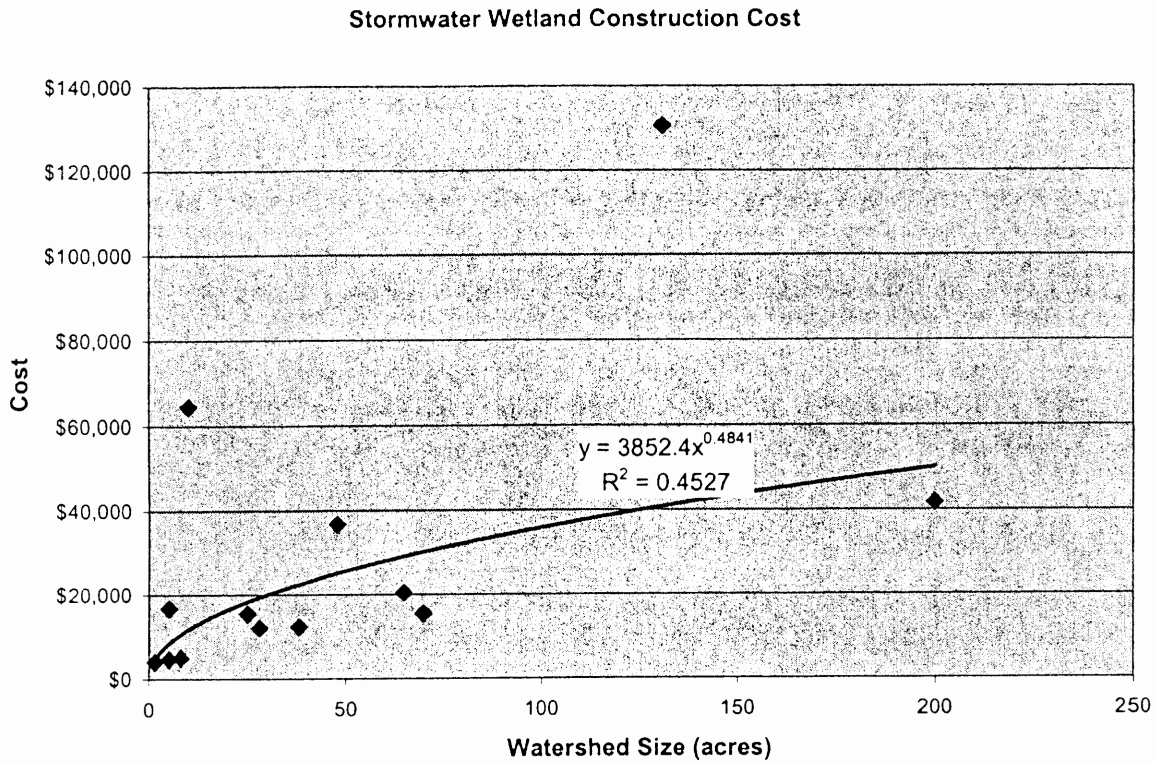
Appendix III. Construction and Maintenance Cost Curves for Four BMPs



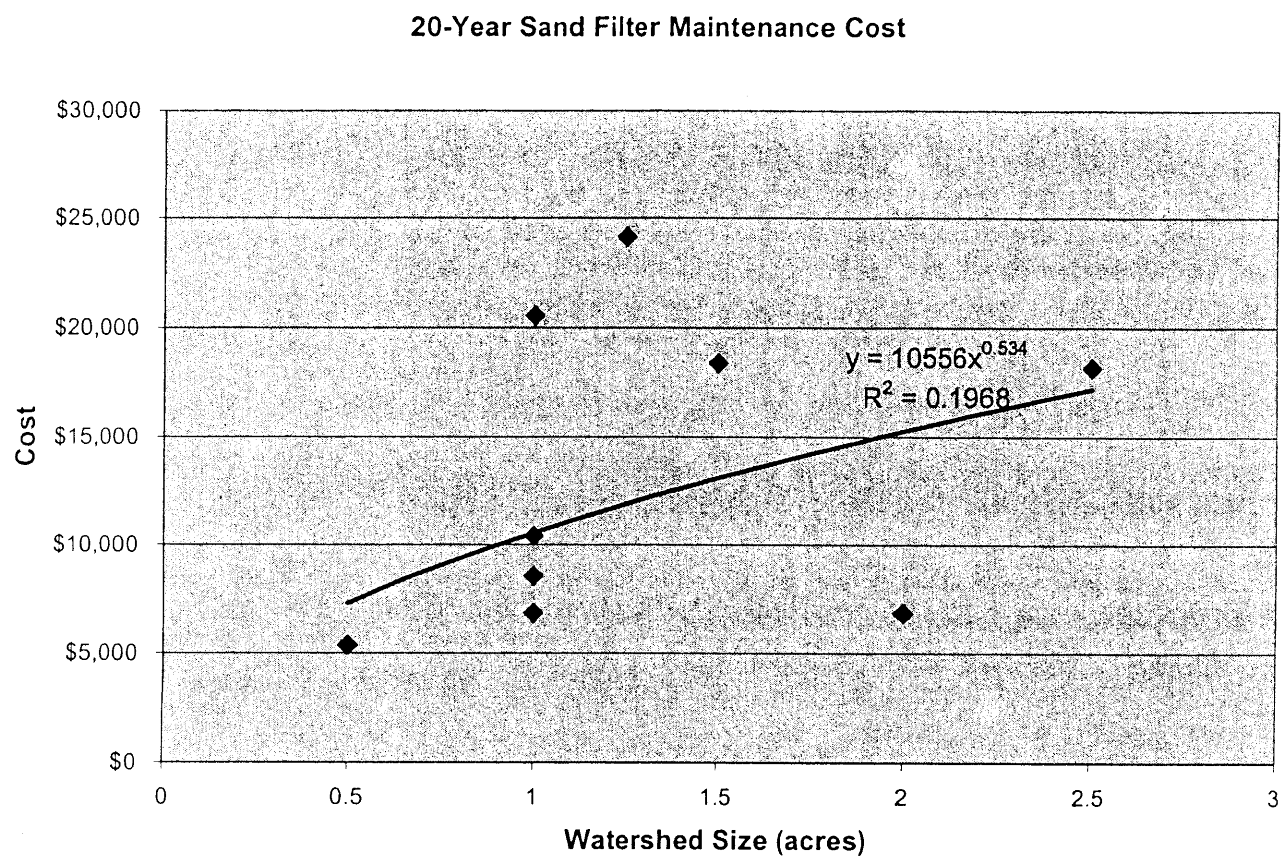

Bioretention Construction Cost
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$0
Cost
0
1
2
3
4
5
6
7
8
9
10
Watershed Size (acres)
y = 9242.1x^1.0901
R^2 = 0.7192
Clay Soil
y = 2860.7x^0.4377
R^2 = 0.2945
Sandy Soil

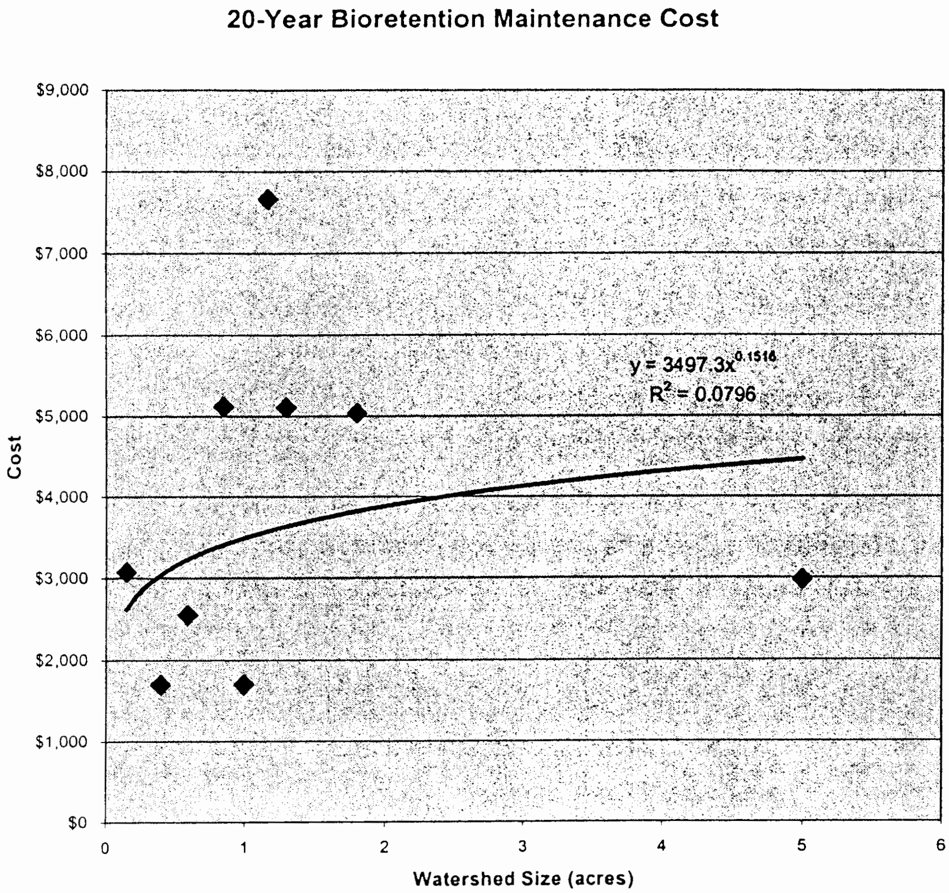


Wet Pond Construction Cost
$1,600,000
$1,400,000
$1,200,000
$1,000,000
$800,000
$600,000
$400,000
$200,000
$0
Cost
0
10
20
30
40
50
60
70
80
Watershed Size (acres)
y = 13909x^0.6715
R² = 0.7006

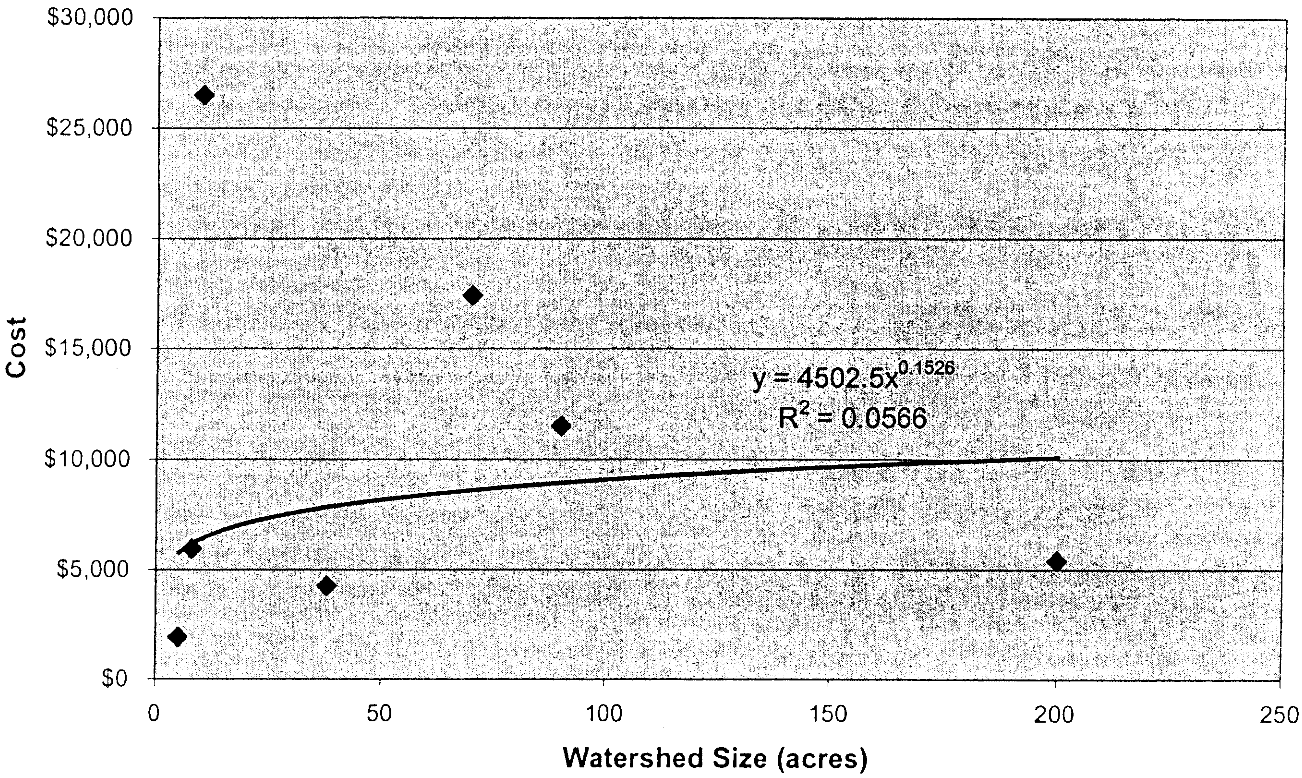


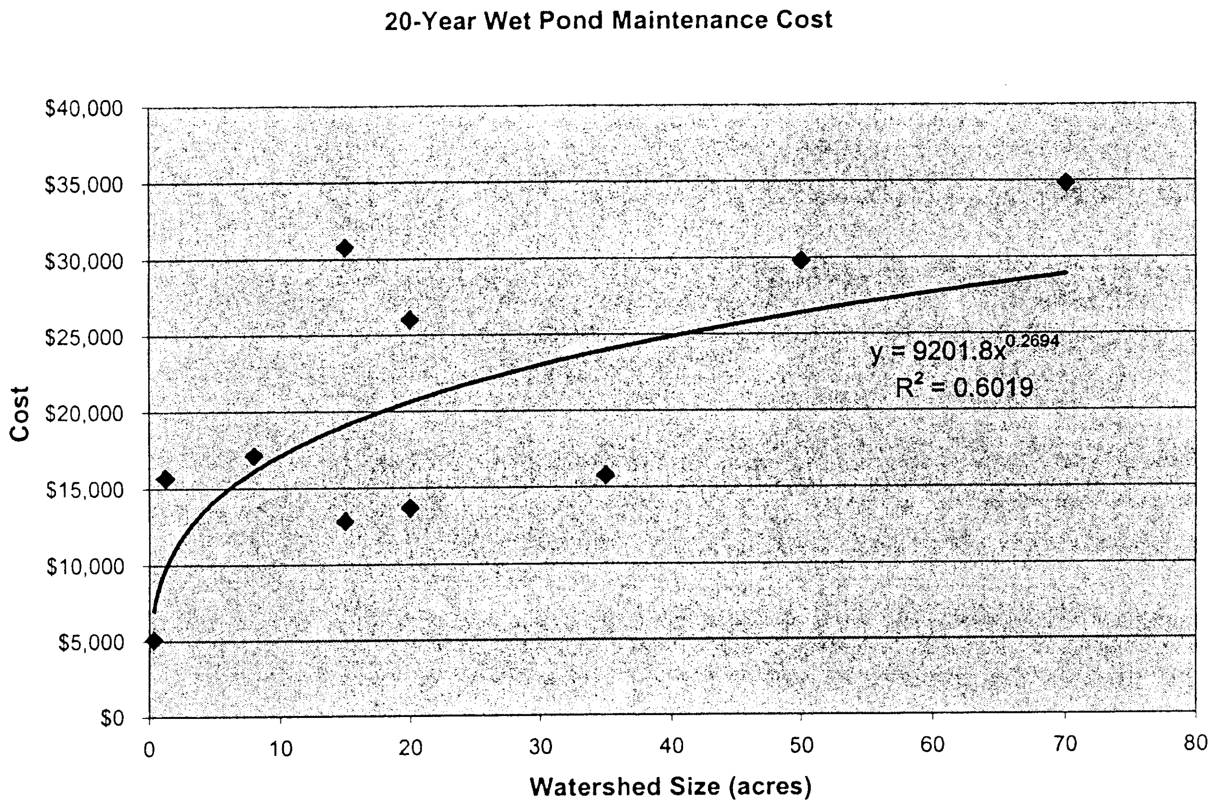
Stormwater Wetland Construction Cost
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$0
Cost
0
50
100
150
200
250
Watershed Size (acres)
$y = 3852.4x^{0.4841}$
$R^2 = 0.4527$


20-Year Sand Filter Maintenance Cost
$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
$0
Cost
y = 10556x^0.534
R² = 0.1968
0
0.5
1
1.5
2
2.5
3
Watershed Size (acres)


20-Year Bioretention Maintenance Cost
$9,000
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$0
Cost
y = 3497.3x^0.1516
R² = 0.0796
0
1
2
3
4
5
6
Watershed Size (acres)

20-Year Stormwater Wetland Maintenance Cost




20-Year Wet Pond Maintenance Cost
$40,000
$35,000
$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
$0
Cost
0
10
20
30
40
50
60
70
80
Watershed Size (acres)
y = 9201.8x^0.2694
R^2 = 0.6019

Appendix IV. Annualized Cost of Five BMPs per Acre Treated in Relation to Size of Watershed, Location and Cost of Land

WET PONDS: Annualized cost in $ per acre treated in relation to size of watershed, location and costs of land									
Location and cost of land	Watershed size (acre)								
	0.75	1	2	4	9	16	25	36	50
Residential Areas in the Piedmont:									
• Opportunity cost land $ 50,000/acre	3,121	2,826	2,227	1,761	1,343	1,112	963	858	774
Residential Areas in the Coastal Plain:									
• Opportunity cost land $ 50,000/acre	3,077	2,782	2,183	1,717	1,299	1,068	919	814	730
Moderately imperv. areas (CN 80)									
• Opportunity cost land $ 5 / square ft	3,545	3,250	2,651	2,184	1,767	1,536	1,387	1,281	1,197
• Opportunity cost land $ 50,000/acre	3,151	2,855	2,257	1,790	1,373	1,142	993	887	803
100 % imperv. areas:									
• Opportunity cost land $ 5 / square ft	4,313	4,017	3,419	2,952	2,535	2,304	2,155	2,049	1,965
• Opportunity cost land $ 50,000/acre	3,327	3,031	2,433	1,966	1,549	1,318	1,169	1,063	979
Any location, when requirement of open space applies (Cost land $0)	3,033	2,738	2,139	1,673	1,255	1,024	875	770	686

STORMWATER WETLANDS: Annualized cost in $ per acre treated in relation to size of watershed, location and costs of land									
Location and cost of land	Watershed size (acre)								
	10	15	20	25	50	75	100	150	200
Residential Areas Piedmont:									
• Opportunity cost land $50,000/acre	331	283	256	238	197	180	170	159	153
Residential Areas in the Coastal Plain:									
• Opportunity cost land $50,000/acre	272	224	197	179	138	121	112	100	94
Moderately imperv. areas (CN 80):									
• Opportunity cost land $5 / square ft	981	933	906	888	847	830	820	809	803
• Opportunity cost land $50,000/acre	389	342	315	297	256	239	229	218	212
100 % imperv. areas:									
• Opportunity cost land $5 / square ft	1,877	1,829	1,802	1,784	1,743	1,726	1,716	1,705	1,699
• Opportunity cost land $50,000/acre	595	547	520	502	461	444	435	424	417
Any location, requirement of open space applies (Opportunity cost land $0):	213	165	138	121	79	62	53	42	35

SAND FILTERS: Annualized cost in $ per acre treated in relation to size of watershed, location and costs of land									
Location and cost of land	Watershed size (acre)								
	0.3	0.5	0.75	1.0	1.5	2.0	4.0	6.0	9.0
100 % imperv. areas:									
• Opportunity cost land $5 / square ft	9,095	8,255	7,675	7,302	6,826	6,518	5,863	5,528	5,222
• Opportunity cost land $50,000/acre	8,760	7,920	7,339	6,967	6,491	6,183	5,528	5,193	4,887
• Opportunity cost land $0 (requirement of open space applies)	8,660	7,820	7,239	6,867	6,391	6,083	5,428	5,093	4,787

BIORETENTION AREAS CLAY SOIL: Annualized cost in $ per acre treated in relation to size of watershed, location and costs of land								
Location and cost of land	Watershed size (acre)							
	0.3	0.5	0.75	1.0	1.5	2.0	4.0	9.0
Residential Areas in the Piedmont:								
• Opportunity cost land $50,000/acre	2,313	1,968	1,797	1,716	1,641	1,611	1,591	1,629
Residential Areas in the Coastal Plain:								
• Opportunity cost land $50,000/acre	2,255	1,910	1,739	1,659	1,583	1,552	1,532	1,570
Moderately imperv. areas (CN 80):								
• Opportunity cost land $5 / square ft	2,964	2,619	2,418	2,366	2,292	2,261	2,241	2,279
• Opportunity cost land $50,000/acre	2,372	2,027	1,856	1,774	1,700	1,670	1,650	1,688
100 % imperv. areas:								
• Opportunity cost land $5 / square ft	3,859	3,514	3,343	3,262	3,187	3,157	3,137	3,175
• Opportunity cost land $50,000/acre	2,578	2,233	2,062	1,980	1,906	1,876	1,856	1,893
Any location, requirement of open space applies (Opportunity cost land $0):	2,196	1,851	1,680	1,598	1,524	1,494	1,474	1,511

BIORETENTION AREAS SANDY SOIL: Annualized cost in $ per acre treated in relation to size of watershed, location and costs of land								
Location and cost of land	Watershed size (acre)							
	0.3	0.5	0.75	1.0	1.5	2.0	4.0	9.0
Residential Areas in the Piedmont:								
• Opportunity cost land $50,000/acre	1,921	1,354	1,038	865	677	573	398	279
Residential Areas Coastal Plain:								
• Opportunity cost land $50,000/acre	1,863	1,296	979	806	618	515	340	220
Highly imperv. areas (CN 80):								
• Opportunity cost land $5 / square ft	2,572	2,005	1,688	1,515	1,327	1,224	1,049	929
• Opportunity cost land $50,000/acre	1,980	1,413	1,096	924	735	632	457	338
100 % imperv. areas:								
• Opportunity cost land $5 / square ft	3,467	2,900	2,583	2,411	2,223	2,119	1,944	1,825
• Opportunity cost land $50,000/acre	2,186	1,619	1,302	1,129	941	838	663	543
Any location, requirement of open space applies (Opportunity cost land $0):	1,804	1,237	920	747	559	456	281	161