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Economic Analysis of Stormwater Management Practices

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ECONOMIC ANALYSIS OF STORMWATER MANAGEMENT PRACTICES

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ABSTRACT

Structural stormwater management practices help reduce the quantity and improve quality of stormwater runoff. This dissertation focuses on costs and cost effectiveness of these practices. Design, construction and maintenance costs data that were collected from six different sources and adjusted for purchasing power differences over time and location are analyzed using stochastic Leontief cost functions. Effects on these costs of land prices, wages for engineering, construction, and landscaping services, water storage or treatment, and differences in designs of the SMPs and the biophysical regions in which they are located are estimated with the Leontief functions. Results indicate that all SMPs exhibit economies of size in at least one of the different regions considered. Land price significantly determines total costs of ponds and wetlands. Input prices and differences in biophysical regions and designs are also significant determinants of the costs of some SMPs.

A comparative study of costs of the SMPs, given the same pollutant removal capacity, is provided. Bioretention cells are less expensive than ponds or wetlands in highly urbanized areas where the land costs are relatively high. Costs per milligrams of pollutant removed per liter of stormwater inflow are analyzed for two bioretention cells. A procedure to calculate the cost effectiveness of a particular SMP in removing pollutant and reducing runoff is illustrated.

DEDICATION

I dedicate this work especially to my mom and dad without whom I could not have come this far. I would also like to dedicate this to my fiancé whose help and support proved crucial for the completion of this dissertation and finally, to my brother whose cheerful attitude consoled me whenever I needed it the most.

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CHAPTER 1
INTRODUCTION

Urban stormwater is a leading contributor to degradation of water quality in estuaries, lakes, rivers, and bays. In particular, runoff from urban areas and storm sewers was a major source of impairment along assessed ocean shoreline in the U.S. (EPA 2002a). Stormwater runoff was attributed as a major source of water pollution along assessed shoreline of the Great Lakes and estuaries (EPA 2002a). In 2002, runoff from urban areas was the second most important source of impairment for 42 percent of rivers and streams used for recreation and 17 percent of lakes, ponds and reservoirs in South Carolina (EPA 2002c). In the most recent state water quality report, urban runoff was a potential source of impairment for 11 of 14 river basins in North Carolina (NCWQR).

Three main components of the stormwater pollution problem directly related to urbanization are increased volume and rate of runoff from impervious surfaces and increased concentration of pollutants in the runoff. Pollutants in this runoff come from diffuse, non-point sources and may include sediment, bacteria from pet waste, and toxic chemicals (EPA 2002a). The urban watershed management branch of the U.S. Environmental Protection Agency (EPA) develops and demonstrates technologies, systems, and methods to manage risks to public health, property and impairments caused by urban stormwater runoff (UWMR). Federal and state level rules and regulations are aimed at controlling the quantity and quality of stormwater runoff.

Rules and Regulation

U. S. Environmental Protection Agency (EPA) regulates discharge of stormwater from urban areas. As required by 1987 amendment to the Clean Water Act (CWA), EPA in Nov. 1990 promulgated Phase I of a comprehensive national program to address stormwater discharges. Phase I requires facilities that engage in ten other types of industrial activities other than constructions and municipal separate storm sewer systems, known as small MS4s, that serve at least 100,000 people in incorporated places or unincorporated urbanized areas of counties to obtain coverage under a National Pollutant Discharge Elimination System (NPDES) permit for discharge of stormwater runoff (EPA 1999b; EPA 1996).

One of the purposes of Phase II, promulgated in Dec. 1999 is to reduce pollutants in post-construction runoff (EPA, 2003). MS4 operators that own or operate smaller (less than 100,000 people) communities or public entities are now required to reduce discharge of pollutants to the maximum extent possible by implementing stormwater management programs, called ‘stormwater pollution prevention plans’ (SWPPP), in order to protect water quality and satisfy the appropriate requirements of the Clean Water Act (WSDE).

Title 40, parts 400 – 471 of the Code of Federal Regulations (CFR) lists the limitations on the amount of pollutants that can be discharged in a given industry (EPA, 2004). The NPDES Multi-Sector General Permit (MSGP) for industrial activities requires SWPPP to identify potential sources of pollution and ensure implementation of management practices that will reduce pollutants expected to affect quality of storm water discharges from the facility (EPA, 2006). The benchmark values required by the permit for the amount of pollutant in the water are given below:

Table 1.1: Effluent Limitation for NPDES MSGP for Industrial Activities

Pollutant	Effluent Limitation for 2006 (mg/l)
Total Suspended Solids	100
Nitrite, Nitrate and Nitrogen	0.68
Total Phosphorus	2
Total Iron	1
Total Lead	0.082
Total Copper	0.14
Total Zinc	0.12

Source: Table 1, MSGP (EPA, 2006)

The federal government has granted the states the responsibility to administer NPDES permit applications (EPA, 1999a). According to the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) of the regional Water Quality Control Board of California, post-construction stormwater quantity (flow peak, volume and duration) controls are required for projects in certain locations that create or replace 1 acre or more of impervious surface (SCVURPPP). The state of South Carolina requires the construction companies to install structural best management practices such that 80 percent of the average annual load of pollutants in storm water is removed after the construction phase in order to meet the water quality standards (Sadler). The North Carolina State Stormwater Management Program, established in the late 1980's, requires the installation of structural management practices to control 1 to 1.5 inches of the stormwater runoff and remove 85% of the total suspended solids for the high density development projects that involve more than 30% impervious surface area (NCSMP).

Implementation of these federal and state regulations governing stormwater quality and quantity necessitates use of stormwater management practices (SMPs). There are two basic types of SMPs: non-structural and structural. Non-structural SMPs consist of administrative, regulatory, or management practices that have positive impacts on non-point source runoff (EPA, 2000b). On the other hand, structural SMPs primarily consist of designed facilities or modified natural environments that help clean and control the stormwater runoff. Structural SMPs include stormwater ponds, wetlands, filtration practices and vegetated open channel practices (SMRC).

Previous Research

In a report submitted to the Chesapeake Research Consortium in 1997, Brown and Schueler analyzed the effect of water storage or water treatment volume on construction and total costs of the SMPs. They estimated Cobb-Douglas cost functions. In their analysis, total costs consisted of design, engineering, sediment control, construction and landscaping costs. Though stormwater ponds and wetlands are two different types of SMPs, they treated both of them as one SMP and estimated one model of costs of these two different SMPs. All their estimates, except that of sand filters, indicated the presence of economies of size.

In 2003 Koustas and Selvakumar estimated the same cost function with the same specifications as those of Brown and Schueler. They, however, used capital and maintenance costs for stormwater ponds, grass swales and wetlands. Their results show that there is a significant correlation between costs and water storage volumes of all the SMPs except the wet detention ponds.

A study conducted in North Carolina (Wossink and Hunt) in 2003 focused on selecting the most effective SMP for the removal of a class of pollutants and its associated cost. In addition to costs of construction and maintenance, they acknowledged the existence of the opportunity cost of land. However, in lieu of any definitive information about land costs, they classified land on which the SMPs were constructed into three categories: 1) undeveloped, 2) residential and 3) commercial. They then assigned $0, $217,800 and $50,000 as the cost per acre of these three types of land. These assumptions on the cost of land seem inappropriate. Specifications on the cost equations in their study were similar to those of Brown and Schuler. The study also calculated cost per percent of pollutant removed and incorrectly used the cost per percent of pollutant removed as their basis to conclude that bioretention cells were cost effective in small areas for most of the pollutants removed.

My analysis contributes to the existing literature in four distinct ways. Design, construction, and maintenance cost data are collected from six different sources and adjusted for purchasing power differences over time and location. Leontief cost functions are then used to analyze these costs. A Cobb-Douglas specification of cost models might be less appropriate than a Leontief specification because the degree to which substitution between inputs can occur in reality is limited, if not impossible. Apart from water storage or treatment effects considered in the earlier studies, effects of units costs of engineering, construction, and landscape services on total costs are also analyzed. In addition to input prices regional and design differences of the SMPs are also analyzed as possible determinants of costs. The effect of land costs, adjusted for costs-of-living differences and inflation, are additionally analyzed for stormwater ponds and wetlands. Cost comparisons of the SMPs assuming the same pollutant removal capacity are also provided. A procedure to determine cost efficient size of the SMPs is illustrated and cost the cost per unit of pollutant removed is analyzed using cost of milligrams per liter of pollutant removed, instead of cost per percent of pollutant removed. Cost per unit of pollutant removed of two bioretention cells compared to stormwater ponds are also analyzed.

CHAPTER 2
DESCRIPTIONS OF SMPs

Stormwater management practices (SMPs) are of two basic types: non-structural and structural. Non-structural SMPs consist of administrative, regulatory or management practices that have positive impacts on non-point source runoff (EPA, 2000b). They are techniques that include advocating the proper use of fertilizers or pesticides and providing information to people to enable them to reduce stormwater pollutant by changing their daily habits, etc. Although such non-structural SMPs are less expensive and quite useful in managing stormwater runoff pollution, their effectiveness is not certain as their performance depends on the compliance of the recommendations, a task which is difficult if not impossible to monitor (FHWA). Structural SMPs, on the other hand, are designed facilities or modified natural environments that help control the quantity of stormwater and also improve its quality. These include various types of stormwater ponds, filtration practices, vegetated channel practices and wetlands (SMRC). Detailed information collected from various sources to provide details about the design and characteristics of these structural SMPs follows.

Stormwater Ponds

Stormwater ponds are basins whose outlets are designed to detain stormwater runoff from a storm for some minimum duration and allow sediments and associated particles to settle out. They require surface area that typically becomes unavailable for other uses. Stormwater ponds can be either dry or wet. Both types can be modified to become extended detention ponds which have better quality control than the normal ponds (SMRC). Although the minimum drainage area required for a stormwater pond is 10 acres, stormwater ponds can be used with a broad range of storm frequency and sizes, drainage area and land uses (CSBMP). They can be built in a residential, commercial or industrial area, but might not be a good choice in highly urbanized areas where the cost of land is high.

A pond is divided into three different zones: 1) an inlet for flow dispersal, 2) the main or primary treatment area, and 3) the outlet, which can be designed to prevent re-suspension (MPCA, 2000). The inlet area is the largest sediment storage area of a pond and also prevents erosion of the pond bottom. The outlet area is a micro-pool containing an outlet structure that provides final settling and prevents re-suspension of sediments. The main treatment area constitutes 30-80% of the total volume of a stormwater pond and is designed to provide sedimentation of fine to medium size particles in stormwater runoff (Entire description based on the manual by MPCA, 2000).

Dry Ponds

Dry ponds, also known as detention ponds, are typically designed to completely drain out between storm events and therefore control water quantity more than water quality. They provide limited settling of particulate matter which can be suspended again during subsequent storm events (USSBMP). As a general rule, dry ponds should be implemented for drainage areas greater than 10 acres, so that the orifice diameter of the outlet is big enough to prevent clogging (SMRC). Figure 2.1 shows a drawing of a typical dry pond.

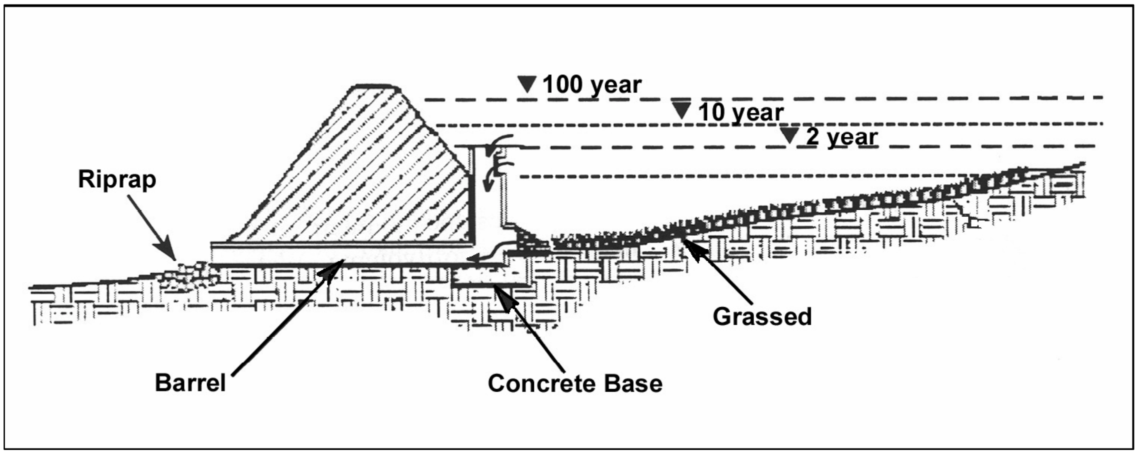

Figure 2.1: Schematics of a Dry Pond, Source: NVPDC, 1992

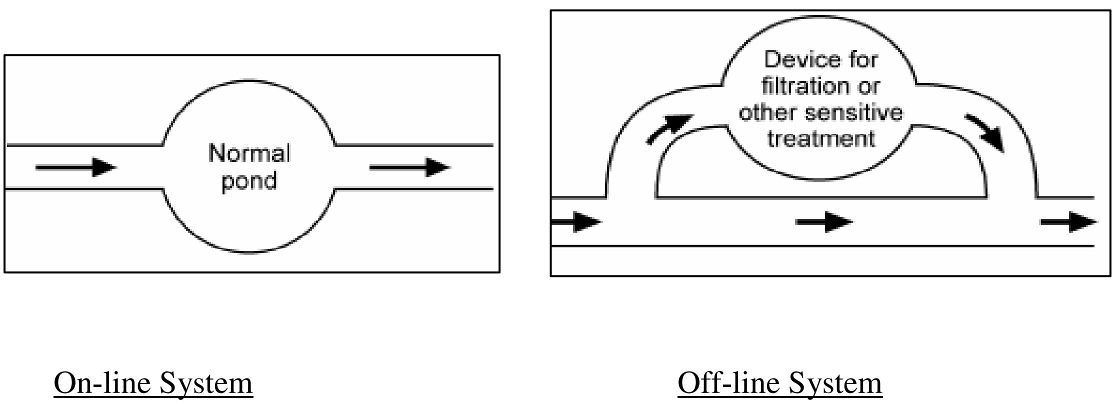

Figure 2.2: On-line versus Off-line Systems, Source: MPCA, 2000

As illustrated in figure 2.2 a dry pond may be designed to be an online or an offline system. Some basic features common to all dry ponds with extended detention facilities includes the capture and removal of the coarse sediments before they enter the practice with the help of a sediment forebay. This sediment forebay treats the runoff which results in improved water quality. The runoff is conveyed through the practice with minimum erosion potential and maximum safety. A micro-pool or other such facilities are used to help reduce clogging and re-suspension of sediments (SMRC).

The required volume of a dry pond should be sufficient to ensure that post-development peak flows can be controlled to pre-development levels for 2-year to 100-year storm events. The minimum detention time should be 24 hours, unless the outlet is susceptible to clogging (USSBMP). Higher detention time typically results in better quality control. The minimum orifice size is a 4-inch diameter opening, unless the orifice is protected by perforations in the riser. The preferred length to width ratio of a pond should be 4:1 to 5:1 with a maximum depth of the pond should be limited to 6 to 10 feet. These designing criteria are mentioned in USSBMP.

The dry extended detention ponds provide water quality treatment, however, to operate properly, these need outlet controls with filters, weirs or other 'energy-dissipation' and flow spreading devices constructed as part of the pond (USSBMP). Though these detention ponds have no minimum slope requirements, enough elevation drop is needed from the pond inlet to its outlet to ensure a smooth flow of the runoff through the system (SMRC). Table 2.1 shows that dry extended detention ponds do not provide quality control as well as wet ponds do and are most commonly used for quantity rather than quality control.

Table 2.1: Pollutants Removed by Dry Extended Detention and Wet Ponds

Pollutants	Percentage Removed by Dry Extended Detention Ponds	Percentage Removed by Wet Ponds
Total Suspended Solids	61	80
Phosphorus	20	51
Nitrogen	31	33
Nitrites and Nitrates	-2	43
Metals	29	29
Bacteria	78	70

Source: Winer, 2000.

Wet Ponds

Wet ponds, also known as retention ponds, unlike their dry counterparts, are generally on-line systems that retain a permanent pool of water. They can be located at residential, commercial or industrial sites (USSBMP). These ponds treat incoming stormwater runoff primarily by sedimentation (SMRC). Dissolved contaminants are also removed by a combination of processes like physical adsorption, natural chemical flocculation and bacterial decomposition (USSBMP). In humid regions, a drainage area of 25 acres (SMRC) is typically needed for the proper functioning of a wet pond, however, a minimum drainage area of 10 acres is required (USSBMP). Wet ponds can be used in almost any area except for arid regions where maintaining a permanent pool of water is difficult. Figure 2.3 gives a longitudinal view of a wet extended-detention pond whereas Figure 2.4 shows the cross sectional view of a typical wet pond.

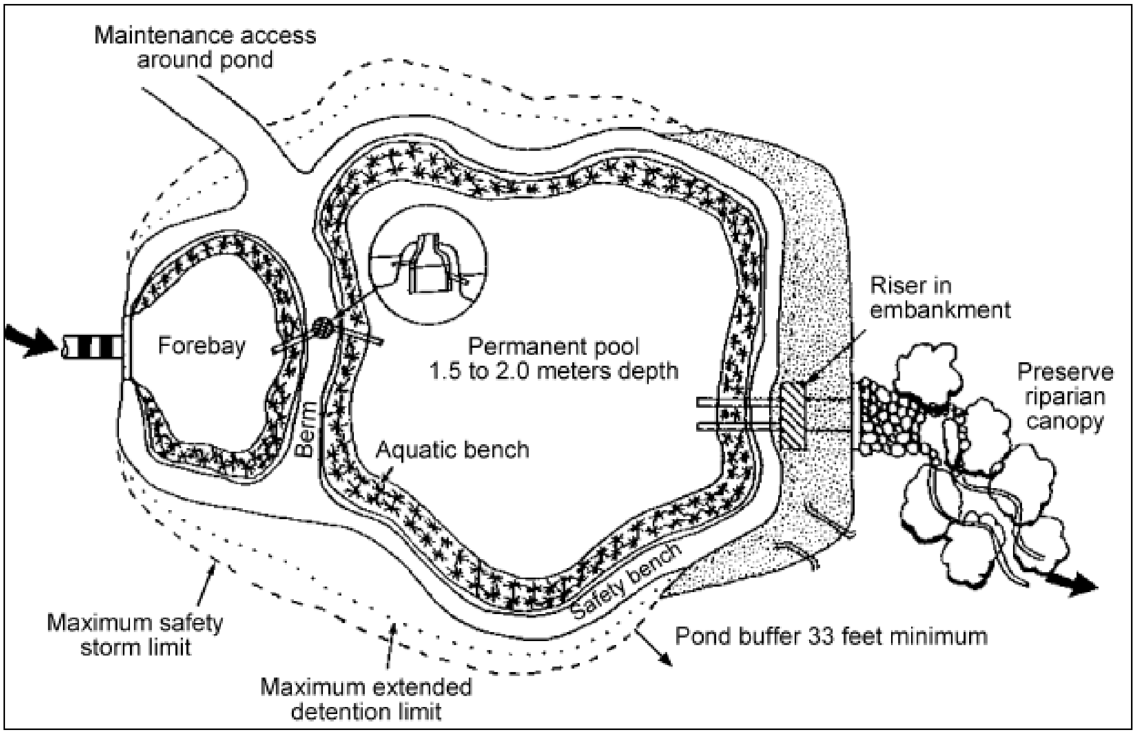

Figure 2.3: Wet Extended Detention Pond, Source: MPCA, 2000

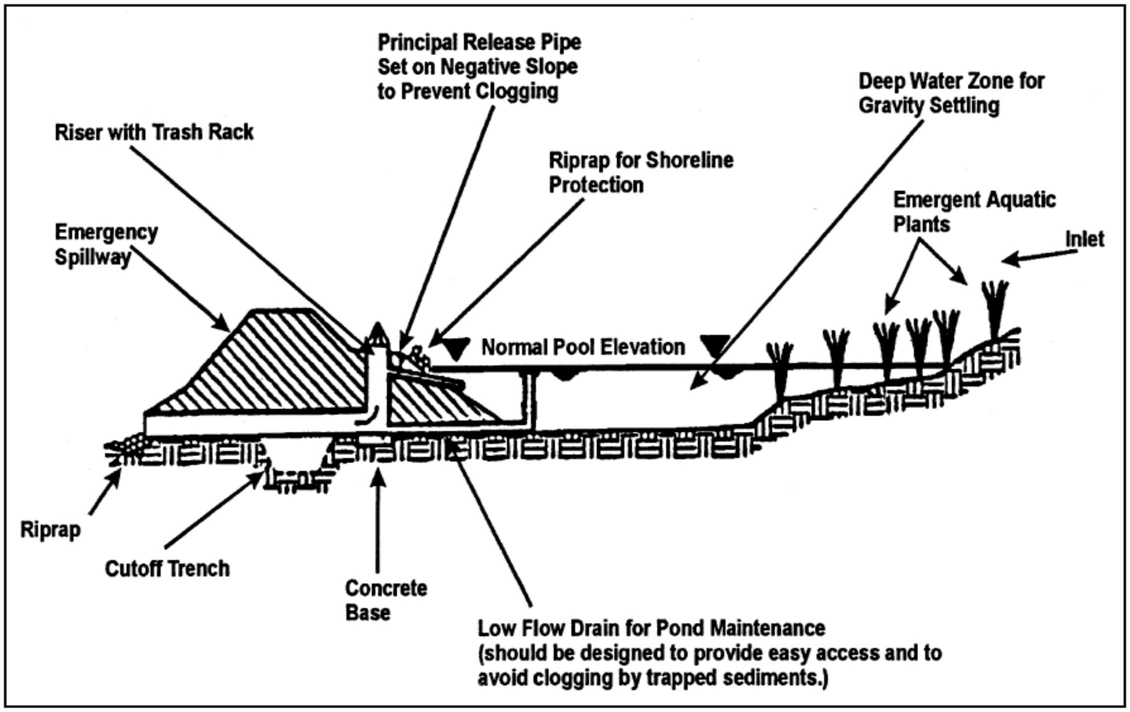

Figure 2.4: Typical Wet Pond Design, Source: MCPA, 2000

Some basic considerations in building a wet pond include erosion control, scour prevention, provision of an emergency spillway to convey large flood events, and a inclusion of non-clogging outlet (SMRC). A wet pond, designed to meet both the quantity and the quality control requirements, should have a minimum pool surface area of 0.25 acres and pool depth of 2 feet (USSBMP) and a maximum depth of 10 feet. Building multiple ponds in series ensure better quality control and also helps in improving the pollutant removal capacity of the ponds (SMRC). These ponds can be considered to be an asset to the community, so proper landscaping is needed to prevent erosion of the banks and enhance its beautification.

As in dry ponds, several modifications can be made to the design of the wet pond to further improve its pollutant removal capacity. Increasing the settling area with the use of a sediment forebay, having a length to width ratio of 3:1 to maximize the residence time of the runoff in the pool, having multi-stage outlet structure to control discharges for storms of different sizes, and addition of chemicals to precipitate certain dissolved chemicals like phosphorus within the pool are some of the techniques that can enhance the quality of stormwater runoff (USSBMP). Wet and dry stormwater ponds, like stormwater wetlands, primarily control the quantity of stormwater runoff while providing some amount of water-quality improvement.

Stormwater Wetlands

Stormwater wetlands, similar to wet ponds, incorporate a combination of plants and water in a shallow pool designed to both treat and control urban stormwater runoff. Constructed wetlands have less biodiversity than natural wetlands (SMRC). Like the stormwater ponds, these wetlands are a widely applicable stormwater treatment practice, but have limited applicability in highly urbanized areas. They use biological and naturally occurring chemical processes in water and plants to remove pollutants and also help to control the peak flows of a storm event (FHWA). Wetlands are relatively shallow with higher evaporation rates, making it more difficult to maintain the permanent pool of water compared to wet ponds (SMRC). There are two basic types of constructed stormwater wetlands, one in which the runoff flows through a soil lined basin at shallow depths known as free water surface constructed wetlands and another where the runoff flows through a basin lined with rock and gravel, known as the subsurface flow constructed wetlands (EPA, 1999e). Figure 2.4 and 2.5 shows the schematics of a typical stormwater wetland.

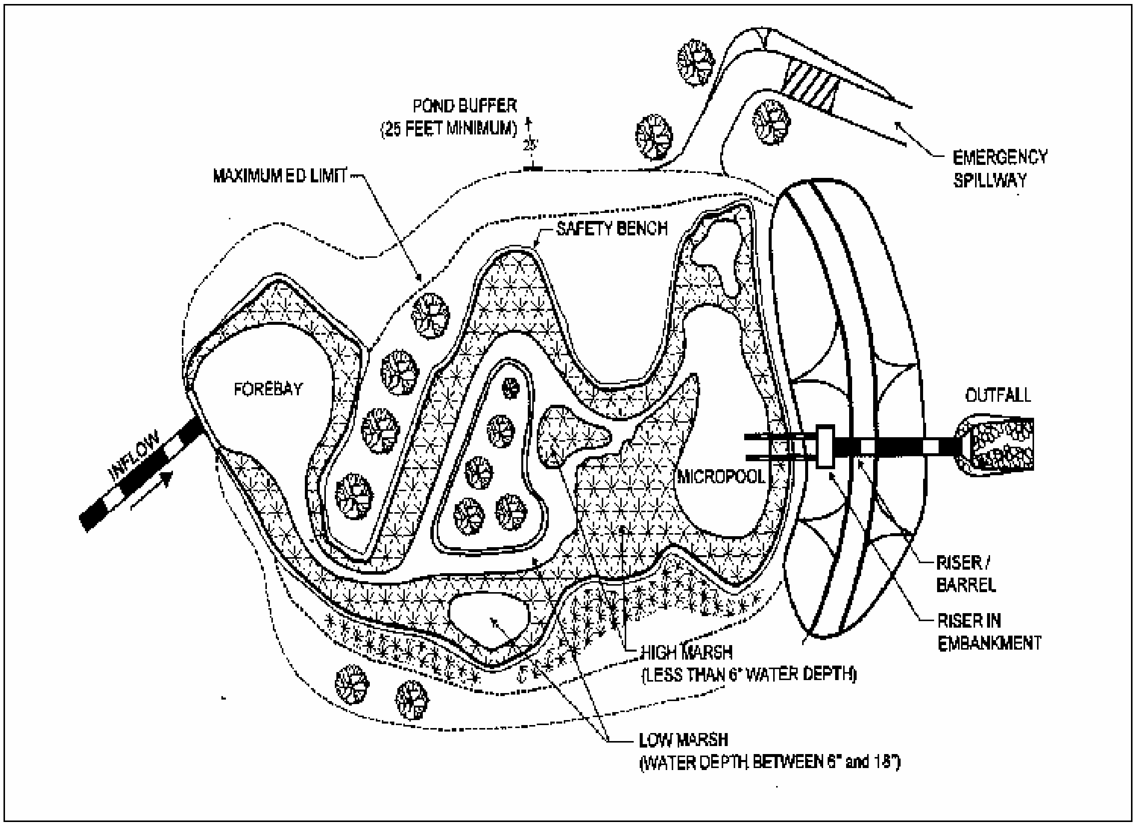

Figure 2.5: Stormwater Wetland, Source: SMRC, 2003

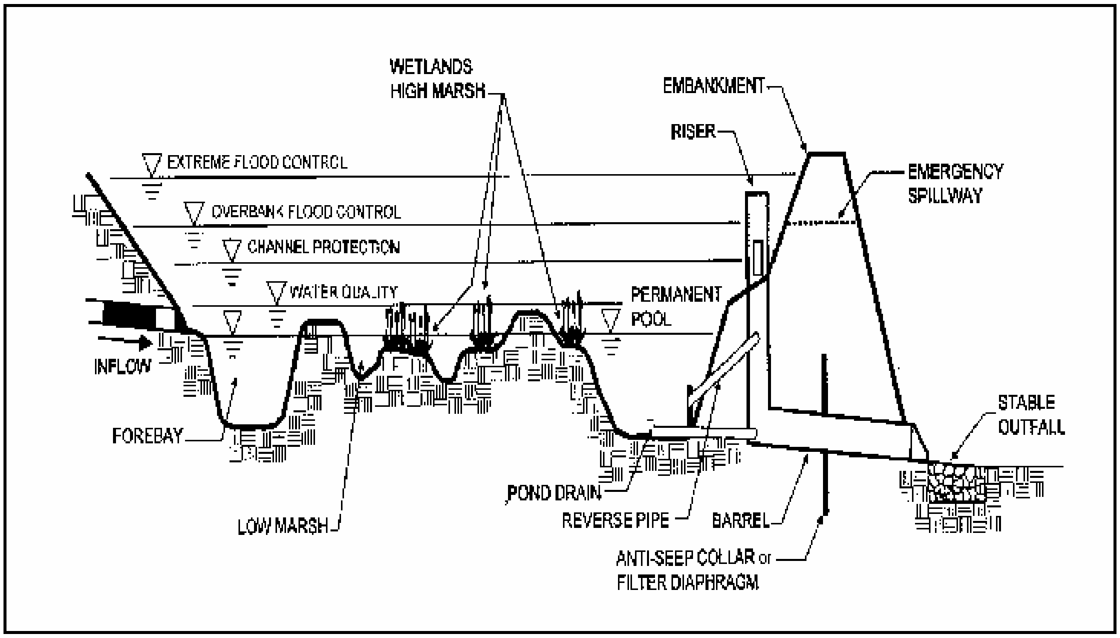

Figure 2.6: Cross-Sectional view of a Stormwater Wetland, Source: SMRC, 2003

The various types of on-line or off-line wetlands include shallow wetlands, pocketed wetland, and extended detention shallow wetlands. Pocketed wetlands are intended for smaller drainage area and use the water table for reliable supply of water to support the system. Extended-detention shallow wetlands have part of the water quality volume as extended detention above the surface of the marsh (SMRC).

Other than pollutant removal mechanisms like vegetative filtering and gravitational settling in the slow moving marsh flow, stormwater wetlands also include chemical and biological decomposition, and volatilization (GSMM). Proper functioning of the stormwater wetlands require a minimum drainage area of 25 acres (5 acres for pocketed wetlands), an elevation difference of 3 to 5 feet (2 to 3 feet for pocketed wetlands) between the inflow and the outflow, and hydrological soil group C or D (GSMM). The volume of the extended detention in a wetland should not be more than 50% of the total treatment volume and its maximum water surface elevation must not extend more than 3 feet above the normal pool (GSMM).

Basic features of a wetland, like the length to width ratio, prevention of erosion and scour while conveying the runoff, prevention of clogging, and the landscaping features are similar to that of a wet pond. The wetland should have a surface area at least 1% of the drainage area and both very shallow and moderately shallow zones to encourage a longer flow path providing better settling and vegetation variety (SMRC). The forebay and the micropool of the wetland should contain 10% each of the treatment volume and should be 4 to 6 feet deep (USSBMP). Planting a diverse plant community of species native to the project area leads to better wildlife and water-quality benefits, while a vegetative buffer strip around the marsh helps reduce sediment inflow and provides additional pollutant filtration (FHWA). Stormwater wetlands help to control the quantity and quality of stormwater runoff and also provide habitats for certain wildlife and aquatic species. However, unlike filtration practices, they are not suited for dense urban areas.

Filtration Practices

Surface or underground filters that use compost, sand/peat, sand or organic filter media are collectively known as filtration practices. Bioretention cells and sand filters are two such filtration practices. Filtration practices provide performance that is independent of local conditions and have designs available for roadside and congested urban applications. The surface area of a filtration practice usually occupies 2 to 3 % of the drainage area; hence they are more commonly used for small to medium drainage areas (FHWA).

Pretreatment is achieved typically by a sediment chamber with a permanent pool to remove large-diameter material that would clog the filter medium. Filtration practices like bioretention cells and various types of sand filters are a pragmatic option where land can be used for various purposes like a parking lot, a residential complex or a dense urban setting. These two types of practices are described in detail below.

Bioretention Cells

Bioretention areas, usually built as off-line systems, are shallow landscaped depressions, commonly located in parking lots or within residential land uses. They are designed to incorporate many of the pollutant removal mechanisms that operate in forested ecosystems (SMRC). They require less infrastructure and maintenance compared to the other SMPs (FHWA). Water quality improvements in a bioretention cell result from sedimentation, filtration, soil adsorption, micro-biological decay processes, and the uptake of pollutants by plants.

The major components of the bioretention area include a grass buffer strip, a ponding area with surface mulch, planting soil, an underground sand bed, an organic layer, plant material, and infiltration chambers (VASM). A bioretention cell uses an organic media filter for treatment purposes. The use of vegetation, modeled from the properties of a terrestrial forest community, is dominated by mature trees, shrubs, herbaceous plants and grass. Native vegetation, which tolerates both wet and dry conditions, should be used for landscaping wherever possible. Figure 2.6 shows the conceptual layout of a bioretention cell.

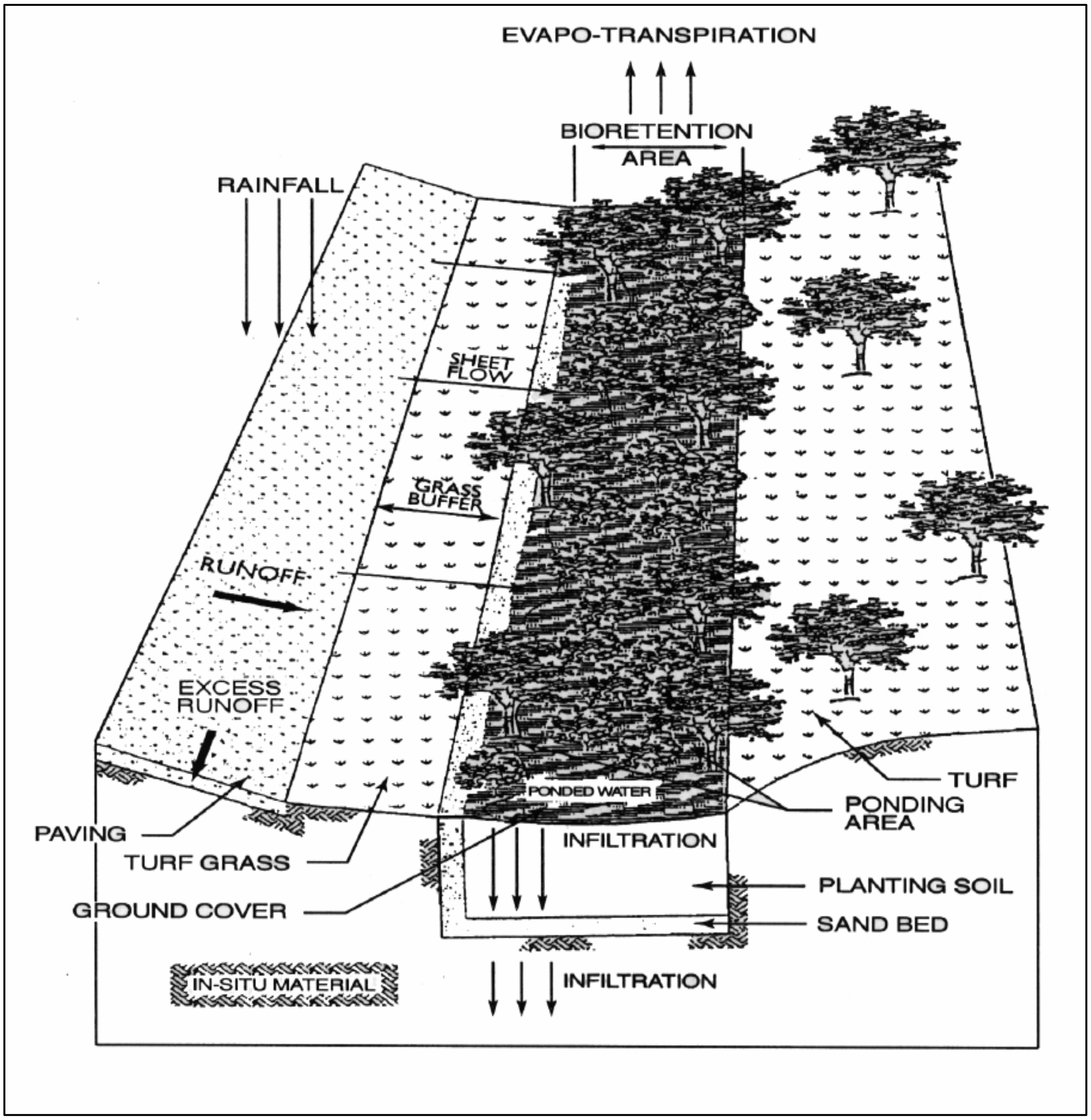

Figure 2.7: Conceptual framework of a Bioretention Cell, Source: USSBMP, 2001

Capturing and removing the coarse sediments before runoff enters the filter bed helps reduce the maintenance burden of bioretention and reduces the likelihood of clogging. Better treatment of the stormwater runoff can be achieved if the cell is designed with a soil bed that has a sand/soil matrix and a mulch layer above it[1]. Bioretention cells are designed with an under-drain system, a perforated pipe in a gravel layer placed along the bottom of the bioretention cell, to collect filtered runoff and direct it to the storm drain system (FHWA). These cells should also incorporate an overflow structure that conveys untreated flow from large storms to the storm drain system.

The drainage area of a bioretention cell should ideally be 5 acres or less, as larger areas tend to clog cells and have problem with conveyance of flow (USSBMP). Though they are generally applied to areas which have gentle slopes, sufficient slope is required to ensure that the runoff that enters a bioretention area can be connected with the storm drain system (SMRC). The surface area of a bioretention cell should be between 5 to 10% of the impervious area draining to it (USSBMP). To replicate the tree and shrub distribution of a forest community, the minimum length and width of a bioretention cell should be 15 and 40 feet respectively (SBMP). The length should be twice the width if it's greater than 20 feet, reducing the likelihood of concentrated flow by dispersing it over a greater distance. The maximum ponding depth should be 6 inches so that stormwater is not stored for more than 4 days to prevent breeding of mosquitoes and other undesirable insects. Finally, for appropriate moisture capacity and sufficient space for root growth, the planting soil should have a minimum depth of 4 feet (SBMP). Unlike sand filters, the bioretention cell with its trees and shrubs provide an aesthetic

[1] A bioretention cell in Anderson County in South Carolina, using this soil bed, had higher removal rates than the average removal rates of a bioretention cell (Templeton et al, 2006, Table 6, Appendix A).

value to the community and reduce stormwater runoff. They recently have been designed to enhance their capacity to control both quality and quantity of runoff.

Sand Filters

Sand filters are multi-chambered structures designed primarily for quality treatment through filtration. They have a sand bed as its primary filter media to remove the finer sediments which escape the sediment forebay. They also contain an under-drain collection system to channel the runoff to the storm drain (GSMM). Modifications of the basic sand filter design include surface sand filter, perimeter sand filter, and underground sand filter. Sand filters maybe may be constructed in underground vaults, paved trenches at the perimeter of impervious surfaces, or in either earthen or concrete open basins (VASM). Figure 2.8, 2.9, and 2.10 gives the layout of the three types of sand filters mentioned above.

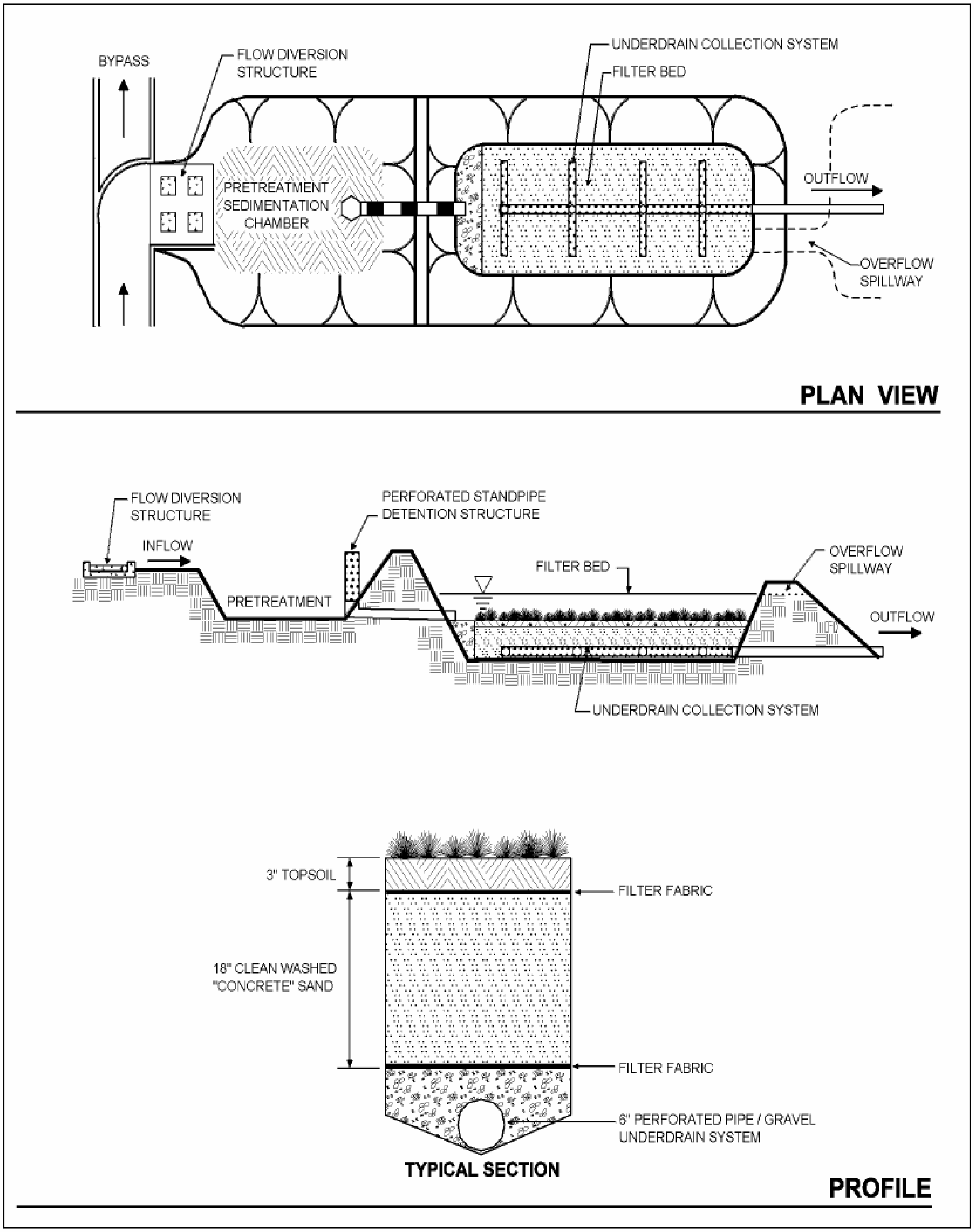

Figure 2.8: Conceptual Framework of a Surface Sand Filter, Source: SMRC, 2003

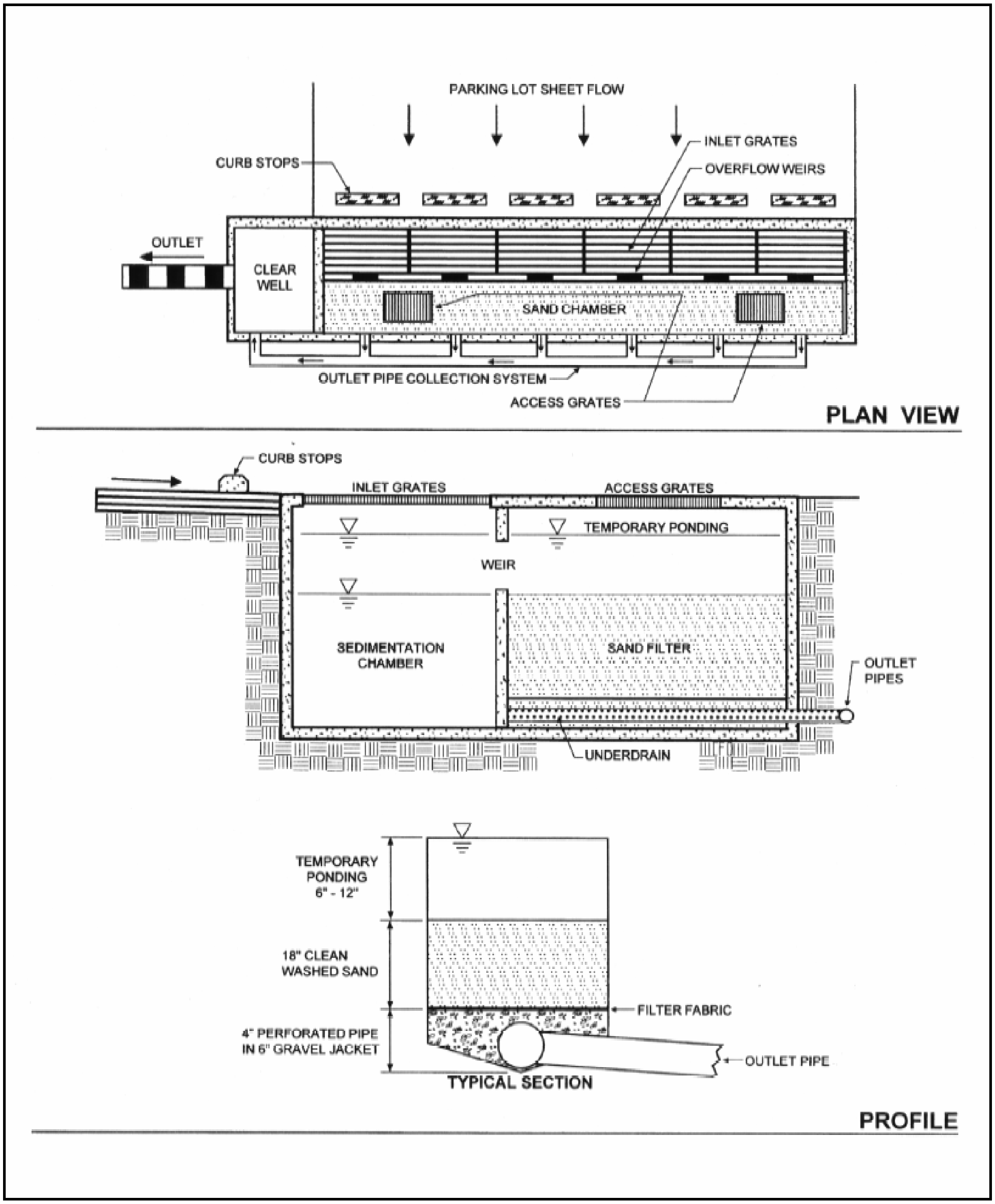

Figure 2.9: Conceptual Framework of a Perimeter Sand Filter, Source: SMRC, 2003

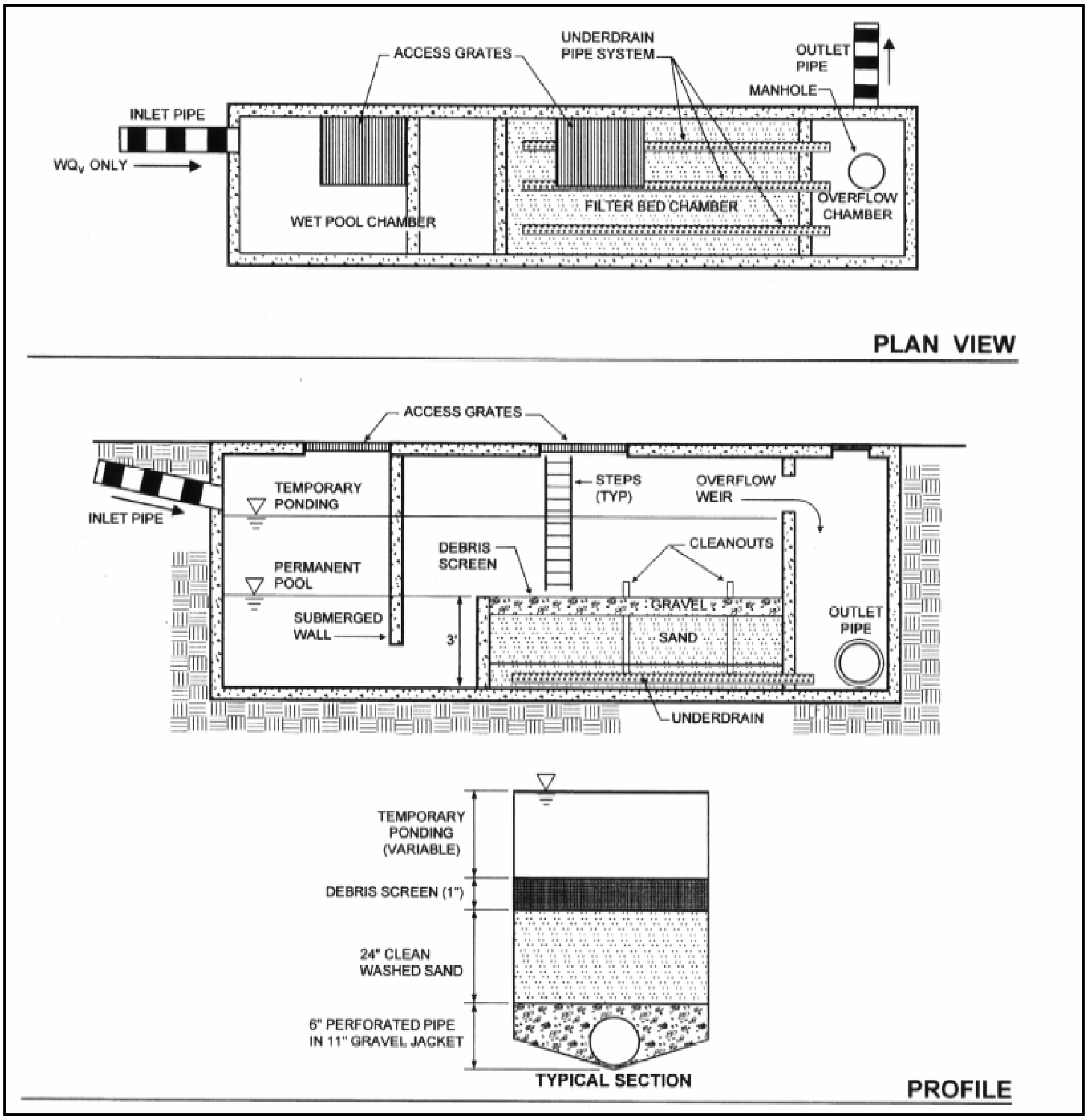

Figure 2.10: Conceptual Framework of Underground Sand Filter, Source: SMRC, 2003

Sand filters are best suited for small sites with a drainage area of 2 acres for perimeter and underground sand filters. The surface sand filters, however, can have maximum drainage area of 50 acres (GSMM and EPA, 1999e). Flat terrain might be suitable for perimeter sand filters but other types require a significant drop in elevation to allow the runoff to flow through the filter (SMRC). The basic design features that should be incorporated into all types of sand filters include pretreatment, treatment, proper conveyance and landscaping. Filtering practices, except the perimeter systems, are typically designed as off-line systems, having only a small amount of the stormwater runoff diverted to them using a flow splitter, which is a structure that bypasses larger flows to the storm drain system (SMRC). Sand filters are generally applied to land uses containing a high percentage of impervious surfaces, as less than 50% imperviousness or high clay/silt sediment loads tend to clog the filter bed (SMRC).

The entire treatment system (including the sedimentation chamber) of the surface sand filter must temporarily hold at least 75% of the stormwater runoff prior to filtration (GSMM). The sedimentation chamber must be sized to hold at least 25% of the runoff and have a length-to-width ratio of at least 2:1. The filter media consists of an 18-inch layer of clean washed medium sand above of the under-drain system. Three inches of topsoil are placed over the sand bed. Permeable filter fabric is placed above and below the sand bed to prevent clogging of the sand filter and the under-drain system.

The structure of the surface sand filter may be either of concrete or earthen embankments. If earthen embankment is used, filter fabric is needed to line the bottom and side slopes of the structures before installation of the under-drain system and filter media. The perimeter sand filter includes the same design structure as that of a surface sand filter but requires little hydraulic head and thus is good option for flat terrains. Here the flow enters the system through grates, usually at the edge of a parking lot. It is the only on-line sand filter with all flows entering the system, but larger events bypass treatment by entering an overflow chamber (SMRC). The underground sand filter typically consists of a multi-chamber underground vault (accessible by access holes or grate openings) having a 3-feet permanent pool sedimentation chamber, 18-24 inch filter bed, a maximum residence time of 40 hours and a main collector pipe having a minimum slope of 0.5 percent (FHWA). The primary function of sand filters and bioretention cells is to provide water-quality treatment.

Vegetated Open Channel Practices

Vegetated open channel practices are systems explicitly designed to treat stormwater runoff in a swale or channel formed by check dams or other means. They usually do not provide quantity control and are combined with other SMPs to meet regulations. These practices that directly receive runoff from an impervious surface should have a temporary ponding time of less than 48 hours and a 6 inch drop onto a protected shelf to minimize the clogging potential of the inlet. Two different types of vegetated open channel practices include grass swales (dry/wet) and grass channels. Figure 2.11 illustrates both wet and dry grass swales, grass channels, and simple drainage channels.

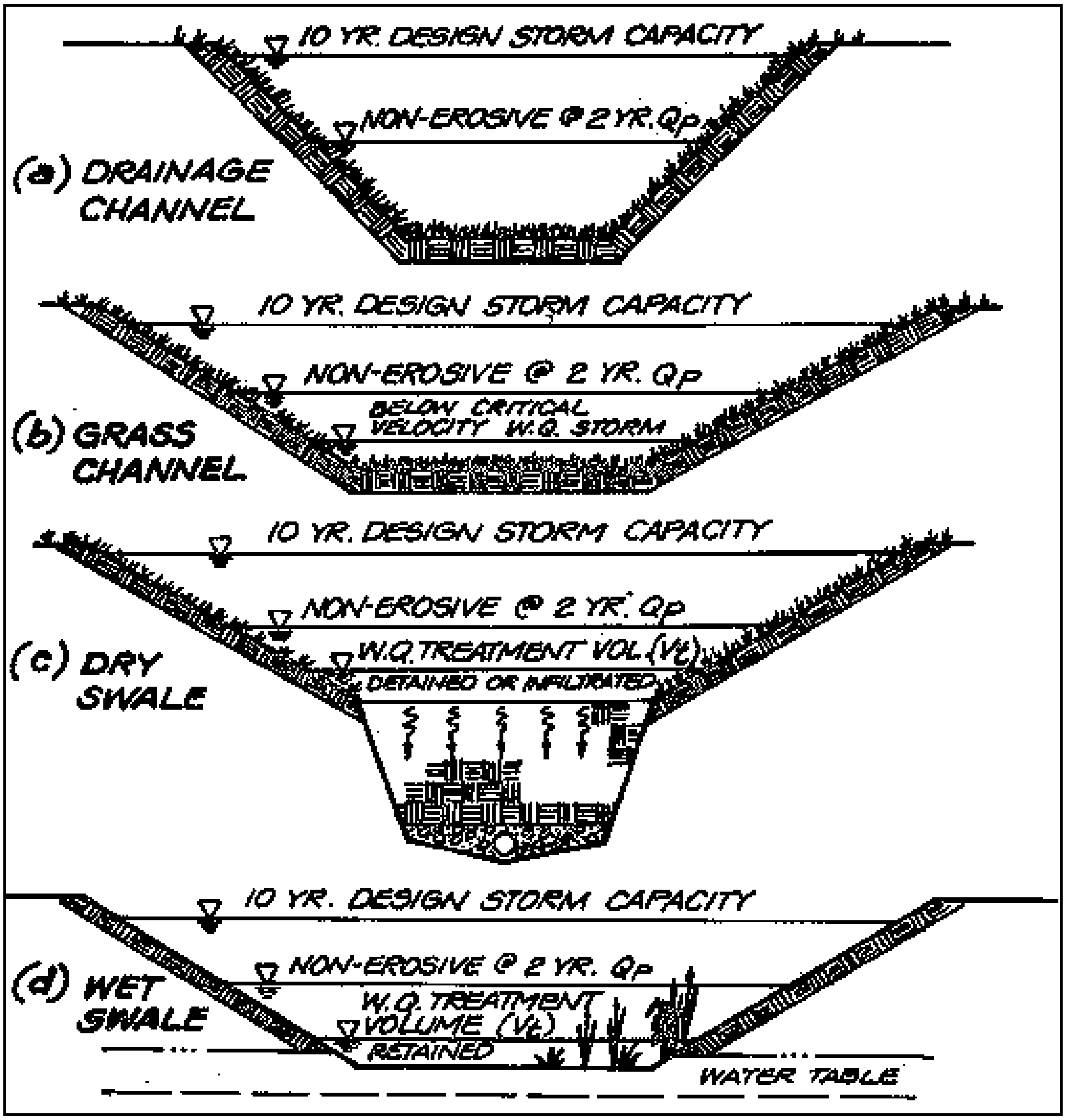

Figure 2.11: Vegetated Open Channel Practices, Source: FHWA, 2006

Grass Swales

Grass swales are broad, shallow earthen channels designed to treat stormwater runoff using erosion resistant and flood tolerant grass. Filtering in these practices occurs through vegetation, a subsoil matrix, and infiltration into the underlying soils (SMRC). They have limited longitudinal slopes with check dams installed perpendicular to flow. This force flows to be slow and shallow and allows the particulates to settle (GSMM). There are two types of grass swales, dry swales having a filter bed of prepared soil that overlays an under-drain system and wet swales designed to retain water or marshy conditions that support wetland vegetation. The use of grass swales is usually prohibited if peak discharges exceed 5 cubic feet per second or if flow velocities are greater than 3 ft/sec. They are also impractical in areas with erosive soils or where a dense vegetative cover is difficult to maintain (EPA, 1999e). Figure 2.12 shows the configuration of a typical grass swale.

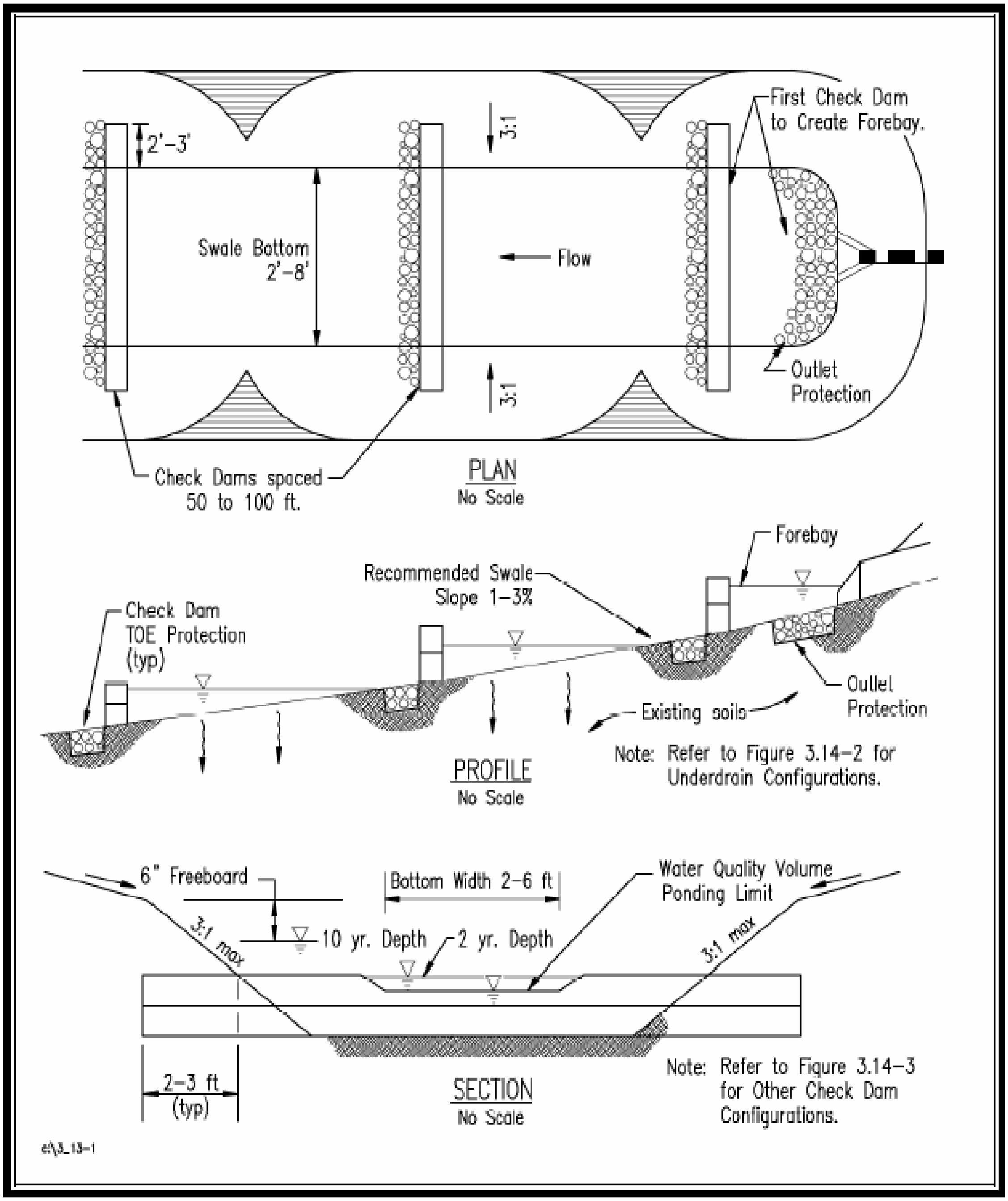

Figure 2.12: Typical Grass Swale Configurations, Source: VASM, 1999

Grass swales, commonly used in low- to moderate density (16 to 21% impervious) single-family residential developments, do not function well with high volumes or velocities of stormwater. They have limited application in highly urbanized or other highly impervious areas, unless used as pretreatment facilities for other SMPs (VASM). They work best when used to treat small drainage areas of less than five acres with relatively flat slopes. Otherwise, the runoff velocity through the practice becomes too great to treat runoff or prevent erosion in the channel. Other than flat slope and preferably parabolic or trapezoidal cross sections, a grass swale should have dense vegetation to help reduce flow velocities, protect the channel from erosion, and act as a filter to treat stormwater runoff. The bottom of the swale should be 2 to 8 feet wide and separated from the groundwater by at least two feet to prevent a moist swale bottom, or groundwater contamination (GSMM). Though swales are usually designed for a 2-year storm event (i.e., the storm that occurs, on average, once every two years) they also have the capacity to pass larger storms (typically a 10-year storm) safely (USSBMP).

Grass Channel

Grass channels are best applicable as a pretreatment mechanism to other structural SMPs. They lack the filter media present in the grass swale and hence provide nominal treatment by partially infiltrating runoff from small storm events in areas with pervious soils (SMRC). They help in reducing the impervious cover and provide aesthetic benefits. Grass channels should be designed on relatively flat slopes of less than 4% and should not be used on soils with infiltration rates less than 0.27 inches per hour. The stormwater runoff should take 5 minutes, on average, to flow from the top to the bottom of the channel (GSMM). Figure 2.13 shows the schematics of a grass channel.

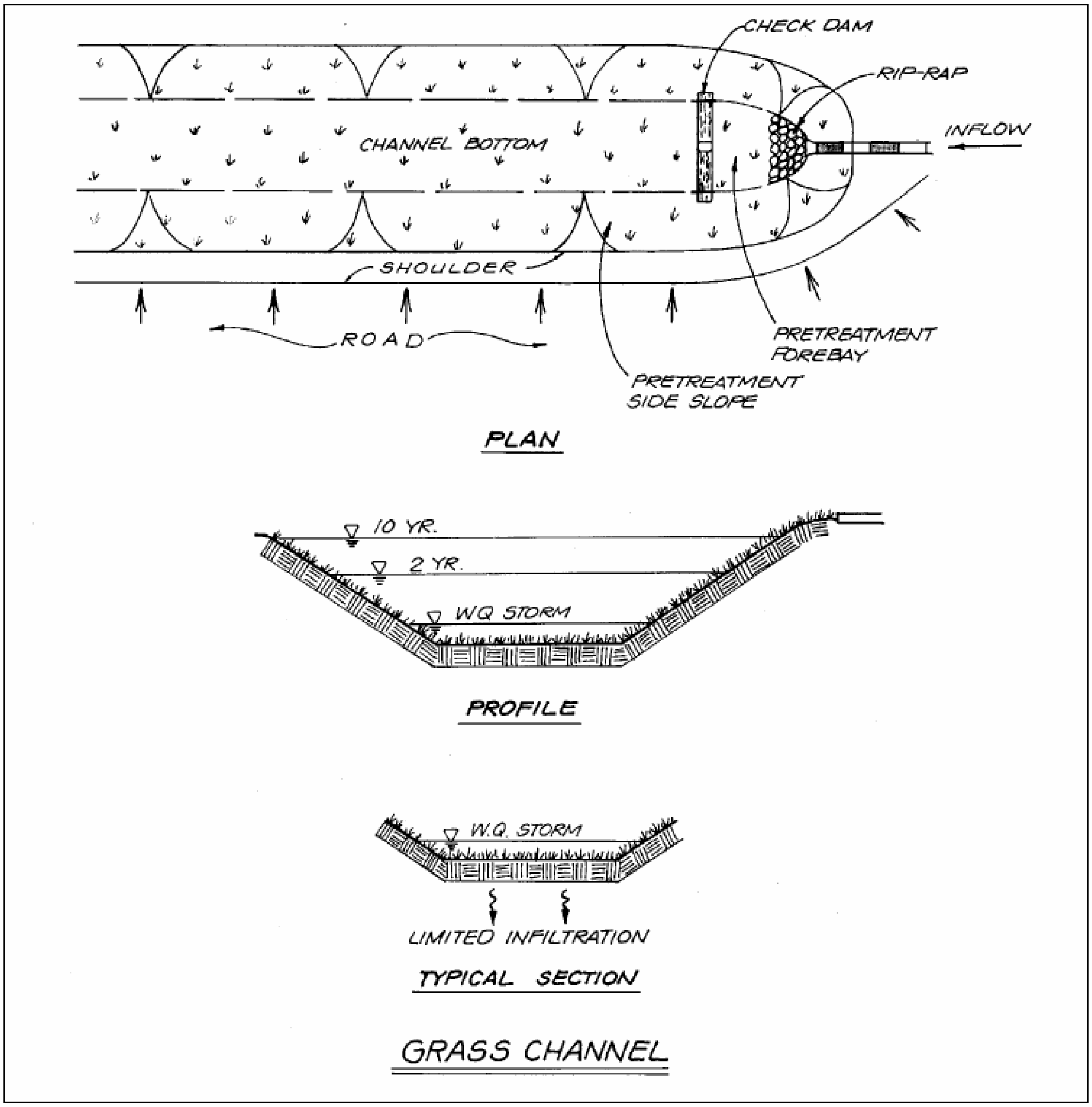

Figure 2.13: Schematics of a Grass Channel, Source: GSMM, 2001

Like the grass swales, the channels should be used to treat small drainage areas of less than 5 acres for its efficient usage (GSMM). They should be designed on relatively flat slopes of less than 4% and should not be used on soils with infiltration rates less than 0.27 in/hr (GSMM). The bottom of the channel should be between 2 and 6 feet wide. A minimum of 2 feet ensures a minimum filtering surface for water quality treatment and a maximum of 6 feet prevents formation of small channels within the bottom. The grass of the channel should be maintained at a height of 3 to 4 inches for the effective removal of particles.

All the above mentioned SMPs have different designs and perform differently. Stormwater ponds and wetlands primarily control the stormwater runoff but also provide some amount of water quality treatment. They usually occupy space which cannot be used for any other purpose and are not commonly found in dense urban areas. Some of the filtration practices, like bioretention cells, focus on water treatment but also control some of the runoff. They are usually found in dense urban areas as the space they occupy can be used for other purposes. Vegetated open channel practices do minimum amounts of both water treatment and control and are usually used in combination with some other SMP.

CHAPTER 3
DATA DESCRIPTION

Cost and other types of data collected from different sources were used in the economic analysis of the above mentioned stormwater management practices. These data were then appropriately modified to be used as the independent and the dependent variables for the different cost models.

Sources of Data

Information about the cost of design, construction, and maintenance of five types of stormwater management practices--stormwater ponds, wetlands, bioretention cells, sand filters, and vegetated open-channel practices--were collected from six different sources:

1. Center for Watershed Protection, Silver Spring, MD
2. Water Resource Research Institute, North Carolina State University, Raleigh, NC
3. Engineering Resource Corporation (ERC) and Clemson University, C. Douglas Clary, P.E. ERC Orangeburg, SC and Charles Privette, Faculty, Clemson University, Clemson, SC
4. Montgomery County Department of Environmental Protection, Mr. Daniel Harper, Manager, Watershed Restoration Program, Rockville, MD
5. Public Utilities Department of Seattle, Ed Mirabella, Project Manager, Seattle Public Utilities, Seattle, WA

6. California Department of Transportation, CALTRAN, Sacramento, CA

Most of the cost data were collected from the first two sources: Center for Watershed Protection (CWP) and Report No. 344 (Wossink and Hunt) of the Water Resource Research Institute. The CWP data were collected from a survey of local engineers and planners from fourteen organizations and from SMP studies and visits to local stormwater management departments (Brown and Schueler, pg 1). In Wossink and Hunt report information about costs of different SMPs was collected from 1999-2001 through phone surveys and site contacts with designers and property owners. These cost data were either the bid prices or the known amount spent by the granting agencies (Wossink and Hunt).

Other than the two sources of data mentioned above, primary cost data on one stormwater pond and two bioretention cells in South Carolina were collected from the Engineering Resource Corporation and Clemson University, respectively (Templeton et. al., 2004, Templeton et. al., 2006, unpublished data provided by C. Douglas Clary from ERC and Charles Privette from Clemson University). Data on cost and design characteristics of three stormwater ponds and one sand filter were provided by the Watershed Restoration Program of the Montgomery County Department of Environmental Protection (unpublished data provided by Daniel Harper from Watershed Restoration Program). Data on four vegetated open-channel practices were collected from the Public Utilities Department of Seattle, Washington (unpublished data provided by Ed Mirabella from Seattle Public Utilities). Data on six vegetated open channel practices, six stormwater ponds and six sand filters were collected from the Final Report prepared by the California Department of Transportation (CALTRANS).

Data on cost of three types of inputs that are used ot produce stormwater management practices and land prices were also collected. Information on the average weekly earnings of construction, engineering and landscape services was collected from the Bureau of Labor Statistics (BLS, 2000a). Land price data were collected from a portal of tax assessor's database (Pulawski). For those counties not listed in the tax assessor's portal[2], the data were collected from the county's webpage directly. Data on the major land resource areas of the SMPs were collected from the Natural Resources Conservation Service of the US Department of Agriculture (NRCS).

Pollutant removal data for the ponds in the database were predicted by the Greenville County Stormwater IDEAL model, version 2.15 (IDEAL). Data on the average 24-hour rainfall for a 10-year storm event at each location of the stormwater ponds were collected from NOAA's Hydrometeorological Design Studies Center (HDSG). Data on the amount of pollutant removed for the SMPs of the CALTRAN report were collected from Appendix F of the report. Primary data on the amount of pollutant removed by the two bioretention cells in South Carolina were collected from Clemson University (Templeton et al., Appendix A). Pollutant removal data for similar SMPs but in different locations were collected from the National Best Management Practice Database (EPA, 1999a). Data on pollutant removal of bioretention cells for which cost information was not available, were collected from five sources: a study conducted at Monticello High School (Yu et al) in VA, Inglewood Demonstration Project (EPA, 2000a), Greenbelt, Landover field studies in Maryland (Davis), and results stated in Table 14 of the Report No. 344 (Wossink and Hunt).

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[2] Counties: Wilson, Columbus and, Gaston in North Carolina.

Description of Variables

The CWP dataset consists of thirty-six stormwater ponds: eighteen dry extended detention ponds, ten wet extended retention ponds, and eight wet ponds. Stormwater ponds from the other sources are all wet ponds, except for that of CALTRANS which consists of five dry extended detention ponds and one wet extended retention pond. All the dry ponds in the dataset have extended detention. Four of the twenty-seven bioretention cells used in the dataset have underground detention. Ten of the twenty-six sand filters are surface sand filters, four are underground sand filters and the remaining ones are perimeter sand filters. Two of the thirteen vegetated open channel practices are grass channels and the remaining are grass swales.

Information on the average weekly earnings of construction workers are based on Standard Industrial Code (SIC) 162, or North American Industry Classification System (NAICS) 234. SIC 162 refers to construction of water and sewer mains, pipelines, power lines, heavy construction, and construction of heavy projects which were not specified elsewhere. Information about earning of engineers is based on SIC 8711 or NAICS 541330. SIC 8711 consists of engineering services like designing ship boats, industrial, civil, electrical and mechanical engineering, machine tool designing, marine engineering services, and petroleum engineering services. Average weekly earnings of those who provide landscape services were for the SIC 078 or NAICS 561730. Landscaping services include landscape counseling and planning, lawn and garden services, and ornamental shrub and tree services. The earnings chosen represented the best possible match of the earnings of workers and engineers engaged in designing and constructing stormwater management practices in the particular county and year.

The hourly wages of people who provide engineering, construction, and landscape services—ENGWAGE, CONWAGE, and LANDWAGE—were calculated as the respective average weekly earnings divided by the average weekly hours worked by those in the manufacturing sector (BLS, 2000b) in the county and year associated with the particular SMP. These wage rates were then adjusted as follows:

$$wage\frac{2005index}{Wageyearindex}\frac{Baltimoreindex}{Wagelocationindex}$$

using the historical cost indices (Murphy) corresponding to Baltimore, Maryland in 2005, which was chosen as the point of reference because of its frequent use as a central location in the study. These historical cost indices represent a composite model of nine different types of buildings constructed in the US and Canada closely representing the usage of materials, labor, and equipment used in the North American Building Construction Industry.

Land price (LANDVAL) data were collected for each city in which the SMP was located. Each SMP was located where the surrounding land use was residential, commercial or both. Ten parcels were randomly chosen among parcels that had the appropriate land use and were located on the outskirts of the particular city on which the SMP was also located. For those data points where the land use of the SMP could not be determined, five residential and commercial land values were randomly selected. These land values were assumed to be for the particular reference city, mentioned in the historical cost indices, for each state. The average of these values was then calculated and appropriately adjusted to correspond to Baltimore, Maryland in 2005. The land values were multiplied by the ratio of the indices for the base year of 2005 to that of the year on which the land was assessed which was again multiplied by the ratio of the indices of Baltimore for 2005 to that of the given location for 2005, i.e.:

$$LANDVAL \frac{2005 index}{LANDVAL year index} \frac{Baltimore index}{LANDVAL location index}$$

CWP and the Montgomery County Department of Environmental Protection defined the water storage volume (QUANVOL) for stormwater ponds and wetlands as the water treatment volume and the runoff from the drainage area for a 10-year storm event. Based on the study by Wossink and Hunt, QUANVOL was measured as 0.5 inch times the drainage area for both the SMPs. For the pond constructed by the Engineering Resource Corporation, QUANVOL was defined as the storage volume of the basin including the sediment storage volume and for the report by CALTRAN, it was measured as the given surface area times the maximum water depth of the pond (Tables 3.1 – 3.5).

The water treatment volume (QUALVOL) for stormwater ponds in the CWP and the Montgomery County Department of Environmental Protection dataset was determined by the responses given in the survey. The QUALVOL of the ponds in Los Angeles and San Diego is the maximum volume that the pond can treat for a 72-hour storm (CALTRANS). Engineering Resource Corporation and Wossink and Hunt described QUALVOL as 0.24 inches times the drainage area for the ponds. Description of the QUALVOL for wetlands in the CWP and Wossink and Hunt dataset is similar to that of the ponds in the two dataset respectively (Tables 3.1 – 3.5).

The QUALVOL of bioretention cells in the CWP dataset and the two cells in South Carolina is measured as 0.75 feet times the surface area of the cell. Wossink and Hunt described these QUALVOL as 0.5 inches times the drainage area. Two cell of the CWP dataset had its QUANVOL as the QUALVOL volume and runoff from the drainage area for a 10-year storm event. Two cells in South Carolina defined QUANVOL as 1.75 ft times the surface area. Water storage volumes were assumed, not measured, to be equal to the water-treatment volumes for the other twenty-three of the twenty-seven bioretention cells in our database (Tables 3.1 – 3.5).

The QUALVOL for sand filters, in the CWP and the dataset of Wossink and Hunt, is measured as 0.5 feet times the product of the drainage area and the imperviousness. For the sand filter from the Montgomery County Department of Environmental Protection, these values are the responses given in the surveys and for the CALTRANS it is the amount of water treated by sand filters for a 1-year 24 hour rainfall event (CALTRANS) (Tables 3.1 – 3.5).

The QUALVOL of the vegetated open channel practices was given for the grass swale in the CWP dataset. For the grass channels of the CWP dataset, it was calculated using the guidelines mentioned in the Greenville County Storm Water Design Management Manual as the first one inch of runoff generated during any given storm event times the drainage area (SWMDM)[3]. For the four swales located in Seattle, QUALVOL was assumed to be the same as the volume of the swale. For the practices in the report by CALTRANS QUALVOL was calculated by dividing the given total unadjusted construction cost by total unadjusted construction cost per water treatment volume. This calculated value is the amount of water treated for 1-year 24 hour storm-event (Tables 3.1 – 3.5).

[3] See Table 3.1 to 3.5 for a concise definition of QUANVOL and QUALVOL volume of all the SMPs from the different sources.

Table 3.1: Details of Information about Water Storage and Treatment Volumes for Stormwater Ponds

	Secondary Sources				
	Center for Watershed Protection	Water Resource Research Institute	Engineering Resource Corporation	Montgomery County Department of Environmental Protection	California Department of Transportation
Data Collections	Data collected from surveys of local engineers and planners from 14 different organizations, other BMP studies and local stormwater management departments	Data collected through phone surveys and site contacts with designers and property owners.	Data were collected personally from the engineers of Engineering Resource Corporation and Clemson University	Data were provided by the manager of Watershed Restoration Program of Montgomery County Department of Environmental Protection	Data were collected by a study team made up of representatives from the parties involved in the BMP Retrofit Pilot Program to the lawsuit, their attorneys, local vector control agencies, and outside technical experts.
No. of Observations	36	9	1	3	6
State(s)	Maryland (24), Virginia (12), North Carolina (1)	North Carolina	South Carolina	Maryland	California

Table 3.1 (Cont.): Details of Information about Water Storage and Treatment Volumes for Stormwater Ponds

	Secondary Sources				
	Center for Watershed Protection	Water Resource Research Institute	Engineering Resource Corporation	Montgomery County Department of Environmental Protection	California Department of Transportation
Storage Volume	Given value : Runoff volume (calculated using engineering application TR-55) from drainage area for 10-year storm event	Stated by Dr. Hunt as 0.5 inch times drainage area (biased downwards)	Given value (calculated using engineering application TR-55): storage volume + volume of sediment storage.	Given value : Runoff from drainage area for 10 year storm event (calculated using engineering application TR-55)	Assumed as the surface area times the given maximum water depth (value suspected to be biased upwards)
Treatment Volume	Given as the permanent pool volume, i.e. 0.5 inch of the runoff from drainage area (includes extended detention volume)	Stated by Dr. Hunt as 2% of the given drainage area	Assumed as 2% of the given drainage area using Dr. Hunts statement.	Given as the permanent pool volume, i.e. 0.5 inch of the runoff from drainage area.	Given as the amount of water treated for a 1 year 24 hours storm event.

Table 3.2: Details of Information about Water Storage and Treatment Volumes for Wetlands

	Secondary Sources	
	Center for Watershed Protection	Water Resource Research Institute
Data Collection	Data collected from surveys of local engineers and planners from 14 different organizations, other BMP studies and local stormwater management departments	Data collected through phone surveys and site contacts with designers and property owners, the costs were either the bid price or the known amount spent
No. of Observations	3	13
State(s)	Maryland (2), Virginia (1)	North Carolina
Storage Volume	Given value: Runoff from drainage area for 10 year storm event (using engineering application TR-55)	Stated by Dr. Hunt as 0.5 inch times given drainage area (values biased downwards)
Treatment Volume	Given as the permanent pool volume, i.e. 0.5 inch of the runoff from drainage area (includes extended detention volume)	Stated by Dr. Hunt as 2% of the given drainage area

Table 3.3: Details of Information about Water Storage and Treatment Volumes for Bioretention Cells

	Primary Source	Secondary Sources	
	Clemson University	Center for Watershed Protection	Water Resource Research Institute
Data Collection	Data were collected from the engineers at the Engineering Resource Corporation and Clemson University for the cells in Orangeburg and Anderson county	Data collected from surveys of local engineers and planners from 14 different organizations, other BMP studies and local stormwater management departments	Data collected through phone surveys and site contacts with designers and property owners, the costs were either the bid price or the known amount spent
No. of Observations	2	12	13
State(s)	South Carolina	Maryland (5), Virginia (7)	North Carolina
Treatment Volume	Stated by Charles Privette as 0.75 times the surface area	Given as 0.75 times the surface area in the report.	Stated by Dr. Hunt as 0.5inch of the drainage area, i.e the permanent pool volume.

Table 3.4: Details of Information about Water Storage and Treatment Volumes for Sand Filters

	Secondary Sources			
	Center for Watershed Protection	Water Resource Research Institute	Montgomery County Department of Environmental Protection	California Department of Transportation
Data Collection	Data collected from surveys of local engineers and planners from 14 different organizations, other BMP studies and local stormwater management departments	Data collected through phone surveys and site contacts with designers and property owners, the costs were either the bid price or the known amount spent	Data were provided by the manager of Watershed Restoration Program of Montgomery County Department of Environmental Protection	Data were collected by a study team made up of representatives from the parties involved in the BMP Retrofit Pilot Program to the lawsuit, their attorneys, local vector control agencies, and outside technical experts.
No. of Observations	9	10	1	6
State(s)	Maryland (5), Virginia (7)	North Carolina (6), Delaware (4)	Maryland	California
Treatment Volume	Given as 0.5 ft * drainage area * percentage imperviousness.	Calculated as 0.5 ft * drainage area * percentage imperviousness following CWP guidelines.	Given as the permanent pool volume (i.e. 0.5 inch of the runoff from drainage area)	Given value: Amount of water treated for a 1 year 24 hour storm event.

Table 3.5: Details of Information about Water Storage and Treatment Volumes for Open Channel Practices

	Secondary Sources		
	Centre for Watershed Protection	Public Utilities Department of Seattle	California Department of Transportation
Data Collection	Data collected from surveys of local engineers and planners from 14 different organizations, other BMP studies and local stormwater management departments	Data provided by the project manager of Seattle Public Utilities on a particular wet extended detention pond built in the King county.	Data were collected by a study team made up of representatives from the parties involved in the BMP Retrofit Pilot Program to the lawsuit, their attorneys, local vector control agencies, and outside technical experts.
No. of Observations	3 (1 swale, 2 channel)	4	6
State(s)	Maryland (1), Virginia (2)	Washington	California
Treatment Volume	One given, two assumed as 0.1 inch of the drainage area as per the Greenville County Design Manual specifications.	Assumed as given surface area times the given depth	Calculated by dividing the given total unadjusted construction cost by total unadjusted construction cost per WQV. It is the amount of water treated for 1-year 24 hours storm event.

Dummies interacted with QUANVOL and QUALVOL are used to separate the SMPs according to their types and region. The stormwater ponds are classified as dry or wet extended ponds (EXTQNV[4]) and non-extended ponds. Four of the bioretention cells having QUANVOL different from the QUALVOL are separated from the others as extended detention cells (EXTDEQLV[5]). The sand filters are classified as surface (SURFQLV), underground (UNGRDQLV), and perimeter sand filters. The vegetated open channel practices are classified as grass swales and channels (GRCHANQLV).

The data points were also classified into major land resource areas according to their locations (NRCS). Three different classifications were noted for bioretention cells, namely the Piedmont region, the coastal plains (COASTQLV), and the Sandhill region (SANDQLV). Stormwater pond and sand filters however were located either in the Piedmont region or the coastal plains whereas wetlands were located in four different regions, the Piedmont, mountain (MOUNTQNV), coastal (COASTQNV), and tidewater (TIDEQNV). Regional distinctions were not made for the vegetated open channel practices. The east coast data were differentiated from the west coast for stormwater ponds, wetlands (WESTQNV) and sand filters (WESTQLV).

The estimated total cost (ESTTOTCST) of the SMPs consisted of design and engineering, construction, and maintenance cost. The construction costs are comprised of excavation and grading, material, control structures[6], sediment control practices put in place during construction of the practice, landscaping including labor directly related to SMP, and the appurtenance which included cost of additional items not included elsewhere (Brown and Schueler). Design and engineering costs were given for the CWP

[4] QNV implies interaction of the particular dummy with QUANVOL.
[5] QLV implies interaction of the particular dummy with QUALVOL.
[6] Example: risers, barrels etc.

data and were estimated as 20% (if construction cost greater than $40,000) or 15% (if construction cost less than $40,000) of the of the construction cost for the data from the report by Wossink and Hunt. For the other sources it was estimated as 10% of the construction cost based on the guidelines of EPA (Muthukrishnan et al) and the design manual by the Canadian Ministry of Environment (UBMPUW). The annual maintenance cost is measured as the given percentage of the construction cost of the SMP following the guidance provided in Table 11.3 of the 'National Management Measures to Control Nonpoint Source Pollution from Urban Areas' (EPA, 2005a). The total maintenance cost for each SMP is then discounted at the rate of 5 percent for the assumed average life span of 20 years. The total cost in this report corresponds to the year in which the SMP was established. In order to facilitate comparison, the nominal total costs were then appropriately adjusted to correspond to Baltimore, Maryland 2005. The total estimated costs were multiplied by the ratio of the indices for the base year of 2005 to that of the year on which the cost was incurred which was again multiplied by the ratio of the indices of Baltimore for 2005 to that of the given location for 2005, i.e.:

$$ESTTOTCST\,\frac{2005index}{ESTTOTCSTyearindex}\,\frac{Baltimoreindex}{ESTTOTCSTlocationindex}$$

In the case of stormwater ponds and wetlands, the estimated total cost (ESTTOTCSTLND) includes the total adjusted land cost calculated using LANDVAL of the SMP and its surface area. Table 3.6 lists the definitions and units of all the variables. The definition of the variables used in the analysis is given in table 3.6.

The IDEAL model for the pollutant removal calculations could be used only for those stormwater ponds that had less than 100 acres of drainage area. Seventy-five percent of the impervious surface of the drainage area was assumed to be connected to the drainage system. Soil series, classification, and the hydrological soil group of each pond were noted (NRCS). The curve number (CN) for the impervious surface was assumed to be 98 and the CN for the pervious surface was calculated using the following equations:

$$WCN = \%impervious * 98 + \% pervious * CNpervious \qquad (3.1)$$

$$S = \frac{1000}{WCN} - 10 \qquad (3.2)$$

$$\text{and, } Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (3.3)$$

where WCN is the weighed curve number, S is the soil retention parameter and P is rainfall and Q is the volume of runoff.

The soil erodibility factor used for the pervious area was 0.28 for the Piedmont region and 0.15 for the coastal region (SCAES). The slope of the pervious area was assumed to be 2% for Piedmont region and 1% for the coastal region to capture the difference in topography of the two regions. Assuming drainage area to be in the form of a square, average slope length[7] of the pervious area was calculated as:

$$\text{Slope Length} = \sqrt{DrainageArea} \qquad (3.4)$$

The time of concentration, i.e. the flow time from the most hydraulically remote point to the watershed outlet as:

$$t_c = 0.0078 L^{0.77} S^{-0.385} \qquad (3.5)$$

where t_c is the time of concentration, L is the slope length and S is the slope.

The effectiveness of cover in erosion control for the pervious area (cover factor) was assumed to be 0.01[8] and the effectiveness of conservation practices was assumed to be

[7] Range = 20 to 300 ft.
[8] Where 0.001 implies maximum cover and 1.2 implies the least cover.

1[9], which is generally the value used for post-construction areas (IDEAL). The percentages of sand, silt and clay particles used for the model were 74.2, 18.1 and 7.7 for the Piedmont region based on the values of a Cecil soil type, and 89.5, 4.1 and 6.4 for the coastal region, based on a sandy loam soil (SCAES). The event mean concentration data for total suspended solids (TSS), nitrogen (N), phosphorus (P) and bacterial indicators (BI) were collected from Table 5.4 and 5.8 of the IDEAL manual (IDEAL).

The height of emergency spillway crest was the calculated height of the pond[10] based on the water storage volume while the height of principal spillway crest was the height based on the water treatment volume of the pond. As no information was available on the design specifications of the ponds, the diameter of the barrel was assumed to be 24 inches to provide the same condition for all the ponds. The other design specifications of the pond used were the same as that given in the IDEAL model. All the above mentioned specifications were used in the IDEAL model to calculate milligrams per liter (mg/L) of TSS, N, P and BI removed by the pond for an average annual storm event.

For CALTRANS dataset the amount of mg/L of TSS, N and P removed by each SMP were collected from appendix F of the CALTRAN report. The report has monitored values of the influents and the effluents for the year 2000 and 2001. The average of eleven monitored points for stormwater ponds, seven for sand filters, and nine for grass swales was used to calculate the mg/L of TSS, N and P removed by all these SMPs. For the bioretention cell in Anderson, South Carolina, an average of six monitored points for the storm events in the year 2005 was used to calculate the amount of N and P removed and for the cell in Orangeburg, South Carolina, one monitored point for the storm event

[9] 0.1 implies maximum effectiveness to conservative practice and 1 implies least effectiveness.
[10] Assume the pond to be a cube.

in the same year was used. These data and the variables were then used according to the methodology described in the next chapter for the cost effectiveness analysis of the SMPs.

Table 3.6: Abbreviations and Definitions of Variables

VARIABLE	UNIT	DEFINITION
ESTTOTCST	2005 $ in Baltimore	Estimated design, engineering, construction, and maintenance cost of the SMP.
ESTTOTCSTLND	2005 $ in Baltimore	Estimated design, engineering, construction, maintenance, and land cost of the SMP.
QUANVOL	ft^3	Volume of water stored by the SMP. Check Tables 3.1 to 3.5 for details.
QUALVOL	ft^3	Volume of water treated by the SMP. Check Tables 3.1 to 3.5 for details.
COASTQNV	ft^3	Water storage volume of the SMP in the coastal region.
COASTQLV	ft^3	Water treatment volume of the SMP in the coastal region.
MOUNTQNV	ft^3	Water storage volume of the SMP in the mountain region.
MOUNTQLV	ft^3	Water treatment volume of the SMP in the mountain region.

Table 3.6 (Cont): Abbreviations and Definitions of Variables

TIDEQNV	ft^3	Water storage volume of the SMP in the tidewater region.
TIDEQLV	ft^3	Water treatment volume of the SMP in the tidewater region.
SAHILQLV	ft^3	Water treatment volume of the SMP in the Sandhill region.
LANDVAL	2005 $ in Baltimore/acre	Estimated value of land in which the SMP is located.
ENGWAGE	2005 $ in Baltimore/hr	Estimated engineering wages for the particular county in which the SMP is located.
CONSWAGE	2005 $ in Baltimore/hr	Estimated construction wages for the particular county in which the SMP is located.
LANDWAGE	2005 $ in Baltimore/hr	Estimated landscaping wages for the particular county in which the SMP is located.

CHAPTER 4
METHODOLOGY

Cost Functions

In previous research (e.g., Schueler, Wossink and Hunt), the specification of the cost function of structural stormwater management practices (SMPs) has been:

$$ESTTOTCST = aWQV^{b}\exp(v), \qquad (4.1)$$

where v ~ N(0, σ), WQV is either stormwater quantity or quality volume, and C represents cost. The natural logarithm of the function

$$\ln ESTTOTCST = \ln(a) + b\ln(WQV) + v\,, \qquad \text{(Model 1)}$$

has been the estimated form. The REGRESS procedure in STATA was used to estimate models of natural logarithm of total costs, denoted ESTTOTCST, of five structural SMPs to allow comparisons to previous study results to more complex specifications.

In the literature, cost functions have been estimated under the assumption that the structural SMPs are designed, engineered, constructed, and maintained at minimum cost for a given volume of water storage or treatment and the volume of water storage or treatment is no larger than necessary for the stormwater discharger to comply with the permits. Hence, random shocks beyond the control of the individual stormwater discharger are the only reasons why actual costs might deviate from the fitted average regression frontier.

In reality, however, the actual cost of a particular SMP might exceed the expected, or mean, minimum cost. Some of these differences in the cost might be due to avoidable producer-specific technical inefficiencies while others might be totally random in nature. To incorporate this subtle nuance in the model, we use the stochastic frontier analysis introduced by Aigner, Lovell and Schmidt 1977. The econometric reformulation using stochastic analysis involves the transformation of the error term, ε = u+v, into a composite error term consisting of a non-negative random part, u, with a half normal distribution, and a random component, v, with a normal distribution (Khumbhakar & Lovell).

Khumbhakar and Lovell describe the cost function as $c(y_i, w_i)*\exp(u_i + v_i)$ where y_i is the vector of outputs, w_i is the vector of input prices and $\exp(u_i+v_i)$ is the composite error term with u_i representing avoidable producer specific technical inefficiencies. Assuming u ~ independently and identically distribution (iid) $N^+ (0, \sigma_u^2)$ and v ~ iid $N (0, \sigma_v^2)$

having density functions $f(u_i) = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_u} \exp(-\frac{u_i^2}{2\sigma_u^2})$ and $f(v_i) = \frac{1}{\sqrt{2\Pi}\sigma_v} \exp(-\frac{v_i^2}{2\sigma_v^2})$

respectively, the joint density function for the composite error term, ε, is given by:

$$f(u_i \varepsilon_i) = \frac{2}{2\Pi \sigma_u^2 \sigma_v^2} \exp(-\frac{u_i^2}{2\sigma_u^2} - \frac{(\varepsilon_i - u_i)^2}{2\sigma_v^2}) \qquad (4.2)$$

The marginal density function derived, after integrating u_i out of $f(u_i \varepsilon_i)$ is given as:

$$f(\varepsilon_i) = \frac{2}{\sqrt{2\Pi}\sigma} (1 - \Phi\left(\frac{-\varepsilon_i \lambda}{\sigma}\right)) \exp(-\frac{\varepsilon_i^2}{2\sigma^2}) \qquad (4.3)$$

where $\sigma = \sqrt{\sigma_u^2 + \sigma_v^2}, \lambda = \frac{\sigma_u}{\sigma_v}$ and Φ(.) is the standard normal cumulative distribution function. Log-likelihood of the above equation (4.3),

$$\ln L = \ln(2) - 0.5\ln(2\Pi) - \ln(\sigma) + \ln(1 - \Phi\left(\frac{-\varepsilon_i \lambda}{\sigma}\right)) - 0.5(\frac{\varepsilon_i^2}{\sigma^2}), \qquad (4.4)$$

is derived by taking the log of the marginal density function and is maximized for the given cost function using the maximum likelihood estimation in STATA.

Description of the SMPs in chapter 2 suggests that the various inputs used in designing, building and maintaining of an SMP are in fixed proportion. That is, substitution between inputs is difficult, if not impossible. In light of the likelihood of fixed inputs, the following Leontief cost function (Diewert) was used.

$$C(y;p) = h(y)\sum b_i p_i \qquad (4.5)$$

where p_i , $y \geq 0$, h(y) is a continuous monotonically increasing function of y, which tends to infinity as y tends to infinity and h(0) = 0 (Diewert). If there is a fixed cost 'g' and $h(y) = Y^h$, then the specification becomes

$$C(y;p) = g + Y^h \sum b_i p_i \qquad (4.6)$$

The natural logarithm of the single output Leontief model can be written as:

$$\log(C) = \log((g + Y^h\{wX\}) + v \qquad \text{(Model 2)}$$

and that of a stochastic single output Leontief model as:

$$\log(C) = \log((g + Y^h\{wX\}) + u + v = \log((g + Y^h\{wX\}) + \varepsilon \qquad \text{(Model 3)}$$

where 'g', 'h' and 'w' are vectors of parameters to be estimated, X is a vector of input prices and Y is the vector of outputs consisting of QUALVOL for bioretention cells, sand filters, and vegetated open channel practices and QUANVOL for stormwater ponds and wetlands. Ideally, the cost function for stormwater ponds and wetlands should be a multi-product Leontief cost (Hall) model involving both QUANVOL and QUALVOL. However, due to lack of sufficient observations it is not possible to estimate the multi-product cost function. Two single-product functions are, therefore, used. Thus two additional models were estimated for stormwater ponds and wetlands using QUALVOL instead on QUANVOL.

The vector of independent variables for stormwater ponds consists of QUANVOL, water storage volume interacted with the coastal region dummy (COASTQNV), the extended ponds dummy (EXTQNV), the west coast dummy (WESTQNV), LANDVAL, and the three wages ENGWAGE, CONSWAGE and LANDWAGE. None of the wetlands in the dataset are located in the west coast nor do they have any design differences like the stormwater ponds. The vector of independent variables of the wetlands, however, consists of two additional regional dummy variables, namely MOUNTQNV and TIDEQNV, in addition to the other variables similar to that of the ponds.

For bioretention cells, the vector of independent variables consists of QUALVOL, water treatment volume interacted with the coastal region dummy (COASTQLV), the Sandhill region dummy (SANDQLV), the extended detention dummy (EXTDEQLV), and the three input costs.

The vector of independent variables for sand filters includes regional dummy for the coast (COASTQLV), two dummy variables for difference in their design, namely, SURFQLV and UNDGRQLV and one for the location of the filters in the west coast, (WESTQLV). The rest of the independent variables of sand filters are the same as that of bioretention cells. The variables in models for vegetated open channel practices include, QUALVOL, water treatment volume interacted with the grass channel dummy, GRCHANQLV, dummy for locations of the practices in the west coast, (WESTQLV) and the three wages.

The significance of the value of $\lambda = \sigma_u / \sigma_v$ is noted for the stochastic Leontief model to determine the presence or absence of technical inefficiency in the model. An insignificant value of λ implies absence of any technical inefficiency in the model because the variance of the technically inefficient component of the error term, σ_u, is zero. In the Leontief models of costs, the elasticities of cost with respect to water storage or water treatment volume of a particular stormwater management practice is

$$E_Q = hY^{h-1}\sum \beta_i P_i \frac{Y}{C} = \frac{hY^h \sum \beta_i P_i}{C} \qquad (4.7)$$

where β_i is the coefficient and P_i is the price of input i and Q is the water storage or treatment volume. The average of the economies of water storage or treatment size is estimated separately for the different regions. The elasticity of the input price, i, for the Leontief model is given by:

$$E_i = \beta_i Y^h \frac{P_i}{C} \qquad (4.8)$$

where β_i is the Leontief estimate of input i and P_i is the price of input i. The elasticity was calculated using the above equation for all the observations in the dataset. Average values of these elasticities in the different regions were then estimated for the given input price of the SMPs.

Maximum likelihood estimation technique, ml in STATA, is used for the above mentioned non-linear models 4, 5, 6 and 7. Algorithms like Newton Raphson (NR), Berndt Hall Hall Hausman (BHHH), Broyden Fletcher Goldfarb Shanno (BFGS) and Davidon Fletcher Powell (DFP) were used to get the results of the models (Greene). NR method is a linear Taylor series approximation estimation procedure (Greene, pg 191) that requires calculation of second order derivatives of the likelihood function. BHHH estimation assumes that the unknown expected value is the covariance matrix of the first derivatives of the function (Greene, pg 132). DFP and BFGS are procedures that eliminate second derivatives altogether (Greene, pg 192).

Cross-Over Volumes and Cost Effectiveness

For the purpose of this analysis a cross-over volume is the volume of inflow treated at which one SMP, either actual or a counterfactually chosen one, becomes a less expensive method of managing water quality than the alternative method, given the input prices that exists in the location of the SMPs. The Leontief models of costs that depend on water-treatment volumes (QUALVOL) are used to determine cross-over volumes.

If a positive cross-over volume for two SMPs exists, two conditions must be obtained. First one SMP must have lower fixed cost than the other. Second, total cost of the SMP with lower fixed costs must increase with water-quality volume (QUALVOL) more than total cost increase with the water-quality volume of the other SMP.

If the two conditions are met, the first step in determining the cross-over volume is to find the expected cost of each SMP as a function of water-quality volume and nothing else. 'Nothing else' means that the values of the explanatory variables, such as input prices, are plugged into the model for an actual SMP in a particular location and a counterfactually chosen SMP in the same location. To find expected total cost as a function of water-quality volume of an SMP in a particular location with given input prices, one must take the anti-log of the stochastic Leontief model and then take the expectation. In particular,

$$\log(C) = (\log(g + Y^h\{wX\}) + \varepsilon) \Rightarrow C = (g + Y^h\{wX\})e^{\varepsilon}$$

$$\Rightarrow E(C) = E[\{g + Y^h(wX)\}e^{\varepsilon}]$$

$$\Rightarrow E(C) = \{g + Y^h(wX)\}E(e^{\varepsilon})$$

$$E(e^{\varepsilon}) = E(e^{(u+v)}) = E(e^u.e^v) = E(e^u).E(e^v)$$

where e^v has a log normal distribution and u and v are independent of each other. Given that $E(v) = 0$,

$$E(e^v) = \mu + \frac{1}{2}\sigma_v^2 = \frac{1}{2}\sigma_v^2, \text{ (Green, pg. 69, 112)}$$

Given that $f(u_i) = \sqrt{\frac{2}{\pi}}\frac{1}{\sigma_u}\exp(-\frac{u_i^2}{2\sigma_u^2})$,

$$E(e^u) = \sqrt{\frac{2}{\pi}}\frac{1}{\sigma_u}\int_0^{\infty} e^u \exp(-u^2/2\sigma_u^2)du \text{ (Khumbhakar and Lovell)}$$

$$= \sqrt{\frac{2}{\pi}}\frac{1}{\sigma_u}\exp(\sigma_u^2/2)\sqrt{2\pi}\sigma_u\left[\frac{1}{\sqrt{2\pi}\sigma_u}\int_0^{\infty}\exp\{-\frac{1}{2\sigma_u^2}(u-\sigma_u^2)^2\}\partial u\right]$$

$$= 2\exp(\sigma_u^2/2)\left[1 - \frac{1}{\sqrt{2\pi}\sigma_u}\int_{-\infty}^{0}\exp\{-\frac{1}{2\sigma_u^2}(u-\sigma_u^2)^2\}\partial u\right]$$

$$= 2\exp(\sigma_u^2/2)\left[1 - \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{-\sigma_u}\exp(-z^2/2)\partial z\right], \text{ substituting } z = (u-\sigma_u^2)/\sigma_u$$

$$= 2\exp(\sigma_u^2/2)\{1 - \Phi(-\sigma_u)\}$$

where $\Phi(.)$ is the distribution function of a standard normal random variable. Therefore,

$$E(e^{(u+v)}) = 2\exp(\sigma_u^2/2 + \sigma_v^2/2)\{1 - \Phi(-\sigma_u)\}$$

Therefore, expected costs are

$$E(C) = 2\{g + Y^h(iW)\}\exp(\sigma_u^2/2 + \sigma_v^2/2)\{1 - \Phi(-\sigma_u)\} \qquad (4.10)$$ [11]

For the standard Leontief model the expected value of the cost function is given by:

[11] Help was provided in the derivation by Dr. Samiran Sinha, Texas A&M University.

$$\log(C) = (\log(g + Y^h\{wX\}) + \varepsilon)$$

$$\Rightarrow C = (g + Y^h\{wX\})e^v$$

$$\Rightarrow E(C) = E[\{g + Y^h(wX)\}e^v]$$

$$\Rightarrow E(C) = \{g + Y^h(wX)\}E(e^v)$$

$$E(C) = \{g + Y^h(wX)\}\exp(\sigma_v^2/2) \qquad (4.11)$$

The expected cost of the SMP as a function of water-quality volume was calculated, using equation 4.11, for each of the observations of the dataset. The expected costs of the counterfactual SMP, assumed to be designed, constructed and maintained at the same location, was also calculated. The water treatment volume at which both the cost of the concerned and the counterfactual SMP would be the same was then estimated individually for every observation. The average water treatment volume was then used to find the cross-over volume at which one SMP would become less expensive compared to the other, for the Piedmont and coastal region separately.

Pollutant Removal and Cost Effectiveness

The determination of the cross-over volume of two SMPs is made under the implicit assumption that pollutant removal capacities of the SMPs are equal. If the removal capacities are the same, then the quality of water effluent should be the same. However, as Table 4.1 indicates SMPs differ in their pollutant removal capabilities. Thus, if stormwater discharges must select SMPs that not only satisfy the design criteria buts also minimize the cost of removing pollutants, one should calculate cross-over volumes that incorporate the difference in pollutant removals.

To calculate the minimum cost per unit of pollutant removed by an SMP, one needs to know not only the expected total cost as a function of water-treatment volume of an SMP and input prices, i.e. C(y,p) (equation 4.7), but also the amount of pollutant removed as a function of the water-treatment volume (y) of the SMP, rainfall (r) and the percentage of imperviousness (m), i.e., R(y, r, m). The cost per unit of the pollutant removed is then calculated as:

$$C_R(y,p,r,m) = \frac{C(y,p)}{R(y,r,m)} \qquad (4.12)$$

The water-treatment volume at which this particular SMP would have the minimum cost per unit of pollutant removed must satisfy this condition:

$$\frac{\partial C_R(y,P,r,m)}{\partial y} = 0 \Rightarrow \partial\left(\frac{C(y,p)}{R(y,r,m)}\right)\Big/\partial y = 0$$

$$\Rightarrow \frac{1}{R^2}(RC'_y - CR'_y) = 0 \Rightarrow RC'_y = CR'_y \Rightarrow \frac{C'_y}{C} = \frac{R'_y}{R} \qquad (4.13)$$

According to equation 4.13, the water-treatment volume at which costs per pollutant removed are minimized must be the volume such that the proportional rate of change of total cost, C'_y/C, equals the proportional rate of change of pollutant removed, R'_y/R.

Table 4.1: Average Amount of Pollutant Removed

Pollutants	Ponds (mg/L)	Wetlands (mg/L)	Bioretention Cells (mg/L)	Sand Filters (mg/L)	Channel Practices (mg/L)
Nitrogen	1.4303	0.4111	0.8137	0.3870	0.5816
Phosphorus	0.1148	0.1002	0.1153	0.0939	-0.2207
Zinc	0.1269	0.0336	0.0673	0.1804	0.0766
Copper	0.0203	0.0015	0.0026	0.0057	0.0100
Lead	0.0567	0.0230	78*	0.0116	0.0225

*Datum given is a percentage; Sources: National Best Management Practice Database (EPA, 1999c) and CALTRANS for all the SMPs (except bioretention cells), Inglewood demonstration project (EPA, 2000a), Maryland's Greenbelt and Landover field study (Davis) and Clemson University for bioretention cells

IDEAL is a model that predicts pollutant removal by a stormwater pond as a function of rainfall, degree of imperviousness, and water treatment volume. Hence in addition to an estimated cost function, there is, implicitly embedded in IDEAL, a pollutant removal function for stormwater ponds. Although there is not pollutant removal function for any other SMP, sample information about pollutant removed of two bioretention cells during different rainfall events exists. The mean volume of water treatment at which the cost per unit of pollutant removed by a counterfactually chosen stormwater pond becomes less expensive than the cost per pollutant removed by the two actual bioretention cells is calculated and reported in chapter 7.

CHAPTER 5
RESULTS AND INTERPRETATIONS OF COST ANALYSIS

Design, construction and maintenance cost data used for the analysis of the stormwater management practices cover six different states. Due to regional and spatial differences, each of the stormwater management practice was tested for heteroscedasticity and spatial correlation. Breusch-Pagan test is performed to check for the presence of heteroscedasticity using the HETTEST function in STATA. As the χ^2 values were 1.15, 0.98, 0.10, 0.16 and 0.10 for stormwater ponds, wetlands, bioretention cells, sand filters and open channel practice, no evidence of heteroscedasticity was found and 10 percent significance level. Values of the Moran's I-statistic, estimated using the MORAN function in MATLAB, were -0.087, -0.046, 0.063, -0.154 and -0.196 for stormwater ponds, wetlands, bioretention cells, sand filters and open channel practice. These values indicate absence of any spatial correlations in the data. Cost analysis of each of the structural stormwater management practices are described in detail below.

Stormwater Ponds

Stormwater ponds are management practices that occupy land area which typically cannot be used for other purposes. Land cost represents fifty-seven percent of the mean cost of stormwater ponds (Table 5.1). Extended ponds are modified stormwater ponds that treat stormwater runoff better than the non-extended ponds. Forty-eight percent of the ponds in the database are wet ponds without any extended detention.

Water storage volume (QUANVOL) for stormwater ponds consists of both water treatment volume (QUALVOL) and some amount of runoff volume which is not treated by the pond.

Results of regression analysis of stormwater ponds are shown in table 5.2. The first model (Model 1, Table 5.2) has the simple specification of previous research. The dependent variable of this model is the natural logarithm of adjusted cost without any land cost and the only independent variable is the water storage volume. In this model a one percent increase in water storage volume (QUANVOL) of a stormwater pond increases total adjusted cost by 0.70 percent. This estimated cost is very close to the estimate (0.705 percent) in the report by Brown and Schueler.

Table 5.1: Descriptive Statistics for Stormwater Ponds (n=55)

Variable	Mean	Std. Dev.	Min.	Max.
ESTTOTCST (2005 $ in Baltimore)	345,647	527,347	8,750	3,439,598
ESTTOTCSTLND (2005 $ in Baltimore)	605,263	1,204,253	21,071	8,211,692
WEST (proportion)	0.11	n.a.	0	1
EXTDE (proportion)	0.62	n.a.	0	1
COASTAL (proportion)	0.47	n.a.	0	1
QUANVOL (ft^3)	234,383	566,617	671	2,962,080
QUALVOL (ft^3)	78,761	205,487	322	1,350,360
LANDVAL (2005 $ in Baltimore/acre)	292,629	263,817	0	1,046,714
ENGWAGE (2005 $ in Baltimore /hr)	36	5	22	47
CONSWAGE (2005 $ in Baltimore /hr)	22	3	15	25
LANDWAGE (2005 $ in Baltimore /hr)	16	2	10	18

Table 5.2: Models of the Natural Logarithm of Costs of Stormwater Ponds

	Estimate, (Standard Error), and *p-value*				
VARIABLE	Model 1 (LQUANVOL)	Leontief Model 2	Stochastic Leontief Model 3	Leontief Model 4	Stochastic Leontief Model 5
Intercept	4.84715 (0.77190) *<.0001*	16321.11 (7285.814) *0.0250*	1256.472 (8358.766) *0.8810*	10269.56 (5485.295) *0.0610*	6405.865 (6357.965) *0.3140*
QUANVOL	0.70040 (0.06933) *<.0001*	0.97810 (0.00758) *<.0001*	0.77908 (0.24796) *0.0020*		
QUALVOL				0.83787 (0.01294) *<.0001*	0.84304 (0.02612) *<.0001*
COASTQNV		0.03024 (0.02987) *0.3110*	0.01827 (0.02467) *0.4590*	0.01503 (0.02241) *0.5020*	0.01586 (0.02226) *0.4760*
EXTQNV		-0.08684 (0.01403) *<.0001*	-0.05575 (0.02371) *0.0190*	-0.10696 (0.01764) *<.0001*	-0.10134 (0.02448) *<.0001*

Table 5.2 (Cont): Models of the Natural Logarithm of Costs of Stormwater Ponds

	Estimate, (Standard Error), and *p-value*				
VARIABLE	Model 1 (LQUANVOL)	Leontief Model 2	Stochastic Leontief Model 3	Leontief Model 4	Stochastic Leontief Model 5
WESTQNV		0.35208 (0.02576) *<.0001*	0.31770 (0.04447) *<.0001*	0.29798 (0.04426) *<.0001*	0.29699 (0.05572) *<.0001*
LANDVAL		6.81e-06 (2.01e-06) *0.0010*	0.00001 (7.43e-06) *0.0640*	0.00010 (0.00003) *0.0030*	0.00004 (0.00003) *0.1660*
ENGWAGE		-0.04303 (0.00510) *<.0001*	-0.63418 (0.19459) *0.0010*	-1.41052 (0.23052) *<.0001*	-0.58993 (0.26363) *0.0250*
CONSWAGE		-0.22223 (0.01008) *<.0001*	-0.12724 (3.34699) *0.9700*	4.15469 (0.61479) *<.0001*	1.89377 (0.41819) *<.0001*
LANDWAGE		0.65237 (0.01515) *<.0001*	2.96052 (7.69420) *0.7000*	0.87091 (0.50319) *0.0830*	0.36088 (0.61311) *0.5560*
Log-Likelihood		-40.1798	-36.7444	-63.5082	-63.1696

Models 2 and 3 are standard and stochastic Leontief cost functions of water storage volume (QUANVOL) and incorporate regional and design differences of ponds along with prices. Models 4 and 5 are standard and stochastic Leontief cost functions of water treatment volume (QUALVOL), instead of water storage volume (QUANVOL), but otherwise has the same exogenous variables as those in model 2 and 3. Ideally a multi-product Leontief cost function involving both QUANVOL and QUALVOL should have been used for the cost analysis of stormwater ponds. Due to insufficiency of data estimates of this model could not be calculated. Results of two single output models are therefore reported.

There is no technical inefficiency in the stochastic Leontief model (Model 3, Table 5.2), as $\lambda = \sigma_u / \sigma_v$ is insignificant (p-value = 0.9970), indicating that the variance of the technically inefficient component of the error term, σ_u, is zero. Estimates of standard Leontief cost model (Model 2, Table 5.2) are, therefore, discussed below.

Similar to results of original model, economies of size are present in the standard Leontief model (Model 2, Table 5.2). That is, for every 1 percent increase in water storage volume of ponds the total adjusted cost increases, on average by 0.79 and 0.90 percent in Piedmont and coastal regions. These values were calculated as the average value of elasticities calculated for each site in the database using equation 4.7.

The value of the land that a stormwater pond occupies is a significant cost of the pond. For every 1 percent increase in value of land per acre the total adjusted cost, on average, increases by 0.25 and 0.20 percent in Piedmont and coastal region. These values were calculated as the average value of the elasticities of for each site in the database using equation 4.8.

Although all the three wages are significant determinants of total adjusted cost in the standard Leontief models, both of the estimated effects of engineering and construction wages are negative. These results are difficult, if not impossible, to interpret. For landscape wages a one percent rise increases the total adjusted cost by 1.52 and 2.86 percent in Piedmont and coastal region. A highly paid landscape worker is likely to employ more sophisticated technologies to obtain superior results which results in high elasticity of these wages. Though we might expect the elasticity of these wages to be high an elasticity of 1.52 is too high and might reflect the effect of other input prices, like machinery costs, in the model.

In all the models in table 5.2, for any increase in the water treatment volume, extended ponds are less expensive compared to the wet ponds without such modification. For standard Leontief model (Model 2), increase in total adjusted cost of ponds for every 1 percent increase in QUANVOL would be lower by 0.09 percent in case of extended ponds when compared to the non-extended wet ponds. A possible explanation of this result might be that extended ponds are usually smaller than the ponds without the extension for the same site (SMRC). Another plausible explanation for lower cost might be that these extended ponds were initially used as silt basins during constructions and were later converted to ponds.

This standard model (Model 2, Table 5.2) also indicates that for every one percent increase in water storage volume, it would cost 0.35 percent more to design, construct and maintain a pond in west coast compared to the east. The rental rates of a backhoe, usually used in the construction of a SMP, are higher in the California compared to those in the east coast (HERC). These and other inputs not included in the model might have a higher cost in the west coast compared to the east which might increase the cost of constructing a pond in the west coast.

For the models with QUALVOL instead of QUANVOL, there is again no technical inefficiency (p-value of $\lambda = 0.5290$) in the stochastic Leontief model (Model 5, Table 5.2). Results of the standard Leontief model (Model 4, Table 5.2) are, therefore, discussed in details. Economies of water treatment size is again present for this model (Model 4, Table 5.2) because for every one percent increase in water treatment volume of ponds total adjusted cost, on average increases by 0.74 and 0.82 percent in Piedmont and coastal region. These percentages are the average elasticity calculated using equation 4.7 (Chapter 4) for each region separately.

For a one percent increase in water treatment volume of ponds, it is less expensive to design, construct and maintain extended detention ponds by 0.11 percent compared to wet ponds. Thus, the design, engineering and construction cost of extended ponds are less than their non-extended counterpart. Results also indicate that for every one percent increase in the water treatment volume of the ponds, it is costlier to design, construct and maintain a pond in west coast by 0.30 percent compared to the east.

All the three wages are a significant determinant of total adjusted costs of stormwater ponds in the standard Leontief model (Model 4, Table 5.2). However, interpretation of the negatively significant engineering wages is again difficult. Unlike model 2, construction wages are now positively significant. In particular, if the construction wages increases by one percent, total adjusted cost increases by 1.09 and 1.27 percent in Piedmont and coastal region. These percentages are the average elasticity calculated using equation 4.8 (Chapter 4) for each region. For landscape wages a one percent rise increases the same cost by 0.23 and 0.27 percent in Piedmont and coastal region. A highly paid construction or a landscape worker is likely to employ more sophisticated technologies in their own fields to obtain superior results. Rise in costs in the proposed models can be attributed to higher wages and higher costs associated with increase in sophistication. Since theses models do not consider machine costs separately, high costs might be due to the better machines used by skilled workers. Though we might agree that sophistication increases cost, a decrease in cost due to increase in engineering wages does not seem to make sense and reflect the need of a more sophisticated database.

All the models for stormwater ponds exhibit economies of water-quantity and quality size and compared to a non-extended pond, it is less expensive to design, construct and maintain an extended stormwater pond in an area where opportunity cost of land is lower. Though elasticity of the construction wages in the standard Leontief cost model involving QUALVOL (Model 4, Table 5.2) is more than 1, this model is preferred over the stochastic model as all three wages are now significant determinant of the cost of stormwater ponds.

Stormwater Wetlands

Land used for the construction of wetlands cannot be used for other purposes. On average land cost represents thirty-eight percent of the total adjusted cost of a wetland (Table 5.3). Although four different regions are being considered for the analysis, 44 percent of the wetlands in the database are located in Piedmont region and 25 percent in coastal region. While average value of wages are almost similar to that of ponds, average value of land is 60 percent lower for wetlands compared to ponds. QUANVOL and

QUALVOL are calculated in the same manner as that of the pond. All the models here have the same specifications as that of ponds. Results of the models are shown in table 5.4.

Table 5.3: Descriptive Statistics for Stormwater Wetland (n=16)

Variable	Mean	Std. Dev.	Min.	Max.
ESTTOTCST (2005 $s in Baltimore)	99,184	147,494	8,298	593,855
ESTTOTCSTLND (2005 $s in Baltimore)	263,181	594,572	9,122	2,403,819
COASTAL (proportion)	0.25	n.a.	0	1
TIDEWATER (proportion)	0.12	n.a.	0	1
MOUNTAIN (proportion)	0.19	n.a.	0	1
QUANVOL (ft^3)	153,786	297,679	2,722	1,210,968
QUALVOL (ft^3)	43,547	46,751	1,307	174,240
LANDVAL (2005 $s in Baltimore/acre)	176,510	134,857	30,324	514,902
ENGWAGE (2005 $s in Baltimore/hour)	33	7	18	42
CONSWAGE (2005 $s in Baltimore/hour)	20	4	14	25
LANDWAGE (2005 $s in Baltimore/hour)	14	3	16	18

Table 5.4: Models of the Natural Logarithm of Costs of Stormwater Wetlands

	Estimate, (Standard Error), and *p-value*				
VARIABLE	Model 1 (LQUANVOL)	Leontief Model 2	Stochastic Leontief Model 3	Leontief Model 4	Stochastic Leontief Model 5
Intercept	3.22992 (1.46548) *0.0450*	9780.085 (2234.578) *<.0001*	-13197.36 (96035.23) *0.8910*	20385.7 (5647.432) *<.0001*	23286.61 (77016.58) *0.7620*
QUANVOL	0.74695 (0.13369) *<.0001*	0.84430 (0.01257) *<.0001*	0.47230 (0.03278) *<.0001*		
QUALVOL				1.37256 (0.01491) *<.0001*	0.49071 (0.01770) *<.0001*
COASTQNV		0.00812 (0.03196) *0.8000*	0.00206 (0.11047) *0.9850*	-0.07097 (0.04455) *0.1110*	-0.13553 (0.33347) *0.6840*
TIDEQNV		-0.03945 (0.04385) *0.3680*	-0.07880 (0.19026) *0.6790*	-0.14657 (0.05093) *0.0040*	-0.21603 (0.26187) *0.4090*

Table 5.4 (Cont): Models of the Natural Logarithm of Costs of Stormwater Wetlands

	Estimate, (Standard Error), and *p-value*				
VARIABLE	Model 1 (LQUANVOL)	Leontief Model 2	Stochastic Leontief Model 3	Leontief Model 4	Stochastic Leontief Model 5
MOUNTQNV		0.00895 (0.03941) *0.8200*	0.03207 (0.04039) *0.4270*	-0.07014 (0.05798) *0.2260*	-0.04306 (0.05607) *0.4420*
LANDVAL		0.00004 (3.53e-06) *<.0001*	0.00770 (0.00405) *0.0570*	6.16e-07 (1.43e-07) *<.0001*	0.02577 (0.00607) *<.0001*
ENGWAGE		0.02992 (0.04311) *0.4880*	13.87184 (63.50851) *0.8270*	0.00072 (0.00062) *0.2450*	-51.62602 (54.32166) *0.3420*
CONSWAGE		0.09881 (0.05994) *0.0990*	38.33863 (44.72284) *0.3910*	0.00165 (0.00045) *<.0001*	232.5613 (178.2138) *0.1920*
LANDWAGE		-0.12713 (0.10199) *0.2130*	-74.87613 (110.4649) *0.4980*	-0.00501 (0.00096) *<.0001*	-274.1465 (314.4476) *0.3830*
Log-Likelihood		-12.4343	-12.3626	-13.7595	-21.3077

The first model (Model 1, Table 5.4), which replicates the specification of previous research, indicates that for every 1 percent increase in QUANVOL of wetland total adjusted cost increases significantly by 0.74 percent. As the percentage increase in total cost is lower than the increase in water storage volume, this model exhibits economies of size.

The standard and stochastic Leontief models (Model 2 and 3, Table 5.4) incorporate regional differences and input prices in addition to water storage volume. Insignificant value of λ (p-value = 0.9880) in stochastic Leontief model indicated absence of any technical inefficiency. Results of the standard Leontief models are therefore discussed in detail. Important difference between results of standard and stochastic Leontief model (Model 2 and 3, Table 5.4) is that construction wage is a significant determinant of total adjusted cost in standard Leontief model and not in the stochastic model.

Economies of size are again present in the standard Leontief model (Model 2, Table 5.4). A one percent increase in QUANVOL of wetlands increases total adjusted cost, on average, by 0.65, 0.68, 0.71, and 0.72 percent (using equation 4.7, Chapter 4) in Piedmont, mountain, coastal and tidewater regions. This also illustrates that, similar to stormwater ponds, economies of size are stronger in Piedmont and mountain region having more slope compared to the flatter coastal or tidewater regions. Significantly high value of the intercept in this model implies that fixed cost plays an important role in determining variation of total adjusted cost.

Similar to results of stormwater ponds, value of land is a significant determinant of total adjusted cost of wetlands (Model 2, Table 5.4). With every 1 percent increase in value of land per acre total adjusted cost increases by 0.63, 0.65, 0.76 and 0.49 percent in

Piedmont, mountain, coastal, and tidewater regions respectively. As value of land is an important determinant of wetlands and ponds, these practices should be more commonly found at outskirts of cities where land cost is lower compared to the densely populated urban areas.

Another significant determinant of standard Leontief cost model (Model 2, Table 5.4) is construction wages. One percent increase in construction wages increase total adjusted cost significantly by 0.25, 0.23, 0.16 and 0.48 percent in Piedmont, mountain, coastal and tidewater region respectively.

Technical inefficiency is again absent (p-value of $\lambda = 0.2510$) in stochastic Leontief model (Model 5, Table 5.4), using QUALVOL as the output instead of QUANVOL. The estimated likelihood function was not concave and hence there is no guarantee that the reported estimates are in fact maximum likelihood estimates. The non-concavity of the estimated likelihood function is the probable reason for the decrease in the log-likelihood compared to the log-likelihood of the standard version. Technical inefficiency and non-concavity are the reasons why the standard Leontief model is discussed in details. Results of the standard Leontief model (Model 4, Table 5.4), with QUALVOL as the output, indicate that economies of water treatment size is present for the wetlands in coastal and mountain regions. For every one percent increase in the QUALVOL of the wetland the total adjusted cost increase by 1.01, 0.85, 0.95 and 1.10 percent in Piedmont, mountain, coastal and tidewater regions.

Results of this standard Leontief model (Model 4, Table 5.4) also indicates that, for every one percent increase in the water treatment volume of the wetland, it would cost 0.15 percent less to construct a wetland in the tidewater region compared to the piedmont region. Wetlands are relatively shallow with high evaporation rate making it difficult to maintain a permanent pool of water. Higher water table in the tidewater region requires less excavation to maintain a permanent pool of water for the wetlands and therefore costs less to construct compared to the Piedmont region.

In this model ((Model 4, Table 5.4) again the value of land is a significant determinant of total adjusted cost. Thus, all the cost models of wetlands exhibit economies of both water storage and quality size in the coastal and mountain regions and have land value as a significant determinant of total adjusted cost.

Bioretention Cells

Bioretention cells are filtration practices which control as well as treat stormwater runoff. All stormwater runoff controlled by a bioretention cell also gets treated. Therefore effect of QUALVOL only is considered in the analysis below. Fifteen percent of the cells in the database are equipped with extra storage at the bottom and are named as extended detention cells in this study (Table 5.5). While 49 percent of the cells are located in Piedmont regions only 7 percent are located in Sandhill regions. The amount of water treated (QUALVOL) is calculated as 0.75 feet times the surface area for the CWP dataset, 0.24 inch times the drainage area for the Wossink and Hunt dataset and given for rest of the data sources.

Results of regression analysis for the various models of bioretention cells are shown in table 5.6. Models specified here are similar to that of ponds or wetlands. The first model (Model 1, Table 5.6) is the simple specification of the previous research. Standard and stochastic Leontief cost models (Model 2 and 3, Table 5.6) incorporates regional and design differences of cells along with input prices in addition to QUALVOL used in the first model.

Table 5.5: Descriptive Statistics for Bioretention Cells (n=27)

Variable	Mean	Std. Dev.	Min.	Max.
ESTTOTCST (2005 $s in Baltimore)	50,983	73,191	2,338	370,814
COASTAL (proportion)	0.44	n.a.	0	1
SANDHILL (proportion)	0.07	n.a.	0	1
EXTDE (proportion)	0.15	n.a.	0	1
QUALVOL (ft^3)	3,734	4,902	272	19,874
ENGWAGE (2005 $s in Baltimore /hour)	40	17	29	101
CONSWAGE (2005 $s in Baltimore /hour)	22	3	15	27
LANDWAGE (2005 $s in Baltimore /hour)	16	3	8	18

Table 5.6: Models of the Natural Logarithm of Costs of Bioretention Cells

	Estimate, (Standard Error), and *p-value*		
VARIABLE	Model 1 (LQUANVOL)	Leontief Model 4	Stochastic Leontief Model 5
CONSTANT	5.42829 (1.40527) *0.0010*		
QUALVOL	0.63180 (0.18482) *0.0020*	0.96410 (0.02025) *<.0001*	1.00623 (0.05071) *<.0001*
COASTQLV		0.02736 (0.02880) *0.3420*	0.03806 (0.03129) *0.2240*
SANDQLV		-0.23784 (0.05348) *<.0001*	-0.23322 (0.05154) *<.0001*
EXTDEQLV		0.03242 (0.03104) *0.2820*	0.00648 (0.00857) *0.4500*
ENGWAGE		0.03690 (0.02579) *0.1530*	0.02804 (0.01954) *0.1510*
CONSWAGE		0.54158 (0.12210) *<.0001*	0.30065 (0.06668) *<.0001*

Table 5.6 (Cont): Models of the Natural Logarithm of Costs of Bioretention Cells

LANDWAGE		0.22362 (0.20864) *0.2840*	0.06450 (0.02109) *0.0020*
Log-Likelihood		-25.1635	-24.2007

In the first model (Model 1, Table 5.6) water treatment volume remains a significant determinant of total adjusted cost of a bioretention cell. A one percent increase in water treatment volume increases total adjusted costs by 0.63 percent. This model, however, explains only 29 percent of the variation in total adjusted costs. Schueler and Brown's report, using unadjusted total construction cost, estimated this coefficient as 0.99 and their model explained 96 percent of the variations.

The standard and stochastic Leontief models (Model 2 and 3, Table 5.6) includes QUALVOL, regional and design differences and the three wages. Significant value of λ (p-value = 0.0590) indicates presence of technical inefficiency in the stochastic Leontief model (Model 3, Table 5.6). This model is therefore discussed in details below.

A one percent increase in water treatment volume increases total adjusted cost of the cell by 1.01, 1.04 and 0.77 percent (using equation 4.7, Chapter 4) in Piedmont, coastal and Sandhill regions (Model 3, Table 5.6). Economies of size are present only for the cells found in the Sandhill regions.

For every one percent increase in the water treatment volume total adjusted cost of the cell is lower by 0.23 percent when cells are located in Sandhill region compared to Piedmont region (Model 3, Table 5.6). Better treatment of stormwater runoff can be achieved if the cell is designed with a soil bed that has a sand matrix and a mulch layer above it. Hence, location of a cell in Sandhill region can be expected to achieve lower excavation and/or transportation cost of sand when compared to Piedmont region.

Pre-construction and construction costs of a bioretention cell depends not only on volume of water that is treated for pollutants, QUALVOL, and region, but also on average wage of engineers, construction and landscape workers in or closest to the urban area where the cell is located. Construction and landscape wages are a significant determinant of total adjusted costs of a bioretention cell in stochastic Leontief model (Model 3, Table 5.6).

Construction cost constitutes major portion of total adjusted costs (90 percent approximately) and results indicate a one percent increase in construction wages increases total adjusted cost by 0.76, 0.75 and 0.77 percent in Piedmont, coastal and Sandhill regions (Model 3, Table 5.6).

A typical bioretention cell that can fit into a parking lot or a residential complex in an urban setting requires a high level of landscaping sophistication. In this model (Model 3, Table 5.6) a one percent increase in the landscaping wages increases total adjusted cost, on average, by 0.20 percent in Piedmont and coastal region and 0.27 percent in Sandhill region.

Overall we find that bioretention cells which exhibit economies of size in the Sandhill regions are less expensive to design, construct and maintain in this region compared to Piedmont and that both landscaping and construction wages significantly affect the cost of a bioretention cell.

Sand Filters

Sand filters, filtration practices primarily used for water treatment, controls negligible amount of stormwater runoff. Average estimated cost of sand filters is 13 percent higher than that of bioretention cells (Table 5.7). If land costs of ponds and wetlands are not considered, this average estimated total cost if higher than all SMPs considered in the analysis. Forty-seven percent of the sand filters in the database are perimeter sand filters which, unlike surface or underground sand filters, are on-line filter with all flows entering the system. Water-quality volume (QUALVOL) of sand filters is calculated in the same way as that of the cells for most of the data points. For the filters located in the west coast, QUALVOL is given as the amount of water treated for a 1-yr 24 hours storm event (CALTRAN). Opportunity cost of land is ignored for the analysis. Estimates of models used in the cost analysis of sand filters have specification similar to that of bioretention cells and are reported in table 5.8.

Table 5.7: Descriptive Statistics for Sand Filters (n=26)

Variable	Mean	Std. Dev.	Min.	Max.
ESTTOTCST (2005 $s in Baltimore)	401,875	376,226	51,200	1683,038
COASTAL (proportion)	0.50	n.a.	0	1
WEST (proportion)	0.23	n.a.	0	1
SURFFL (proportion)	0.38	na	0	1
UNGRDFL (proportion)	0.15	n.a.	0	1
QUALVOL (ft^3)	12,529	14,890	907	59,242
COASTQLV (ft^3)	4,304	9,238	0	41,382
WESTQLV (ft^3)	1,448	2,940	0	10,100
SURFQLV (ft^3)	6,194	13,924	0	59,242
UNGRDQLV (ft^3)	2,909	7,572	0	24,812
ENGWAGE (2005 $s in Baltimore /hour)	35	6	16	43
CONSWAGE (2005 $s in Baltimore /hour)	19	3	13	24
LANDWAGE (2005 $s in Baltimore /hour)	16	4	11	24

Table 5.8: Models of the Natural Logarithm of Costs of Sand Filters

Estimate, (Standard Error), and *p-value*			
Variable Name	Model 1 (LQUANVOL)	Leontief Model 4	Stochastic Leontief Model 5
Intercept	10.90094 (1.58161) *<.0001*		
QUALVOL	0.17836 (0.17739) *0.3250*	0.49041 (0.02218) *<.0001*	0.78548 (0.12368) *<.0001*
COASTQLV		-0.01176 (0.02637) *0.6560*	-0.03687 (0.03484) *0.2900*
WESTQLV		0.24201 (0.05572) *<.0001*	0.22311 (0.03047) *<.0001*
SURFQLV		-0.14454 (0.03372) *<.0001*	-0.1894 (0.00844) *<.0001*
UNGRDQLV		-0.09326 (0.04166) *0.0250*	-0.18228 (0.00486) *<.0001*
ENGWAGE		-65.48897 (27.26457) *0.0160*	-16.11295 (47.50811) *0.7340*
CONSWAGE		290.2709 (83.08759) *<.0001*	84.33007 (161.526) *0.6020*

Table 5.8 (Cont): Models of the Natural Logarithm of Costs of Sand Filters

	Estimate, (Standard Error), and *p-value*		
Variable Name	Model 1 (LQUANVOL)	Leontief Model 4	Stochastic Leontief Model 5
LANDWAGE		68.60146 (30.82786) *0.0260*	-0.40404 (8.53029) *0.9620*
Log-Likelihood		-29.2433	-26.1498

In the simple model (Model 1, Table 5.8) QUALVOL is not a significant determinant of total adjusted cost and explains only 0.0004 percent of the variations in cost. Schueler and Brown report also states that it was not possible to define a valid relationship between costs and water-treatment volumes of sand filters (Schueler and Brown).

Model 2 and 3 (Table 5.8) are standard and stochastic Leontief functions of water treatment volume (QUALVOL) and incorporate regional and design differences along with the input prices. Convergence of maximum likelihood of Leontief models could only be achieved in the absence of any fixed cost. Insignificant value of λ (p-value = 0.9810) in the stochastic Leontief model (Model 3, Table 5.8) indicates absence of any technical inefficiency. Estimates of standard Leontief model (Model 2, Table 5.8) are therefore discussed in details.

Unlike the first model (Model 1, Table 5.8) QUALVOL is a significant determinant of total adjusted cost in the standard Leontief model (Model 2, Table 5.8). Every one percent increase in the volume of water treatment treated by sand filters increases total adjusted cost, on an average, by 0.41 and 0.53 percent in Piedmont and coastal region.

This indicates the presence of economies of size.

As for the stormwater ponds, higher cost of living in the California region is reflected by a positively significant dummy for the west coast. For every one percent increase in QUALVOL it is 0.24 percent costlier to design, construct and maintain a filter in the west compared to the east coast (Model 2, Table 5.8). This might be due to the higher rental rates of the machines and other inputs, used in the construction of the filters, in the west coast compared to the east.

For every one percent increase in QUALVOL, surface sand filters are 0.14 percent and underground sand filters are 0.09 percent less expensive to design, construct and maintain compared to perimeter sand filter (Model 2, Table 5.8). Perimeter sand filters are the only filters where all the flow enters the filtration practice and therefore require a little hydraulic head as compared to other sand filters. One might expect more construction and engineering activity which might be indicative of the higher costs for this type of filters compared to the others.

As most of the sand filters are found in dense urban areas, proper planning and organization seems be an important constituent of the construction of a sand filter. Standard Leontief cost model (Model 2, Table 5.8) indicates that all the three input prices significantly affect total adjusted cost of a sand filter. One percent increase in construction wage increases total adjusted cost by 1.28 percent in Piedmont region, 1.32 percent in coastal region. High elasticity of construction wages might be expected due to the high level of construction sophistication required to fit them alongside a curb in a dense urban setting, however, an elasticity of 1.28 is too high for any valid interpretations.

Elasticity of landscape wage is 0.25 for both Piedmont and coastal region. As these filters are usually constructed in the middle of a dense urban setting landscaping is expected to be an important consideration for the construction of a sand filter. Engineering wages, however, are negatively related to total adjusted cost in the standard Leontief model. This negative relationship is difficult to interpret and reflects the need of a better database.

New improved cost models indicate that sand filters exhibit economies of water-quality size and that for every one percent increase in the water treatment volume surface and underground filters are less expensive to design, construct and maintain than perimeter filters. All the three wages are also significant determinant of the adjusted cost of a sand filter.

Vegetated Open Channel Practices

Vegetated open channel practices consist of 11 grass swales and 2 grass channels. Water treatment volume for the grass channels were calculated as 0.1 inch times the drainage area in acres. For 4 of the grass swales located in Seattle it was calculated as surface area times the depth of the swale and for those in the California region QUALVOL was the amount of water treated for a 1 year 24 hours storm event. As grass swales typically do very limited amount of water treatment compared to the other SMPs, the average total cost of these SMPs are lower than most of the other SMPs (Table 5.9). Cost models used in the analysis are similar to that of sand filters described above. Table 5.10 gives estimates of the simple and the standard and stochastic Leontief cost models.

Table 5.13: Descriptive Statistics for Grass Swales (n=13)

Variable	Mean	Std. Dev.	Min.	Max.
ESTTOTCST (2005 $s in Baltimore)	146,052	111,546	8,489	327,754
GRCHAN (proportion)	0.15	n.a.	0	1
WEST (proportion)	0.77	n.a.		1
QUALVOL (ft^3)	19,293	38,236	1,040	145,200
GRCHANQLV (ft^3)	11,867	40,140	0	145,200
WESTQLV (ft^3)	6,904	6,780	0	19,715
ENGWAGE (2005 $s in Baltimore /hour)	33	7	13	40
CONSWAGE (2005 $s in Baltimore /hour)	20	4	11	24
LANDWAGE (2005 $s in Baltimore /hour)	12	2	8	17

Table 5.8: Models of the Natural Logarithm of Costs of Open Channel Practices

Estimate, (Standard Error), and *p-value*			
Variable Name	Model 1 (LQUANVOL)	Leontief Model 4	Stochastic Leontief Model 5
QUALVOL	13.49231 (2.43356) *<.0001*	0.39086 (0.48744) *0.4230*	0.55311 (0.27267) *0.0430*
GRCHAN	-0.22114 (0.26680) *0.4250*	0.09150 (0.08990) *0.3090*	-0.19287 (0.27430) *0.4820*
WEST		0.41071 (0.10492) *<.0001*	0.22400 (0.27103) *0.4090*
ENGWAGE		0.32901 (5.32677) *0.9510*	-1.90648 (8.60872) *0.8250*
CONSWAGE		-2.97086 (25.10191) *0.9060*	0.81598 (27.86285) *0.9770*
LANDWAGE		12.94983 (16.76538) *0.4400*	11.2866 (27.69865) *0.6840*
Log-Likelihood		-18.5914	-10.9411

Water treatment volume, QUALVOL, is insignificant in the simple model (Model 1, Table 5.10) indicating that water treatment does not play an important role in determining total adjusted cost of an open channel practice.

Normal and stochastic Leontief models (Model 2 and 3, Table 5.10) incorporate difference in design and location of the practices along with input prices. Convergence of maximum likelihood could only be achieved in the absence of any fixed costs. Insignificant value of λ (p-value = 0.9020) indicates absence of any technical inefficiency in stochastic Leontief model (Model 3, Table 5.10). Results of the standard Leontief model are, therefore discussed in details below.

Amount of water treated, QUALVOL, is not a significant determinant of total adjusted cost in standard Leontief model (Model 2, Table 5.10). However, for every one percent increase in the QUALVOL of these practices it would cost 0.41 percent more to construct these practices in the west coast compared to the east. All other variables in the stochastic Leontief model (Model 3, Table 5.10) are insignificant. In the stochastic Leontief model (Model 3, Table 5.10) we find that the QUALVOL is a significant determinant of the total adjusted cost.

All the SMPs, except open channel practices, exhibit economies of size in at least one region. Results of four of the five SMPs discussed above indicate absence of technical inefficiency in the stochastic Leontief cost models using QUALVOL as the output. Standard Leontief models are therefore used, in the next chapter, to calculate the cross-over volumes at which one SMP would be less expensive compared to the other for all SMPs except bioretention cells.

CHAPTER 6
COST-EFFECTIVENESS: A FIRST STEP

In chapter 5, we find absence of technical inefficiency in the design construction and maintenance of four of the five SMPs. Standard Leontief models are therefore used to calculate the water-treatment volume at which a particular SMP is less expensive compared to a counterfactual other in the same location. Analysis in this chapter assumes the same pollutant removal capacity for all the SMPs. Open channel practices like grass swales and channels are not a part of the determination of cross-over volumes because these practices are usually used in combination with some other SMP and not used separately. Stormwater ponds, wetlands and bioretention cells are SMPs that have similar design criteria. Hence, stormwater dischargers could, in principle, choose which SMP to use to manage stormwater runoff (MCPA, 2006). Stormwater ponds are therefore compared to wetlands and bioretention cells and additionally wetlands are compared to bioretention cells. Sand filters and bioretention cells are also compared because they both are filtration practices with similar physical feasibility (MCPA, 2006).

Stormwater Ponds and Stormwater Wetlands

Stormwater ponds and wetlands are basins used for storing and treating stormwater runoff. Unlike ponds, wetlands incorporate both plants and water in a shallower pool. The effect of water treatment volume (QUALVOL) on estimated total adjusted cost is calculated for both stormwater ponds and wetlands using standard

Leontief models 4 of tables 5.2 and 5.4. From the results of these models it is inferred that estimated fixed costs are higher for wetlands ($20,386) than ponds ($10,270). For each site in the dataset the effect of water treatment volume on expected cost of a stormwater pond was estimated using equation 4.11 and the estimates of model 4, table 5.2 while that of a wetland was estimated using estimates of model 4, table 5.4. Cross-over water treatment volume at which both original and imaginary substituted SMP would have the same cost was then calculated for every observation of the two SMPs. The average value of these observations was then noted for Piedmont and coastal regions separately for the observations in the east coast. The average QUALVOL of the ponds in the dataset is 78,761 ft^3 while that of the wetland is 43,547 ft^3.

In Piedmont regions, the average water treatment volume for which stormwater ponds and wetlands have the same cost is 17,100 ft^3. Thus, a stormwater pond is a less expensive management practice compared to a wetland in Piedmont regions for volumes of water treatment less than 17,100 ft^3. For example, the predicted cost of a wetland with the minimum water-treatment volume in the sample (1,307 ft^3) is $1,244 more than the predicted cost of a hypothetical stormwater pond at the same location.

The same cross-over volume for coastal regions is 18,768 ft^3, implying that on an average stormwater ponds would be less expensive compared to wetlands for treating volumes of stormwater less than 18,768 ft^3. For the range of QUALVOL between 17,100 and 18,768 ft^3 wetlands on the east coast are costlier than ponds in coastal regions and cheaper in Piedmont regions. Probable explanation of this is that wetlands, management practices shallower than ponds, are expected to occupy a larger surface area in the relatively flatter coastal regions to treat same amount of water as that in Piedmont regions, increasing cost of land and thus cost of wetland.

Stormwater Ponds and Bioretention Cells

While stormwater ponds are basins used to control and treat stormwater runoff, bioretention cells are filtration practices designed to perform similar functions. Although cost of land is included for pond, it is ignored for cells because unlike ponds, land used by bioretention cells can be used for other purposes. From the estimates it is inferred that stormwater ponds in model 4, table 5.2 have higher fixed costs ($10,270) compared to the bioretention cells ($0) in model 2, table 5.6.

In the Piedmont regions of the east coast, the average water treatment volume at which both the SMPs have the same cost is 2,651 ft^3. This indicates that bioretention cells would be less expensive than stormwater ponds for volumes of water treatment less than 2,561 ft^3. For example, the predicted cost of a stormwater pond with the minimum water-treatment volume in the sample are $1,392 more then the predicted cost of a counterfactual bioretention cell at the same location and water-treatment volume.

Bioretention cells are less expensive than stormwater ponds, in the coastal region of the east coast, for average water-treatment volumes less than 707 ft^3. For example a stormwater pond would have cost $1,209 more to treat the minimum water treatment volume of a bioretention cell (272 ft^3) in the database. SMPs treating smaller amount of stormwater runoff are expected to be found in more crowded areas where demand for land and hence its cost is higher. A bioretention cell, which does not incorporate land cost would therefore be a less expensive alternative compared to a pond in such dense areas.

Stormwater Wetlands and Bioretention Cells

Stochastic Leontief model 4 (Table 5.4) of stormwater wetlands and model 2 (Table 5.6) of bioretention cells were used to calculate the volumes at which one SMP becomes less expensive compared to the other. From the results of the above mentioned models it is inferred that estimated fixed costs are higher for wetlands ($20,386) than the cells ($0).

Under the assumption that these SMPs have similar treatment capacities, the average water-treatment volume at which both have the same costs is 969 ft^3 in the Piedmont regions of the east coast. Stormwater wetlands on average are therefore costlier than cells for water-treatment volumes less than 969 ft^3. For example, the predicted cost of a wetland with the largest water-treatment volume in the sample (174,240 ft^3) are $117,326 less than the predicted cost of a bioretention cell with the same water quality volume.

In coastal regions, of the east coast, this average cross-over volume is 917 ft^3, which indicates that bioretention cells are less expensive compared to the wetlands for water-treatment volumes less than 917 ft^3. For example, a stormwater wetland would have cost $3,223 more to treat the minimum water treatment volume (272 ft^3) of a bioretention cell. As with the stormwater ponds, the cost of building a wetland with a very small treatment volume is higher compared to the cell due to the higher land cost associated with building a wetland in highly urbanized area. Wetlands are however less expensive compared to cells, in coastal regions, for water-treatment volumes more than 917 ft^3.

Bioretention Cells and Sand Filters

Bioretention cells and sand filters both are filtration practices used primarily for water treatment control. Bioretention cells, however, manage both the quantity and quality of stormwater runoff while sand filters only manage the quality of the runoff. If neither bioretention cells nor sand filters have fixed costs, as indicated by the estimated cost function, then there will not be an average cross-over volume where one SMP becomes more expensive compared to the other at a particular location. That is, given a specific location and input costs associated with the location, one of the SMP will be less expensive than the other regardless of the volume of stormwater that is treated. Comparisons of the predicted costs of bioretention cells to predicted costs of sand filters for every location of an actual bioretention cell or sand filter in the dataset indicate that bioretention cells are always less expensive compared to the sand filters. For example, the predicted cost of a sand filter with the smallest volume of water treatment in the sample (3,743 ft^3) is \$368,459 more than the predicted costs of a bioretention cell with the same water-quality volume. Therefore for all positive volumes of water treated, bioretention cells are less expensive compared to sand filters in both Piedmont and coastal regions of the east coast. The average design, construction and maintenance costs of the sand filters in the database are 13 percent higher than that of the bioretention cells.

Analysis in this chapter indicates that bioretention cells are less expensive management practices compared to ponds and wetlands for smaller volumes of water treated in both Piedmont and coastal regions. They also are cheaper compared to the sand filters for all volumes of water treated in both the regions. Stormwater ponds, on the other hand, are cheaper compared to the wetlands for treatment volumes less that 17,100 ft^3 in the Piedmont region and 15,098 ft^3 in the coastal region.

CHAPTER 7
COST EFFECTIVENESS AND POLLUTANT REMOVAL

According to the Greenville County manual, regulation for the state of South Carolina requires that wet ponds should be designed to store and treat at least the first half inch of the runoff from the site for a minimum of 24 hours. For all other SMPs—dry ponds, stormwater wetlands, bioretention cells and sand filters—the design criterion requires storage and treatment of the first one inch of the runoff from the site over a period of 24 hours (SWMDM). If we assume that the designs of all the SMPs meet this criterion then the cost comparison done in chapter 6 is sufficient to determine which SMP is cost-effective method of regulatory compliance.

However, different SMPs have different capacities of pollutant removals as shown in table 4.1 (Chapter 4). As a result the concentration of remaining pollutants in the stormwater effluent might vary and some concentration might not satisfy regulatory standards for water quality. If government officials regulate stormwater discharges to meet effluent standards, rather than design-of-SMP standards and, thereby, require removal of certain amounts of pollutants, then the simple cost comparison is not sufficient to determine which SMP is the cost-effective method of achieving water quality standards. As mentioned in chapter 4, in order to calculate the minimum cost of treating the runoff by a particular SMP we need to know the cost of building the SMP, given water treatment volume and input prices, i.e., C(y,p) (equation 4.7, Chapter 4) and amount of pollutant removed by the SMP for given water treatment volume (y), amount of rainfall (r) and percentage of imperviousness (m), i.e., $R(y, r, m)$. Cost per unit of pollutant removed is then calculated using equation 4.12 (Chapter 4). The optimal size or the water treatment volume at which this particular SMP would have the minimum cost of removing a particular pollutant is when $\frac{C'_y}{C} = \frac{R'_y}{R}$ (equation 4.13, Chapter 4), where C'_y/C is the proportional rate of change of total adjusted cost and R'_y/R is proportional rate of change of pollutants removed.

A pollutant removal function for stormwater ponds, $R(y, r, m)$, is available in the IDEAL model. Pollutant-removal functions for the other SMPs do not exist. Moreover information about actual removal of pollutants by wetlands is not available. Hence comparisons between stormwater ponds and wetlands of cost per unit of pollutant removed are not possible. Information about actual pollutant removal of two bioretention cells exists, however. The cells are those in South Carolina. Hence given the available data, determination of water treatment volume at which the two bioretention cells cease or begin to have costs per pollutant removed lower than those of hypothetical stormwater ponds in the same locations were the only such determinations possible.

Data on amount (mg) of nitrogen (N) and phosphorus (P) removed during six different storm events were collected from Clemson University for the bioretention cell located in Anderson, South Carolina. For the cell in Orangeburg, South Carolina information was available on only one storm event. The amount of stormwater runoff entering the cell was also collected for each of these storm events. Milligrams per liter of the two pollutants removed were then calculated. Estimates of these pollutants that would have been removed by stormwater ponds in place of these cells were calculated with the Greenville County Stormwater IDEAL model, version 2.15 (IDEAL) for each storm events. For the cell in Anderson, averages over the six storm events of the amount of phosphorus and nitrogen removed by the cell were then calculated. Estimated effect of water treatment volume on total adjusted cost of these bioretention cells was calculated using equation 4.11 and estimates of model 2, table 5.6. The same effect on total adjusted cost of designing, constructing, and maintaining a stormwater pond in place of these cells were calculated using model 4, table 5.2. The average cost per unit of each pollutant removed by the cells and the hypothetical ponds was calculated by dividing respective estimated effect of water treatment volume on total adjusted cost by its average amount of pollutant removed. Cross-over volumes at which one SMP becomes less expensive compared to the other, in removing a particular pollutant, was then estimated for the two cells.

With fixed costs of ponds ($10,270) being higher than cells ($0) estimates of the cross-over volume, incorporating differences in pollutant removal, indicates that for volumes of water treatment less than 747 ft^3, bioretention cells would be less expensive than stormwater ponds in removing phosphorus. Average cross-over volume assuming that both the SMPs had equal pollutant removal capacity was 707 ft^3 in the coastal region (chapter 6). Table 4.1 (Chapter 4) shows that the average amount of phosphorus removed by the cells is higher than the ponds. This indicates that if the difference in pollutant removal capacity is considered bioretention cells would be less expensive in removing phosphorus compared to ponds for greater range of stormwater treated. For the amount of nitrogen removed by these practices, volume of water treatment at which cells would be less expensive compared to ponds is less than 553 ft^3. Table 4.1 (Chapter 4) shows that the average amount of nitrogen removed by the cells is lower than the ponds. This indicates that once the pollutant removal differences in the two SMPs are considered the SMP which removes more of the concerned pollutant can treat higher amount of stormwater more effectively.

In addition to pollutant removal data of 2 bioretention cells mentioned above, the amounts (mg/L) of nitrogen (N) and phosphorus (P) removed by 25 of the 55 stormwater ponds in the database were calculated using Greenville County Stormwater IDEAL model, version 2.15 (IDEAL). This model could however be used only for those stormwater ponds that had less than 100 acres of drainage area. Apart from some design specifications (mentioned in chapter 3) particular to the pond, most of the specifications used for calculations were same as that given in IDEAL model. Removal data on amount (mg/L) of nitrogen (N), phosphorus (P), Copper (Cu) and Zinc (Zn) removed by six stormwater ponds and sand filters were also collected from appendix F of CALTRAN report (CALTRANS).

As the cross-over volume could not be calculated for the other SMPs, average cost per unit of pollutant removed was used to get a rough idea of the cost difference in removal capacities of the SMPs in the dataset. Cost per unit of pollutant removed was calculated by dividing total costs of each SMP with the amount of the particular pollutant removed per storm event. Table 7.1 shows the average cost per unit of the particular pollutant removed per storm event by the SMPs.

Table 7.1 indicates that, for almost all pollutants considered above, bioretention cells have minimum average cost per unit of pollutant removed per storm event followed by stormwater ponds and sand filters. Relatively low costs per unit of pollutant removed by cells indicates that even when difference in pollutant removal capacity are considered, bioretention cells would be less expensive than sand filters for all volumes of water treatment in both Piedmont and coastal regions.

This average cost per unit removed figures in table 7.1 gives us an idea of how cross-over volumes calculated in chapter 6 might change once differences in pollutant removal capacity of various SMPs are considered. Though cross-over volume in chapter 6 does indicate correctly whether a particular SMP is inexpensive compared to another in a particular region, exact values of these volumes might be different if we account for pollutant trapping efficiencies of the two SMPs. Once the difference in pollutant removal capacities of the SMPs are considered cross-over volume is expected to favor the more efficient SMP.

Table 7.1: Average Cost per Milligram of Pollutant Removed per Liter of Stormwater Inflow during a Storm Event

Type of Pollutant	Stormwater Ponds ($/mg/l)	Bioretention Cells ($/mg/l)	Sand Filters ($/mg/l)
Phosphorus	$62,883,225	$227,467	$105,544,298
Nitrogen	$9,220,171	$38,372	Added N
Copper	$105,197,702	$37,208,214	$1,071,625,560
Zinc	$12,490,572	$36,060,393	$35,231,197
Lead	$57,435,966	not available	$381,503,624

Sources: IDEAL, CALTRANS and Clemson University

Structural stormwater management practices both control and treat stormwater runoff. Stormwater dischargers should therefore incorporate cost per unit of the pollutant removed and runoff reduced in their cost calculations. The average of the cost per unit of pollutant removed and runoff reduced should then be used to find the cross-over volume at which one SMP would be cheaper compared to the other. Data on the amount of runoff reduced was available only for the two bioretention cells in South Carolina thus cost effective cross-over volumes could not be calculated for any of the practices in the database.

CHAPTER 8
IMPLICATIONS FOR RESEARCH AND POLICY

Earlier studies only considered the effect of water storage or treatment volume on costs of SMPs and only use a Cobb Douglas specification of the cost functions. In this study, cost adjustments for purchasing power differences in time and location, regional and design effects, and input prices were incorporated into the cost function. Leontief cost functions used in the analysis indicate that all SMPs exhibit economies of size at least in one of the different regions were the SMPs are located.

The value of land is a positive and significant factor that affects the total adjusted costs of stormwater ponds and wetlands. Costs of bioretention cells do not include land costs. As a result, bioretention cells are less expensive than stormwater ponds and wetlands in areas with relatively high land costs, such as densely populated or high income urban areas. This cost however is an approximate average value collected from county's tax assessment database. Exact value of land at the time of construction would have given more precise estimates. Economies of size and significant land costs imply that policies should encourage construction of large stormwater ponds or wetlands on the outskirts of a city where the land costs are comparatively low.

Landscaping wages are positively significant determinant of total adjusted costs of stormwater ponds, bioretention cells and sand filters, and construction wages are positively significant for all SMPs except open channel practices. Insignificant and negatively significant wages of some SMPs reflect the need of better data and are concerns for future research.

Total adjusted costs of an SMP depend on its design. An extended detention stormwater pond is less expensive to design, construct, and maintain compared to a wet pond for every one percent increase in the volume of water treated by the pond. It is also expected to enhance the treatment facility of the stormwater ponds which results in more efficient pollutant removal capacity compared to the wet ponds. Policies should therefore encourage the use of extended detention ponds. Surface or underground sand filters would be less expensive than a perimeter sand filter for any increase in the amount of water treated by the sand filter. Differences in design consideration could not, however, be analyzed for wetlands due to lack of information.

Bioretention cells are less expensive than stormwater ponds and wetlands in treating relatively small volumes of water and are less expensive than sand filters for all volumes of water treated in both Piedmont and coastal regions.

Earlier studies had calculated the cost efficiency of the SMP based on cost per percent of pollutant removed. In this study total adjusted cost per milligram of pollutant removed per liter of stormwater inflow was estimated. Average cost per unit (mg/l) of pollutant removed is least for bioretention cells. These costs could not, however, be calculated for wetlands due to lack of information. Most of the literatures on stormwater management have information on event mean concentration of pollutant removed which is usually collected at one particular time during the storm event. Total amount of pollutant removed, per unit of stormwater inflow during a storm event, would be a better estimate of the cost per unit of pollutant removed of the SMPs.

Once differences in pollutant removal capacity are considered, results indicate that the SMP which removes more pollutants is likely to be cost effective for larger volumes of water treated compared to the case where pollutant removal capacity is assumed to be the same. A pollutant removal function, which calculates the amount of pollutant removed by a particular SMP, was not available for most of the SMPs. Water treatment volume at which one SMP becomes relatively inexpensive compared to another one in removing pollutants could, therefore, only be calculated for 2 bioretention cells in the database. Determination of precise ranges of water treatment and storage volumes, over which an SMP is less expensive than another in removing pollutants and reducing stormwater runoff according to regulatory standards, remains an important question for future research.

One standard definition of water storage and treatment volume of various SMPs should be a consideration of policy makers because data collected from different states define these differently. Though these differences in definitions did not change results significantly, a more uniform definition might help in providing more precise estimates.

The methodology used in this study may help EPA to enhance their accuracy in estimation of design and construction related costs of compliance with water quality regulation (e.g., EPA 2002b). The estimated cost functions may also benefit engineers by aiding them to decide which SMP is cost effective in attaining water storage and water treatment standards in a specific region.

APPENDIX
COST EQUATIONS OF THE SMPs

Stormwater Ponds

Cost of a stormwater pond with QUANVOL as the output:

$$C = 16321.11 + QUANVOL^{(0.97810 + 0.03024 * COASTAL - 0.08684 * EXTDE + 0.35208 * WEST)} (6.81e - 06 * LANDVAL - 0.04303 * ENGWAGE - 0.22223 * CONSWAGE + 0.65237 * LANDWAGE)$$

Cost of a stormwater pond with QUALVOL as the output:

$$C = 10269.56 + QUANVOL^{(0.83787 + 0.01503 * COASTAL - 0.10696 * EXTDE + 0.29798 * WEST)} (0.00010 * LANDVAL - 1.41052 * ENGWAGE - 4.15469 * CONSWAGE + 0.87091 * LANDWAGE)$$

Stormwater Wetlands

Cost of a stormwater wetland with QUANVOL as the output:

$$C = 9780.08 + QUANVOL^{(0.84430 + 0.00812 * COASTAL - 0.03945 * TIDEWATER + 0.00895 * MOUNTAIN)} (0.00004 * LANDVAL + 0.02992 * ENGWAGE + 0.09881 * CONSWAGE - 0.12713 * LANDWAGE)$$

Cost of a stormwater wetland with QUALVOL as the output:

$$C = 20385.70 + QUANVOL^{(1.37256 - 0.07097*COASTAL - 0.14657*TIDEWATER - 0.07014*MOUNTAIN)}(6.16e-07 * LANDVAL + 0.00072 * ENGWAGE + 0.00165 * CONSWAGE - 0.00501 * LANDWAGE)$$

Bioretention Cells

Cost of a bioretention cell:

$$C = QUALVOL^{(1.00623 + 0.03806 * COASTAL - 0.23322 * SANDHILL + 0.00648 * EXTDE)}(0.02804 * ENGWAGE + 0.30065 * CONSWAGE + 0.06450 * LANDWAGE)$$

Sand Filters

Cost of a sand filter:

$$C = QUALVOL^{(0.49041 - 0.01176 * COASTAL + 0.24201 * WEST - 0.14454 * SURFACE - 0.09326 * UNGRND)}(-65.48897 * ENGWAGE + 290.2709 * CONSWAGE + 68.60146 * LANDWAGE)$$

Open Channel Practices

Cost of an open channel practice:

$$C = QUALVOL^{(0.39086 + 0.09150 * GRCHAN + 0.41071 * WEST)} (0.32901 * ENGWAGE - 2.97086 * CONSWAGE + 12.94983 * LANDWAGE)$$

LIKELIHOOD ESTIMATION PROGRAMS

Stormwater ponds

Normal Leontief Cost Model Using QUANVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUANVOL^(`B1' +
`B2'*COASTAL + `B3'*EXTDE + `B4'*WEST))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)
  5. end
```

end of do-file

```
. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:),
technique(nr bhhh)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood = -13415.302
improve:       log likelihood = -10034.396
rescale:       log likelihood = -4888.4063
rescale eq:    log likelihood = -94.993746

. ml max
```

Normal Leontief Cost Model Using QUALVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUALVOL^(`B1' +
`B2'*COASTAL + `B3'*EXTDE + `B4'*WEST))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
```

```
  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:),
technique(nr bhhh)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood = -11140.047
improve:       log likelihood = -7687.9937
rescale:       log likelihood = -3977.7931
rescale eq:    log likelihood = -99.488469

. ml max
```

Stochastic Leontief Cost Model Using QUANVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma lamda
```

2. tempvar res

3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUANVOL^(`B1' + `B2'*COASTAL + `B3'*EXTDE + `B4'*WEST))*(`B5'*LANDVAL + `B6'*ENGWAGE +

> `B7'*CONSWAGE + `B8'*LANDWAGE))

4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)

5. end

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:)(lamda:), technique(bhhh)

. ml search

initial: log likelihood = -<inf> (could not be evaluated)

feasible: log likelihood = -13377.18

improve: log likelihood = -8165.3614

rescale: log likelihood = -4949.476

rescale eq: log likelihood = -98.061816

. ml max, nonrtolerance

Stochastic Leontief Cost Model Using QUALVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma lamda
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUALVOL^(`B1' +
`B2'*COASTAL + `B3'*EXTDE + `B4'*WEST))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
  4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-
normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:)(lamda:),
technique(bhhh nr)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
```

feasible: log likelihood = -11101.951

improve: log likelihood = -10292.178

rescale: log likelihood = -4568.4426

rescale eq: log likelihood = -98.52198

. ml max

Stormwater Wetlands

Normal Leontief Cost Model Using QUANVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUANVOL^(`B1' +
`B2'*COASTAL + `B3'*TIDE + `B4'*MOUNT))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)
  5. end
```

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:), technique(nr bhhh)

. ml search

initial: log likelihood = -<inf> (could not be evaluated)

feasible: log likelihood = -2462.8063

improve: log likelihood = -972.13943

rescale: log likelihood = -271.99743

rescale eq: log likelihood = -25.412053

. ml max

Normal Leontief Cost Model Using QUALVOL

. program define leoncst

1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma

2. tempvar res

```
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUALVOL^(`B1' +
`B2'*COASTAL + `B3'*TIDE + `B4'*MOUNT))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:),
technique(nr bhhh)

. ml max
```

Stochastic Leontief Cost Model Using QUANVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma lamda
  2. tempvar res
```

```
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUANVOL^(`B1' +
`B2'*COASTAL + `B3'*TIDE + `B4'*MOUNT))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
  4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-
normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:)(lamda:),
technique(bhhh)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood =  -2451.716
improve:       log likelihood = -706.84215
rescale:       log likelihood = -300.14192
rescale eq:    log likelihood = -24.473694

. ml max, nonrtolerance
```

Stochastic Leontief Cost Model Using QUALVOL

```
. program define leoncst
  1. args lnf B0 B1 B2 B3 B4 B5 B6 B7 B8 sigma lamda
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln(`B0' + (QUALVOL^(`B1' +
`B2'*COASTAL + `B3'*TIDE + `B4'*MOUNT))*(`B5'*LANDVAL +
`B6'*ENGWAGE +
> `B7'*CONSWAGE + `B8'*LANDWAGE))
  4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-
normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B0:)(B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(B8:)(sigma:)(lamda:)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood = -2116.8596
improve:       log likelihood = -916.18824
```

rescale: log likelihood = -459.34795

rescale eq: log likelihood = -24.312893

. ml max

<u>Bioretention Cells</u>

Normal Leontief Cost Model

```
. do lognorbio

. program define leoncst

  1. args lnf B1 B2 B3 B4 B5 B6 B7 sigma

  2. tempvar res

  3. quietly gen `res' = LESTTOTCSTMNT - ln((QUALVOL^(`B1' + `B2'*COASTAL +
`B3'*SANDHILL + `B7'*EXTDE))*(`B4'*ENGWAGE + `B5'*CONSWAGE + `B
> 6'*LANDWAGE))

  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)

  5. end

end of do-file
```

```
. ml model lf leoncst (B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(sigma:), technique(nr bhhh)

. ml search

initial:       log likelihood =     -<inf>  (could not be evaluated)

feasible:      log likelihood = -343.51578

improve:       log likelihood = -343.51578

rescale:       log likelihood = -343.51578

rescale eq:    log likelihood = -41.844815

. ml max
```

Stochastic Leontief Cost Model

```
. program define leoncst

  1. args lnf B1 B2 B3 B4 B5 B6 B7 sigma lamda

  2. tempvar res

  3. quietly gen `res' = LESTTOTCSTMNT - ln((QUALVOL^(`B1' + `B2'*COASTAL +
`B3'*SANDHILL + `B7'*EXTDE))*(`B4'*ENGWAGE + `B5'*CONSWAGE + `B
> 6'*LANDWAGE))
```

```
  4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-
normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(B7:)(sigma:)(lamda:), technique(nr
bhhh)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood = -397.42425
improve:       log likelihood = -397.42425
rescale:       log likelihood = -397.42425
rescale eq:    log likelihood = -35.000213

. ml max
```

Sand Filters

Normal Leontief Cost Model

```
. program define leoncst
  1. args lnf B1 B2 B4 B5 B6 B7 B8 B9 sigma
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln((QUALVOL^(`B1' + `B2'*COASTAL +
`B4'*WEST + `B5'*SURFFL + `B6'*UNGRDFL))*(`B7'*ENGWAGE + `B8'*C
> ONSWAGE + `B9'*LANDWAGE))
  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B1:)(B2:)(B4:)(B5:)(B6:)(B7:)(B8:)(B9:)(sigma:), technique(nr
bhhh)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood =  -998.0459
improve:       log likelihood =  -998.0459
rescale:       log likelihood =  -998.0459
rescale eq:    log likelihood = -50.507095
```

```
. ml max
```

Stochastic Leontief Cost Model

```
. program define leoncst
  1. args lnf B1 B2 B4 B5 B6 B7 B8 B9 sigma lamda
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln((QUALVOL^(`B1' + `B2'*COASTAL +
`B4'*WEST + `B5'*SURFFL + `B6'*UNGRDFL))*(`B7'*ENGWAGE + `B8'*C
> ONSWAGE + `B9'*LANDWAGE))
  4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-
normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B1:)(B2:)(B4:)(B5:)(B6:)(B7:)(B8:)(B9:)(sigma:)(lamda:),
technique(bhhh)

. ml max, nonrtolerance
```

Vegetated Open Channel Practices

Normal Leontief Cost Model

```
. program define leoncst
  1. args lnf B1 B2 B3 B4 B5 B6 sigma
  2. tempvar res
  3. quietly gen `res' = LESTTOTCSTMNT - ln((QUALVOL^(`B1' + `B2'*GRCHAN +
`B3'*WEST))*(`B4'*ENGWAGE + `B5'*CONSWAGE + `B6'*LANDWAGE))
  4. quietly replace `lnf' = - 0.5*ln(2*_pi) - ln(`sigma') - 0.5*(`res'^2/`sigma'^2)
  5. end

end of do-file

. ml model lf leoncst (B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(sigma:), technique(bhhh)

. ml search
initial:       log likelihood =     -<inf>  (could not be evaluated)
feasible:      log likelihood = -106.19749
```

```
improve:       log likelihood = -106.19749

rescale:       log likelihood = -106.19749

rescale eq:    log likelihood = -20.162833


. ml max, nonrtolerance
```

Stochastic Leontief Cost Model

```
. program define leoncst

  1. args lnf B1 B2 B3 B4 B5 B6 sigma lamda

  2. tempvar res

  3. quietly gen `res' = LESTTOTCSTMNT - ln((QUALVOL^(`B1' + `B2'*GRCHAN +
`B3'*WEST))*(`B4'*ENGWAGE + `B5'*CONSWAGE + `B6'*LANDWAGE))

  4. quietly replace `lnf' = ln(2) - 0.5*ln(2*_pi)-ln(`sigma') + ln(1-
normal(`res'*`lamda'/`sigma')) - 0.5*(`res'^2/`sigma'^2)

  5. end


end of do-file


. ml model lf leoncst (B1:)(B2:)(B3:)(B4:)(B5:)(B6:)(sigma:)(lamda:), technique(dfp)
vce(o)
```

```
. ml search

initial:       log likelihood =     -<inf>  (could not be evaluated)

feasible:      log likelihood = -107.29544

improve:       log likelihood = -107.29544

rescale:       log likelihood = -107.29544

rescale eq:    log likelihood = -20.242279


. ml max
```

SPATIAL CORRELATION PROGRAMS

Stormwater Ponds

```
>> clear all;

>> load regpond.mat;

>> y = Sheet1(:,1);

>> n = length(y);

>> x = [ones(n,1) Sheet1(:,2:5)];

>> xc = Sheet1(:,6);
```

```
>> yc = Sheet1(:,7);

>> [j W j] = xy2cont(xc,yc);

>> result = moran(y,x,W);

>> prt(result);
```

Stormwater Wetlands

```
>> clear all;

>> load regwetland.mat;

>> y = Sheet1(:,1);

>> n = length(y);

>> x = [ones(n,1) Sheet1(:,2:5)];

>> xc = Sheet1(:,6);

>> yc = Sheet1(:,7);

>> [j W j] = xy2cont(xc,yc);

>> result = moran(y,x,W);

>> prt(result);
```

Bioretention Cells

```
>> clear all;
>> load regbio.mat;
>> y = Sheet1(:,1);
>> n = length(y);
>> x = [ones(n,1) Sheet1(:,2:5)];
>> xc = Sheet1(:,6);
>> yc = Sheet1(:,7);
>> [j W j] = xy2cont(xc,yc);
>> result = moran(y,x,W);
>> prt(result);
```

<u>Sand Filters</u>

```
>> clear all;
>> load regsand.mat;
>> y = Sheet1(:,1);
>> n = length(y);
>> x = [ones(n,1) Sheet1(:,2:5)];
>> xc = Sheet1(:,6);
>> yc = Sheet1(:,7);
>> [j W j] = xy2cont(xc,yc);
```

```
>> result = moran(y,x,W);
>> prt(result);
```

Vegetated Open Channel Practices

```
>> clear all;
>> load regswales.mat;
>> y = Sheet1(:,1);
>> n = length(y);
>> x = [ones(n,1) Sheet1(:,2:5)];
>> xc = Sheet1(:,6);
>> yc = Sheet1(:,7);
>> [j W j] = xy2cont(xc,yc);
>> result = moran(y,x,W);
>> prt(result);
```

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