PHYTOREMEDIC RAIN GARDENS:

RESIDENTIAL APPLICATIONS IN THE PIEDMONT REGION OF THE SOUTHEASTERN UNITED STATES

by

JONATHAN F. KORMAN

(Under the Direction of Jon Calabria)

ABSTRACT

Only limited research and in-depth analysis is available on phytoremedic rain garden design in the Piedmont region of the United States. The purpose of this thesis is to answer the question, what are the possibilities and limitations of phytoremedic rain gardens in the Piedmont region of the Southeastern United States. This thesis investigates the development of storm water control measures in the United States, residential rain garden design, phytoremediation in rain gardens, and the aesthetic value of rain garden plants. In addition, a study was conducted to provide a detailed analysis of four plant species and their potential performance in rain gardens based on levels of storm water inundation. The recorded information will provide insight into the possibilities and limitations of using these four plants in Piedmont regional rain garden designs.

INDEX WORDS: residential rain gardens, phytoremediation, piedmont, storm water, bioretention, LID

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DEDICATION

I dedicate this work to my loving family.

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CHAPTER ONE

INTRODUCTION

Development of Storm Water

Citizens of the United States of America constitute approximately 4.5% of the world's population, which is approximately 315.6 million people (United States Census Bureau, 2013). This is nearly double the total population in 1950 of 152.3 million people (Shrestha & Heisler, 2011). As the population of the United States expands at a rapid rate it's residents are shifting toward urbanized and coastal areas (Brown, Cromartie, & Kulcsar, 2004). Population increase can negatively effect the environment through land use modifications that degrade ecosystem functions (Camill, 2010).

Land use change increases the rate, peak flow and volume of storm water runoff because of increased impervious surfaces (O'Driscoll, Clinton, Jefferson, Manda, & McMillan, 2010). As impervious surfaces increase, a resulting, reduction in forested lands, wetlands and other types of open space that typically absorb storm water (Brabec, Schulte, & Richards, 2002) are lost. Due to the land use changes associated with urbanization, storm water runoff transports constituents of concern into the waters of the United States. Urbanization and increased impervious surfaces decrease infiltration and reduce groundwater recharge (Leopold, 1968), which can lead to groundwater level reduction and surface water contamination. Contamination of drinking water presents risks and is a serious human health hazard (Lucas, Cabral, & Colford Jr, 2011).

According to the Environmental Protection Agency, nonpoint source pollution is the leading cause of water quality problems (U.S. Environmental Protection Agency, 2012). Nonpoint source pollution takes place when rainfall and snow melts moving across or through the ground accumulates pollution. This rainfall collects harmful pollutants during its movement and ends up in rivers and streams. The result of this nonpoint source pollution has damaging effects on drinking water, wildlife, recreation and fisheries, in addition to human population.

The Environmental Protection Agency, manages several programs set in place to protect the environment. The National Pollutant Discharge Elimination System (NPDES) is a national program created in 1972. The NPDES permit program controls water pollution by regulating point sources that discharge pollutants into the waters of the United States (Cross & Duke, 2008). The EPA has also enacted legislation to safeguard and analyze the environmental health of real estate property. An environmental site assessment (ESA) or Phase I ESA is required on commercial property to identify potential or existing environmental contamination, during property sale and or other triggering actions (Witkin, 2004). If a Phase I ESA detects environmental contamination then the EPA requires a Phase II ESA. A Phase II ESA is an intrusive investigation that collects samples of building material, soil and groundwater to analyze for quantitative values of contaminants (Witkin, 2004).

In urban settings, storm water networks transfer water into treatment facilities or back into the natural hydrologic cycle. Storm water infrastructure is required to mitigate flooding and channel water to storm drains. During storm events a large amount of pollutant load is transported during a ‘first flush’, the initial portion of the storm event. Urban water runoff can be highly polluted in terms of solids and organic matter and often exceeds regulation levels (Taebi, 2004). A recent study of construction material additives indicated that large amounts of these additives used in building envelopes enter storm water in urban settings (Burkhardt et al., 2011).

Low-Impact Development and Rain Gardens

Since the year 2000 there have been advancements in treating urban storm water. Moving away from traditional techniques, many states and local governments have begun to implement low impact development (LID) strategies. The object of low-impact development is to plan and engineer a site to meet the hydrologic function equivalent to pre-existing conditions, prior to development (Coffman, 2002). Low-impact development accomplishes this objective by conserving natural spaces while also treating storm water on-site through methods such as infiltration, evaporation, detention or capture (Prince George's County & Planning, 1999, 2000). One technique used in low-impact development design is bioretention. Biorentenion areas capture storm water in a designed space and subsequently treat it in a combination of methods: infiltration through designed soil, transpiration through hydrophilic plants, evaporation through the atmosphere and a variety of other processes. The term evapotranspiration is also associated with 'bioretention' and refers to the amalgamation of evaporation and transpiration. Bioretention cells, or ponds, designed to treat storm water runoff from structures such as parking lots and large impervious areas. As the expansion of low-impact development evolved, new designs emerged and smaller bioretention cells treated storm water runoff from roofs, walkways, driveways and compacted lawns. These smaller bioretention cells are called rain gardens (Coffman, 2002; Hunt, 2001).

While rain gardens may be a relatively new concept, they are quickly growing into one of the more popular possibilities used to treat storm water in residential landscape design (Burdett

& McCann, 2005). Basically, a rain garden is a shallow depression in the ground, at approximately three to eight inches in depth depending on conditions and design (Prince George's County & Planning, 2000). Rain gardens contain both soil capable of infiltrating storm water in an efficient manner and plant material that is capable of thriving in its conditions, while treating excess nutrients and pollutants. Rain gardens are able to treat storm water on site, which protects local water sources downstream from erosion and pollution. Rain gardens can also be economical, reducing costs of pipe installation needed to transport water into storm drains or surface waters (Dunnett & Clayden, 2007).

Rain gardens take the treatment of storm water to a level above simply ensuring infiltration and ground water recharge. The use of rain gardens is a effective method of removing pollutants through the process of phytoremediation. Phytoremediation is a form of bioremediation, in which plants are used to degrade, extract, contain or immobilize contaminants. Common contaminants include heavy metals, pesticides, excess nutrients and pathogens (Ruby & Appleton, 2010). Both low-impact and cost effective, phytoremediation is an ideal method to lessen environmental degradation.

This thesis will investigate the possibilities and limitations of phytoremedic rain gardens in residential applications of the Piedmont region of the Southeastern United States. It will include the development of storm water control measures in the United States, residential rain garden design principles, phytoremediation in residential rain gardens, and the aesthetic value of rain gardens. This thesis topic is worthy of investigation due to the relatively small of amount of research and information available about phytoremedic residential rain gardens. The additional experimental plant trial of four species potentially suited for rain gardens hopes to further the research in the field of rain garden design and phytoremediation. The experimental plant trial is designed to determine if four selected plant species are suited for rain garden implementation, based on water inundation levels correlating to plant survivability. Determining if a plant species is suited for rain garden design is a prerequisite for studying the plant species for phytoremedic properties, if a plant is to be installed in a phytoremedic rain garden.

CHAPTER TWO

DEVELOPMENT OF STORM WATER CONTROL MEASURES IN THE UNITED STATES

Historical Overview of Storm Water Control Measures

The United States' modern storm water control management and regulation began in the 1970's with the establishment of the Environmental Protection Agency or EPA. The EPA brought cases of storm water pollution to the public attention, specifically nonpoint source pollution. Nonpoint source pollution was identified as pollution occurring when pollutants from mixed sources were transported by rainwater, snowmelt, or irrigation water through, or over, land surfaces (U.S. Environmental Protection Agency, 2012; United States General Accounting Office, 1999). In 1972 pollutants being deposited into rivers, lakes, coastal waters and groundwater led to the creation of the Federal Water Pollution Control Act, also known as the Clean Water Act (CWA). In general, nonpoint source pollution was difficult to track because its sources were dispersed (U.S. Environmental Protection Agency, 2012). Identifying the exact amount of pollutants and their sources, either natural or man-made, were very difficult. It was especially difficult to pinpoint erosion sources (United States General Accounting Office, 1999). The CWA also provided matched federal funding for states to develop individual nonpoint source pollution management programs. The CWA offered grant money to states under Section 319 of the CWA. This established a national nonpoint source grant program, in which states assessed the extent of nonpoint pollution and its affects on waterways and then developed a management program. The EPA reviewed grant applications and approved watershed management plans. The establishment of the CWA was significant because it created guidelines to address storm water management, referred to today as Best Management Practices. These BMPs are practical, effective, structural or nonstructural methods which have the ability to reduce or prevent the transportation of sediment, pesticides and other pollutants from entering surface water or ground water (Prince George's County & Planning, 2002). Storm water BMPs are now used to alleviate the impacts of development on storm water quantity and quality (Roy-Poirier, Champagne, & Filion, 2010).

In 1972 the EPA created the National Pollutant Discharge Elimination System (NPDES) subsequent to the formation of the CWA. The National Pollutant Discharge Elimination System permit program controls water pollution by regulating point sources that discharge pollutants into the waters of the United States (Cross & Duke, 2008). The EPA initiated setting limits on the effluent that could be introduced into water bodies through permitted facilities. The National Pollutant Discharge Elimination System gained strength in 1987 when congress enacted the Water Quality Act that expanded them to challenge nonpoint source pollution.

The CWA, along with its amendments, laid the initial legislative groundwork to inspire a progressive change in storm water management and regulation. The Environmental Protection Agency also enacted legislation to safeguard and analyze the environmental health of real estate property. An environmental site assessment (ESA) or Phase I ESA is requirement on commercial property to identify potential or existing environmental contamination, during property sale and or other triggering actions (Witkin, 2004). If a Phase I ESA detects environmental contamination then the EPA required a Phase II ESA. A Phase II ESA is a intrusive investigation that collects samples of building material, soil and groundwater to analyze for quantitative values of contaminants (Witkin, 2004). Residential properties do not require an ESA, only a site inspection.

Innovation in Storm Water Control Measures

Managing flooding and drainage is a vital part of design in both commercial and residential settings (Pollution & Council, 2008). Storm water control measures (SCMs) are techniques put in place to assist in regulating and controlling storm water. These practices include infiltration, filtration, detention, retention, wetlands and other vegetated systems (Roy-Poirier et al., 2010). Numerous types of SCM's exist, including both structural and non-structural SCMs all of which are part of low-impact development. These low-impact development techniques try to minimize the impact of development on local hydrology and promote green infrastructure.

The Environmental Protection Agency defines the term 'green infrastructure' as systems and practices that mimic natural processes to infiltrate, evapotranspirate or reuse storm water or runoff on the site where it is generated (United States Environmental Protection Agency (US EPA), 2007). Green infrastructure can be used on varying scales and featuring techniques including: vegetated roofs, trees and tree boxes, rain gardens, vegetated swales, pocket wetlands, infiltration planters, vegetated median strips, reforestation, and protection and enhancement of riparian buffers and floodplains (United States Environmental Protection Agency (US EPA), 2007). Green infrastructure keeps rainwater out of the sewer system so that it does not contribute to a sewer overflow and allows storm water to be absorbed and cleansed by soil and vegetation (United States Environmental Protection Agency (US EPA), 2007).

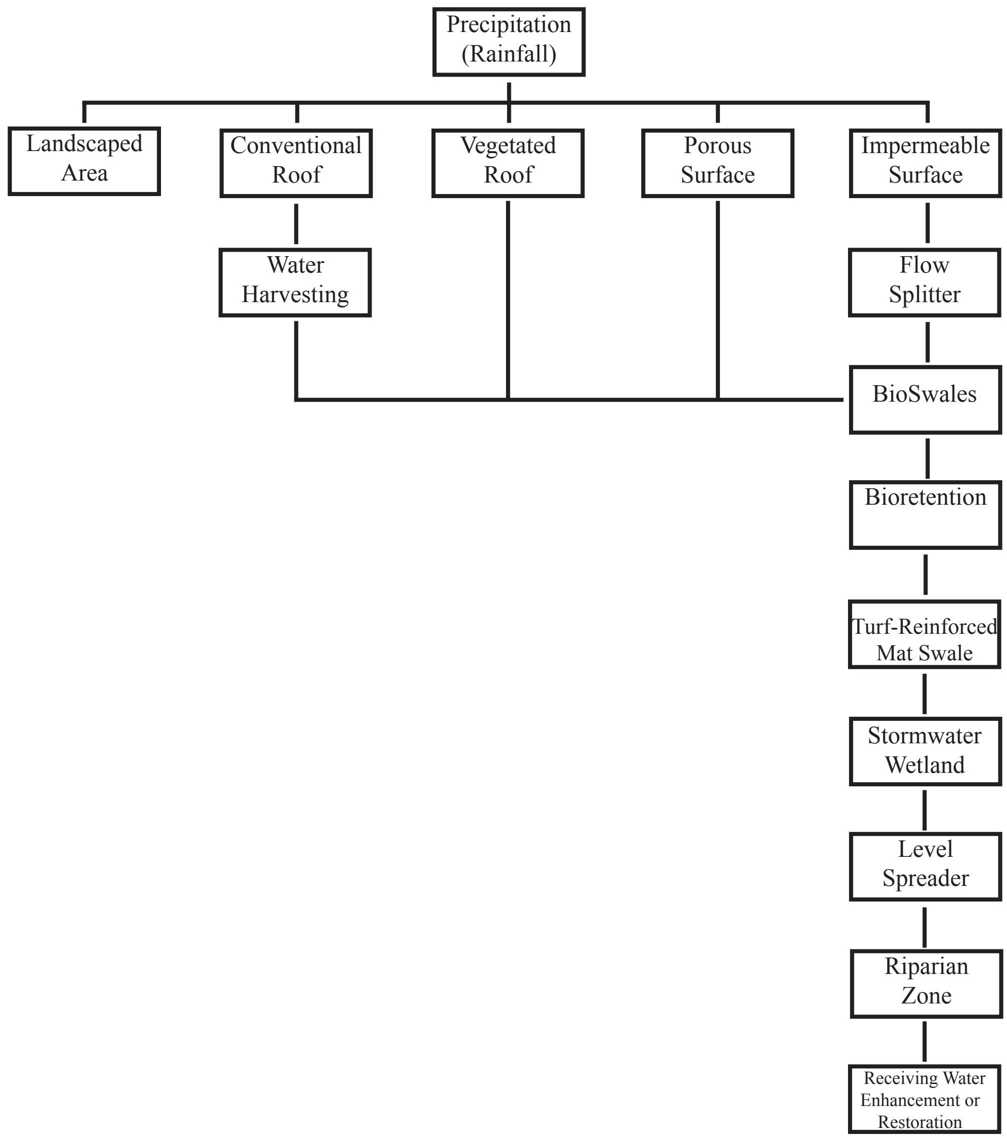

Figure 2-1. Green infrastructure storm water management flow path. Depending on site conditions landscape areas, conventional roofs, vegetated roofs, and porous surfaces can be directed through a flow splitter into numerous low-impact development techniques. Adapted from (Calkins, 2011)

Examples of low-impact development SCM's (as seen in Figure 2-1.) include water harvesting and reuse, vegetated roofs, porous pavement and permeable pavers, landscape swales, vegetated filter strips, level spreaders, sand filters, storm water planters, wet ponds, and storm water wetlands. SCMs include the use of infiltration, evaporation, detention or capture as a method replicating local hydrology (Prince George's County & Planning, 2000).

Water Harvesting and Reuse

Cisterns and rain barrels (are storage devices used for) temporarily store storm water runoff. Both cisterns and rain barrels are installed with the intention of capturing rainfall from roofs. Rain barrels typically are smaller in size than cisterns and offer a convenient and effective method of detaining runoff (Clark & Acomb, 2008). Rainfall is directed into cisterns and rain barrels by gutters, downspouts, 'rain chains' which have been used in Japan for hundreds of years, are a series of chain links or cups that visibly move rainwater from a roof to ground level (Dunnett & Clayden, 2007). The capture of water minimizes the volume of water heading to the sewer system or adjacent area as runoff (Aad, Suidan, & Shuster, 2010). Cisterns and rain barrels are inexpensive and cost-effective, and offer a pleasing method of water reuse. Water captured in cisterns and rain barrels can be reused in non-potable applications such as irrigation and washing vehicles. If water in cisterns and rain barrels is of high quality, the uses for the stored water can include bathing, household uses, toilet flushing and possibly cooking (Woelfle-Erskine & Uncapher, 2012).

Figure 2-2. Large above ground cistern installation in Athens, GA. (photo credit: Frank Henning)

Cistern and rain barrel design include many methods that accommodate various sites, including small spaces under decks and between buildings (as seen in Figure 2-2.). Recent designs include, pillow or bladder tanks in shallow crawl spaces or under buildings and decks and tall narrow tanks affixed to fences or narrow passageways (Woelfle-Erskine & Uncapher, 2012). The capture of runoff from roofs is only a small portion of the total runoff from an entire developed site. Cisterns and rain barrels are used as part of a larger scale, low-impact development design since they may be limited in capacity size. The cistern or rain barrel can direct captured runoff water into another SCM by direct route or in an overflow situation. Cisterns and rain barrels are installed on residential sites adjacent to buildings at an elevation that is up-slope from plants to be irrigated in order to take further advantage of gravity. In a drought situation, the water stored in the cistern or rain barrel provide irrigation (Woelfle-Erskine & Uncapher, 2012). The use of cisterns and rain barrels offers advantages such as minimizing piping and keeping water stored at an optimal temperature for tender plants and propagation (Dunnett & Clayden, 2007). One modern innovation in rainwater harvesting employs the use of filters and pumps. The recently developed CULTEC Residential Rainwater Harvesting System captures storm water runoff directly from downspouts, moves it through a filter (to remove debris), and sends the water into underground cisterns. The underground cisterns rely on pumps to get the stored water back into use. The captured water is available for irrigation, cleaning and fire suppression (Speckhardt, 2012).

Vegetated Roofs

Vegetated roofs have been used in parts of northern Europe for hundreds of years but are now just gaining momentum in the United States. In brief, vegetated roofs are layers of living vegetation installed on tops of buildings. These installations reduce the amount and rate of storm water runoff from a building surface (Dunnett & Clayden, 2007). In most developed cities roofs make up forty to fifty percent of impervious surfaces (Stovin, 2010). A typical vegetated roof consists of a waterproof base layer, a drainage layer, a geotextile mat, growing medium or substrate and vegetation layer (Dunnett & Clayden, 2007). In addition to reducing the amount and rate of storm water runoff, vegetated roofs also promote benefits such as increasing roof life, decreasing energy costs of buildings, reduction of the 'urban heat island effect' and bolstering the aesthetic appeal of the building's landscape (Snodgrass & McIntyre, 2010). Vegetated roofs are built on both flat and sloped roofs but, flat roofs allow for easier installation and typically less engineering (University of Arkansas, Architecture, & Press, 2010).

There are two fundamental types of vegetated roofs; intensive and extensive. Intensive green roofs are the more structural of the two designs. Intensive green roofs are designed to accommodate trees and shrubs with deep soil layers. The structural integrity of these vegetated roofs requires large amounts of engineered support and are commonly built on top of underground parking decks (William F. Hunt, 2006). Intensive vegetated roofs (as seen in Figure 2-3.) can have a depth greater then six inches and often require irrigation and fertilization (William F. Hunt, 2006). Comparatively, extensive vegetated roofs are thinner than intensive green roofs, with a depth of three to five inches. Despite their shallower planting depth, an extensive roof can be highly effective as a SCM, managing substantial runoff amounts.

Figure 2-3. An intensive green roof above a parking facility in Athens, GA. (photo credit: The University of Georgia)

Studies conducted on extensive vegetated roofs indicate they have the ability to reduce annual runoff by forty to seventy percent (Kolb, 2004). An additional study concludes vegetated roofs can contribute to sixty percent of total rainfall retention and eighty-five percent reduction in peak flow rate (Moran, 2010). The design of extensive vegetated roofs includes; low-lying vegetation with minimal maintenance requirements and light weight structural capacities (William F. Hunt, 2006). These lighter, low-profile roofs allow installation on a variety of surfaces and offer conducive growing conditions to plant species such as Sedum and Sempervivum, which require minimal care and low irrigation (Steiner & Domm, 2012).

Porous Pavement and Permeable Pavers

Porous pavements are paved surfaces made using void spaces that allow water and air to infiltrate the surface (Bruce K. Ferguson, 2005). Porous pavement and permeable pavers promote absorption of rainwater and snowmelt while reducing the amount of surface runoff from small to moderate storms (Dunnett & Clayden, 2007). There are five main types of permeable and porous material: pervious concrete, pervious asphalt, permeable interlocking concrete pavers (PICPs), concrete grid pavers, and plastic reinforced grass pavement (Bruce K. Ferguson, 2005; William F. Hunt, 2006). These types of installations are made out of different materials but the concept for each is similar. Typically, there is a layer of gravel or crushed stone underneath the surface material. This allows for temporary water storage and provides structural support (University of Arkansas et al., 2010). Permeable interlocking concrete pavers and concrete grid pavers consist of concrete blocks with gaps between them filled with a permeable material like pea gravel or sand. The blocks rest on a bedding layer of fine gravel, which overlays a layer of coarse gravel (Bruce K. Ferguson, 2005; William F. Hunt, 2006). Existing soil conditions, specifically the infiltration rate of the soil and the installing contractor influence the functionality and success of permeable and porous pavement systems (Bruce K. Ferguson, 2005). Porous pavements offer the ability to capture pollutants by infiltrating runoff and reducing flooding (William F. Hunt, 2006). While they offer benefits, permeable and porous pavements require regular maintenance (sweeping/vacuuming) to avoid the clogging of void spaces within the paving, and they are expensive to install (Bruce K. Ferguson, 2005; William F. Hunt, 2006).

In residential applications with light traffic volume, porous pavement can reduce runoff from driveways, walkways and terrace spaces. Porous pavements can resolve many environmental problems at the source (Bruce K. Ferguson, 2005). They are capable of infiltrating some rainwater without the need for piping and offer great advantage in urban areas with limited space (Bruce K. Ferguson, 2005). Porous pavement is primarily designed to accept water only falling on it (as seen in Figure 2-4.). Storm water arriving from supplemental locations should bypass the porous pavement and be directed into the aggregate base layer (Godwin, Sowles, & Tullos, 2008).

Figure 2-4. Porous pavement installation in Athens, GA. (photo credit: Jonathan Korman)

Landscape Swales

Landscape swales are linear shallow depressions that temporarily store and transport runoff water. Swales can moderately reduce flow rate, reduce total runoff, and aid in pollution reduction (Dunnett & Clayden, 2007). The ability to remove pollutants increases by altering the swales with features such as turf reinforcement matting, small check dams, and underground treatment layers of soil beneath the base of the swale (Dunnett & Clayden, 2007; William F. Hunt, 2006). Landscape swales are more successful when constructed with fairly flat slopes that aid in slowing runoff velocity. They are used as one component of a larger SCM or used as a pretreatment area. The main variable, which may hinder the success of a landscape swale installation, is the velocity of water runoff. A study indicates that mean velocity is the most influential parameter on sediment trapping followed by flow depth (Tollner, Kao, Haan, &

Barfield, 1976). If the mean velocity of water moving through the swale is too high, erosion or overflowing may occur. Additional rock or rip-rap strengthen the channel in situations of high velocity; check dams can also mitigate overflow (William F. Hunt, 2006).

Narrow landscape swales are more effective. If too wide, then the swales begin to function like a basin or pond (Dunnett & Clayden, 2007). Landscape swales should have a storage depth of approximately six inches and a maximum width of two feet for residential or commercial developments (City of Portland Environmental Services, 2004). There are two primary types of landscape swales: 'vegetated swales' and 'grassy swales'. Vegetated swales are typically used to promote infiltration and are planted with shrubs and herbaceous perennials (Dunnett & Clayden, 2007). Grassy swales are used in situations where the movement of water is the primary design target. Both vegetated swales and grassy swales require maintenance (mowing, clipping and weeding) in order to function effectively and remove unwanted nutrients. Grass clippings contain excess nutrients (especially nitrogen), which will flow into subsequent SCMs if not removed, negatively effecting water quality. The effectiveness of landscape swales to remove nutrients is marginal with a removal percentage of approximately fifteen percent (Hunt, 1999). Studies also indicate the vegetated swales are successful in removing heavy metal concentrations when depth flow is small relative to vegetation height (Kirby, Durrans, Pitt, & Johnson, 2005).

In recent years, the design of landscape swales has been modified and made appropriate for placement along city streets and within parking lots. Portland, Oregon is one example of a city that has integrated landscape swales in urban environments. Portland has pioneered urban retrofit projects that have included the installation of 'street swales', which capture road runoff in street side swales planted with hydrophilic plant species (Owens-Viani, 2011). Water from streets is directed into the swales, reducing the amount of water flowing into sewer systems and capturing roadside pollutants in an aesthetically pleasing method.

Vegetated Filter Strips

Vegetated filter strips (VFS) are gently sloping vegetated areas that receive runoff from adjacent impervious surfaces or hardened surfaces (Dunnett & Clayden, 2007). These VFSs slow the rate of flow, reduce total storm water runoff, and trap sediment and pollutants. Similar to landscape swales, VFSs are typically installed as a pretreatment device for a larger SCM. Vegetated filter strips are a technique used in agricultural areas and are one of the commonly implemented off-field structural BMPs (Krutz, Matocha, Zablotowicz, & Senseman, 2005). When designed and placed correctly, they can significantly improve the water quality (Qi & Altinakar, 2011). Vegetated filter strips can be planted with a variety of species, although grass species is a common installation material. Recent studies investigated using VFSs with subsurface drainage systems but results show that while a VFS can be very effective in reducing runoff and nutrients from surface flow, the presence of a subsurface drain underneath the VFS may not be environmentally beneficial(Rabin, Prasanta Kumar, & Mita Kanu, 2009). While nutrient levels were significantly reduced in surface flow, subsurface nutrient levels showed marginal reductions of orthophosphorus and total phosphorus and increases of nitrate nitrogen (Rabin et al., 2009).

Level Spreaders

A level spreader is a SCM technique typically used in conjunction with a vegetated filter strip. A vegetated filter strip is designed to handle sheet flow moving over its surface; therefore, the potential for concentrated flow exists (Dunnett & Clayden, 2007). To improve vegetated filter strip performance, level spreaders are used to distribute flow evenly across the length of the upslope end of the vegetated filter strip (Winston, Hunt, Petre, & Line). In 2009, a study was conducted in coastal North Carolina that examined a 'vegetated filter strip /level spreader' installation along a highway interchange. The findings indicate that the 'vegetated filter strip /level spreader' installation reduced inflow volumes by forty-nine percent during fourteen storm events (Line & Hunt, 2009).

Sand Filters

Sand filters are SCMs that capture and temporarily store storm water runoff and pass it through a filter bed of sand (Barrett, 2003). Most sand filter systems consist of two-chambers. The first chamber, the sediment forebay, removes floatables (organic matter) and heavy sediments (assorted debris). The second chamber, the filtration chamber, removes additional pollutants and finer sediments by filtering the runoff through a sand bed (City of Charlotte and Mecklenburg County, 2010). Once the runoff that is filtered through the system it is discharged or passed on to another type of SCM. Sand filters are effective at removing non-soluble pollutants, especially sediment particles. Removal rates are near eighty percent for total suspended solids and almost sixty percent for phosphorus in certain studies (Hunt, 1999). There are two main types of sand filters: surface and underground. Surface sand filters are installed at ground level and function exposed to open air. They feature both a sediment forebay and filter bed chamber. Underground sand filters are installed in a vault and used in areas with high density and limited space (City of Charlotte and Mecklenburg County, 2010). While sand filters offer benefits, such as high percentages of pollution removal rates and minimal space requirements, they also have limitations (Barrett, 2003). They can be expensive to install and maintain. Regular maintenance service is required and clogging problems are associated with sand filters, especially those filters treating large impervious surfaces such as parking lots (Hunt, 1999).

Storm Water Planters

Storm water planters are above or at-ground planting containers that receive water runoff from roofs (Dunnett & Clayden, 2007). They are typically small contained vegetated areas that treat storm water using bioretention (Charles River Watershed Association, 2008). In many cases storm water planters receive runoff directly from gutters or downspouts from buildings. Depending on the amount of runoff received, the planter can either infiltrate the water into the ground or allow the water to overflow. There are two main types of storm water planters: infiltration planters and flow-through planters (Charles River Watershed Association, 2008). Infiltration planters receive water from roofs and use stones/gravel to dissipate the water's energy. The water is then allowed to filter into the soil; or, if the flow of water is of high velocity, the water spills into a runnel or another SCM. Flow-through planters capture water and allow it to move slowly through the soil and recharge the groundwater. Flow-through planters are fitted with a built-in overflow system that enables excess water to be piped away from the planter to avoid flooding (Dunnett & Clayden, 2007). Flow-through planters differ from infiltration planters because they are sealed and water cannot visibly overflow.

Wet Ponds

Wet ponds are water storage areas referred to as retention basins, storm water ponds or wet extended detention ponds. They are constructed storm water basins which feature a pooling area that holds water permanently and a forebay area that initially accepts storm water runoff

(City of Charlotte and Mecklenburg County, 2010). These ponds are typically one of the final components in storm water management, providing a final destination for water and targeting pollutant removal (Dunnett & Clayden, 2007). Wet ponds have a forebay area and a four to eight feet deep pool. The forebay is the location where storm water enters the pond and sediment is allowed to settle (Hunt, 1999). The purpose of the forebay is twofold. It allows the trapping of sediment that in many cases contains harmful pollutants and it provides access for excavation equipment to remove the contaminated soil and sediment. After the forebay, water enters the pooling area of the pond (in cases via a flow distributor). A shallow submerged shelf installed with wetland plants surrounds the pooling area (Hunt, 1999). The shelf provides a place for plants to thrive as well as a safety feature in case of emergencies. The water then exits the wet pond through an outlet. The outlet may contain risers and weirs which allow water to exit the wet pond before overflowing a dam (Hunt, 1999).

The basic functions of a wet pond include flood control, water quality enhancement and ecological and aesthetic value. The latter function, aesthetic value, is exemplified in the following ways: For aesthetic value we know that wet ponds with permanent pools attract wildlife and waterfowl, and when landscaped, are attractive and add value to adjacent land. Groundwater is recharged while helping mosquito control. And according to Wang, wet ponds with temporary water provide some wildlife habitat value (D. S. Wang, 2002).

Wet ponds have four main categories of planting zones which feature plants specific to those soil moisture conditions: (1) marginal plants that grow in permanently moist soil around the edges of wet ponds, (2) emergent plants that are rooted in mud under shallow water and their shoot, leaves and flowers that push up into the air above, (3) floating-leaved aquatics that live in deeper water at the base of the wet pond, (4) submerged aquatics that mainly stay below the surface of the water and serve as the main oxygenators of the water (Dunnett & Clayden, 2007).

Wet ponds are associated pathogens that are present in fecal matter. As impervious surfaces increase in a watershed, amounts of indicator bacteria in nearby waters increase (Mallin, Ensign, Wheeler, & Mayes, 2002). Bacteria, partiality fecal coliform, thrive in wet ponds since they retain water, drain slowly and attract wildlife (which can produce large amounts of waste around ponds). While wet ponds have more issues with fecal coliform than some other SCMs they are also capable of reducing fecal coliform levels. A study conducted by Charlotte-Mecklenburg Stormwater Services and the North Carolina State Biological and Agricultural Engineering department, investigated fecal coliform removal capabilities of several different types of BMPs. The study analyzed one wet pond that showed positive fecal coliform removal reduction, as the ponds fecal coliform geometric mean influent was 9033 (per 100ml) and geometric mean effluent was 2703 (per 100ml) (Hathaway, Hunt, Wright, & Jadlocki, 2008).

Storm Water Wetlands

Storm water wetlands are also called constructed storm water wetlands or treatment wetlands. Constructed storm water wetlands temporarily store runoff in shallow pools designed to encourage the growth of wetland plants (City of Charlotte and Mecklenburg County, 2010). Water entering a storm water wetland first arrives into a forebay area. The forebay is primarily a settling area for solids and can be easily excavated. Water then flows out of the forebay area into the main body of the wetland which is designed with high and low areas to create a sinuous flow of water increasing detention time (Hunt, 1999). Through settling, filtering, and uptake by vegetation, the water moving through these shallow wetlands aids in pollutant removal. Typically, these wetlands are no more then one to two feet deep.

Deep pools, shallow water, shallow land, and upland zones are the four main areas comprising storm water wetlands. Deep pools are areas of more then one foot deep and include the inlet forebay, outlet pools, and other deep areas within the body of the wetland. Deep pools encourage submerged or floating vegetation. Shallow water zones are areas that exist from zero to six inches below the normal permanent pool or water surface elevation. Emergent wetland plant species and herbaceous plant material primarily make up this zone. Shallow land zones are areas that extend from surface pool elevation to one foot above the pool elevation. This area is wet only after rain events and is conducive to plants that can withstand irregular inundation and drought-like conditions. The upland areas are above the shallow land zone and only receive water from rainfall and large storm events. The upland areas can accommodate a variety of plant species including those that can tolerate occasional flooding (City of Charlotte and Mecklenburg County, 2010).

In addition to the methods of treatment mentioned here, wetlands also treat pollutants in several ways. Settling suspended particulate matter, filtration and chemical precipitation through contact of the water with the substrate and litter, chemical transformation, adsorption and ion exchange on the surfaces of plants, substrates, sediment, and litter, breakdown and transformation of pollutants by microorganisms and plants, uptake and transformation of nutrients by microorganisms and plants, and finally predation and natural die-off of pathogens (Environmental Protection Agency, 1994). Studies show that on average wetlands can remove almost eighty percent of total suspended solids and more nitrate-nitrogen then wet ponds (Hunt, 1999). Both nitrogen and nitrate is removed from wetlands through the process of denitrification. Denitrification is a critical process regulating the removal of bio-available nitrogen from natural and human-altered systems (Seitzinger et al., 2006). The wetland allows aerobic and anaerobic microbes to digest nitrate turning the harmful pollutants into innocuous nitrogen gas (Hunt, 1999).

In a recent proposal, the city of Baltimore, Maryland considered installing a ‘floating wetland’ in its Inner Harbor Park. The wetland would be built on sheets of recycled plastic and polyurethane foam in order to remain buoyant. Plants would be installed on the platform and over time grow into the harbor (McIntyre, 2013). In this revolutionary design, visitors could walk out into the wetland on a boardwalk and enjoy the harbor, while learning about the important role of living ecosystems.

Residential Application of Storm Water Control Measures

Storm water development in urban environments has improved and advanced over the past thirty years. Many of the above SCMs began in a commercial or large-scale application in an effort to improve storm water quality and reduce storm water quantity. In fact, even residential landscapes are now able to use some of the more refined SCMs.

In February of 2013, the city of Atlanta, Georgia approved major changes to its ‘post-construction stormwater ordinance’. The changes state any new or re-development property site greater then five hundred square feet is required to treat the first inch of storm water runoff with BMPs (Hoffner, 2013). The BMPs can include rain gardens, porous paving, vegetated roofs and other acceptable low-impact development techniques. The changes also state new homes or large additions of one thousand square feet or more treat the first inch of storm water runoff with BMPs (Hoffner, 2013).

For many homeowners and renters, little thought is given to how storm water runoff gets to a water treatment facility, the location of the water treatment facility, the operational cost of the facility and the impact on the local environment. The last point 'impact on the local environment' is what has inspired environmentally-conscience residents and leading designers to alter their thinking on residential landscape design and include thoughtful methods of storm water control at the home front. Not only can SCMs on a residential scale benefit the environment, but they also offer significant financial savings to homeowners by reducing water costs (United States Environmental Protection Agency (US EPA), 2012a). In a year of normal rainfall, landscape irrigation accounted for nearly forty-three percent of all water use in the western United States and twenty-six percent in the eastern United States (Thayer, 1982).

One type of SCM not yet discussed is popular in residential landscape design and offers great potential: the rain garden (Burdett & McCann, 2005). A rain garden is a planted shallow depression in the ground, typically three to eight inches deep (as seen in Figure 2-5.). Rain gardens accept runoff water from storm events and infiltrate the water typically within 48 hours. Rain gardens have gained popularity because of environmental benefits (recharge groundwater, conserve water, protect rivers/streams, filter runoff pollution, improve water quality, create habitat for wildlife), and creative aesthetic appeal. Further investigations of the possibilities and limitations of rain gardens in the residential landscape are discussed in Chapter Three.

The investigation of the possibilities and limitations of phytoremedic rain gardens is related to many of the SCM's listed in Chapter Two. These SCM's have been studied for their ability to remove pollutants and some are frequently installed with phytoremedic plants. The study of many of these SCM's led to the development of rain garden design and phytoremedic rain gardens.

Figure 2-5. Rain garden installation in Athens, GA. (photo credit: Jonathan Korman)

CHAPTER THREE

RAIN GARDEN DESIGN

The Rise in Popularity of Rain Gardens

Rain gardens or ‘bioretention cells’ were first introduced in the late 1980’s in Prince George’s County, Maryland. Biotention cells or rain gardens are land forms adapted to provide on-site capture and treatment of storm water through both infiltration of water within soil medium and through uptake facilitated by planted vegetation (Prince George's County & Planning, 2002). Most commonly, rain gardens are shallow depressions that collect storm water from surface run off. Rain gardens are typically used on smaller scale sites and in urbanized areas where space is limited (as seen in Figure 3-1.). They can also be adapted to a variety of climatological and geological conditions with minor design alterations (Prince George's County & Planning, 2002; United States Environmental Protection Agency (US EPA), 2012b).

Figure 3-1. Parking lot island rain garden installation in Athens, GA. (photo credit: Jonathan Korman

The burgeoning concept of rain gardens began over twenty years ago on an eighty-acre subdivision in Prince George's County Maryland. The subdivision of Somerset featured nearly two hundred homes on ten thousand square foot lots (Wisconsin Natural Resources, 2003). Opposing conventional subdivision design, featuring curbs, gutters, sidewalks and retention ponds, Somerset featured large grassed swales to direct storm water runoff with individual biorentention cells located on each lot sized at three hundred to four hundred square feet (Wisconsin Natural Resources, 2003). Larry Coffman, Associate Director for Program and Planning with Prince George's County of Environmental Resources, was largely responsible for this innovative application of low-impact development (Wisconsin Natural Resources, 2003). The consulting firm, Hanifin Associates, dubbed the bioretention cells 'rain gardens' (Wisconsin Natural Resources, 2003). The Somerset subdivision was an early and successful example of low-impact development technology. Ever since this development, rain garden installations have expanded throughout the country. A recent example of rain garden design applications exists in St. Louis, Missouri. In 2011, design firm HOK, designed and trademarked 'Ferno'. These 'Ferno' units are segmented wall and curb systems installed alongside roadways. The systems are essentially modular rain gardens designed to accept storm water runoff from urban roads (Hazelrigg, 2011). An example of a rain garden accepting street runoff is indicated in Figure 3-2.

Figure 3-2. A rain garden in Athens, GA designed to receive street runoff. (photo credit: UGA, Office of Sustainability)

Functionality of Bioretention

The overarching idea of low-impact development is to mimic the natural hydrologic function of a site. In order to accomplish this, two objectives must be met: the control of storm water quantity and the protection of its quality.

Storm water quantity control is a key part to the success of a rain garden (Woelfle-Erskine & Uncapher, 2012). The quantity of water that a rain garden treats is dependent on local climatic conditions and the amount of impervious area at a given site. In order to accurately construct a rain garden, the previous factors must be weighed along with soil conditions and design options, which will be investigated subsequently. The functionality of storm water quantity control in rain gardens incorporates the methods listed below.

Interception is the process of the collection or capture of storm water. Water is diverted in rain gardens and allowed to pool for treatment. Interception is facilitated through surface flow or concentrated flow (inline flow) where water is piped underground or channeled into the rain garden (as seen in Figure 3-3.). Inline flow can capture storm water runoff directly from downspouts or other target areas.

Figure 3-3. Underground piping transports water in rain gardens. (photo credit: UGA, Office of Sustainability)

Infiltration is the process of water entering the soil from the ground's surface. Infiltration will occur at different rates depending on soil types and conditions. In many cases, infiltration is the method that treats the most storm water. Sometimes soil may require amendments to facilitate the process. Heavy clay soils will take a longer period of time to allow water to permeate while sandy soils allow more rapid permeation. When installing rain gardens, soil conditions are one of the most important factors to consider. Without rain gardens, storm water runoff would be quickly transported into adjacent streams and water bodies and depending on soil types, could transport sediment to unwanted areas (Hunt, 2001).

Evaporation entails water transforming from a liquid to a gas state. In order to encourage evaporation, rain gardens attempt to maximize surface area of water pooling areas. Evaporation can also occur from soil surfaces and plant surfaces (Dunnett & Clayden, 2007).

Transpiration is the process in which moisture is carried through plants from roots to small pores on the undersides of leaves. The moisture transported through the plant vaporizes and releases into the atmosphere (Evenson et al., 2012). Well-designed rain gardens contain plants with higher rates of transpiration. The combination of evaporation and transpiration is commonly referred to as evapotranspiration. Evapotranspiration is important because, over half of all annual rainfall discharges as evapotranspiration from soil and plants prior to reaching a stream or without passing through one (B. K. Ferguson, 2002). Evapotranspiration plays a vital role in supporting the terrestrial ecosystem. All terrestrial vegetation subsists by the flow of water through soil and roots and exiting through leaves (B. K. Ferguson, 2002). Rain gardens create an ideal location for evapotranspiration to occur and thrive with the use proper plants and water surface area.

Storm water quality control is the complementary function to quantity control. As stated previously, the goal of low-impact development is to mimic the natural hydrology of a site. Therefore, reducing pollutants that enter a site, both organic and inorganic, caused by development is essential. Typical pollution sources include oil leakage, animal waste, excess fertilizer, disintegrating roof shingles, grease and detergent (Kraus & Spafford, 2009). Rain gardens treat these nonpoint pollution sources in a variety of ways including absorption, settling, filtration, microbial action and plant uptake.

Absorption is a chemical process that involves the attraction of dissolved substances on a surface. The process can take place on mulch and soil particles at the bottom of a rain garden and primarily removes heavy metals and phosphorus (Hunt, 2001). This chemical process is based on soil particles which contain charges. These charges attract dissolved phosphorus and metals. Once all the available soil particles with active charges are bonded to introduced pollutants, this process will cease (Hunt, 2001). While absorption is an effective removal technique, it contains limitations and maintenance. Once the soil particles are bonded with pollutants, the combined substrate will require excavation.

Settling is when movement of water ceases and begins to pond, allowing suspended solids in the water to settle out (Dunnett & Clayden, 2007). This technique is used in forebay areas of retention ponds and storm water wetlands. This settling action, or "sedimentation", happens essentially because water loses velocity. When water loses energy it loses its ability to carry large particles (in many cases, pollutants) and elements settle (Hunt, 2001). If a rain garden site is known to have significant issues with sediment pollution, then settling can be a powerful removal technique with the proper design.

Filtration occurs in rain gardens with the aid of both plant material and soil. As water moves through planted vegetation, fibrous plant roots and other plant parts capture pollutant particles. The amount of filtration rain gardens can provide is limited, as rain gardens lack dense plantings (Hunt, 2001). Filtration can also occur through the soil and is another method of removing total suspended solids (TSS). TSS often have pollutants affixed to them such as phosphorous and harmful bacteria (Hunt, 2001). Both filtration and settling are effective methods of treating storm water runoff quality but they can require maintenance. If a rain garden is situated in area that receives high levels of sediment pollution, clogging and sediment buildup will need to be addressed.

Microbial action also referred to as degradation or decomposition, is the breaking down of chemicals and organic matter by soil microorganisms (Dunnett & Clayden, 2007). The shallow root zone soil interface of rain gardens creates a conducive medium for the microbial process to occur. Additionally, sunlight and dryness aides in terminating pathogens, which favor wet conditions (Hunt, 2001). Rain gardens are designed to infiltrate storm water runoff within forty-eight to seventy-two hours, eliminating standing water and the risk of pathogen breeding conditions. Pet and wild animal waste can increase the amount of pathogens transported in storm water runoff at residential sites (Kraus & Spafford, 2009).

Plant uptake or "phytoremediation" is a topic that will be discussed in length subsequently in this thesis. Concisely, *phytoremediation* is the process of plants removing harmful pollutants from the ground as their roots take in water and nutrients from polluted soil, runoff and groundwater (United States Environmental Protection Agency (US EPA), 2012b).

See pollution removal techniques used in rain gardens below in Table 3-1. (Brix, 1993; Hunt, 2001).

Table 3-1. Pollution removal techniques used in rain gardens. Adapted from (Brix, 1993 and Hunt, 2001)

Pollutant Removal Mechanism	**Pollutants**
Absorption to soil particles Plant uptake (phytoremediation)	Dissolved metals and soluble phosphorus Small amounts of nutrients including phosphorous and nitrogen
Microbial process	Organics, pathogens
Exposure to sunlight and dryness	Pathogens
Infiltration of runoff	Minor abatement of localized flooding, minor increase in localized base flow of groundwater, allowing some nutrients to be removed when groundwater flows through buffer
Settling and filtration	Total suspended solids, floating debris, trash, soil-bounded phosphorus, some soil-bound pathogens

Residential Rain Garden Benefits

Turf lawns are a monoculture that require high, on-going maintenance and large quantities of inputs that can have negative effects on the bioregion. While the turf lawn is still valued and demanded by many private residents, a growing number of homeowners recognize the added benefits of reducing the amount of turf grass and implementing design alternatives. Residential rain gardens are a trend that is picking up momentum in the field of landscape architecture and garden design. In addition to improving the hydrology of the local area by improving water runoff control and water quality, many homeowners appreciate the ecological benefits of rain gardens. A well-manicured turf lawn offers very little in the way of shelter or food for insects, bird species and wildlife (Steiner & Domm, 2012). Ecological benefits are just one example of what rain gardens can offer homeowners. In terms of economic benefits, rain gardens also can reduce the cost of fertilizer and pesticides needed to treat turf (United States Environmental Protection Agency (US EPA), 2012a). One of the most common occurrences on residential sites is the over-application or misapplication of nitrogen-rich fertilizers to lawns. When this happens the leaching of nitrates into the groundwater may occur. The leaching of nitrates is exacerbated especially after heaving periods of rain or snow (Prince George's County & Planning, 2002). In one of first studies conducted to publish field performance data on rain gardens pollutant capabilities, both ammonia and total nitrogen were significantly reduced in storm water that passed through a rain garden (Michael E. Dietz & Clausen, 2005). Rain gardens will also reduce irrigation needs (which is an expensive commodity throughout the United States) and lessen the amount of time needed to operate lawn mowers or tractors (United States Environmental Protection Agency (US EPA), 2012a). Finally, rain gardens can add an effective aesthetic value, which will be discussed in a following chapter.

Residential Rain Garden Design

Site inventory and analysis of a rain garden site are required in the design process. Inventory and analysis items include; water flow on property, slope of the ground, installation location, and existing soil conditions (soil texture, soil pH, soil fertility and chemical composition), sizing, water arrival method, sun/shade patterns, important views, existing vegetation and underground/overhead obstructions (Kraus & Spafford, 2009; Steiner & Domm, 2012; Woelfle-Erskine & Uncapher, 2012).

Water Flow

Choosing the appropriate location for a rain garden requires analyzing the water flow on the site. Locate rain gardens between the sources of storm water runoff (roof, driveway, patio, pathway or downspouts) and the final destination of storm water on a site (drains, low spots, depressions, sewer or stream) (W. F. Hunt, 2006). The rain garden should intercept the storm water before it enters the final destination/storm water collection system. When analyzing the water flow on a site, it is necessary to consider overflow situations where the rain gardens reach the site's capacity to hold water. A buffer between the rain garden and the final destination of storm water on a site, such as planted vegetation can help mitigate overflow (Kraus & Spafford, 2009).

Slope

The slope of the ground is another factor that will determine the location of the rain garden. Working with the natural topography of a site is the ideal design strategy and involves the least cost. In order to move water from the sources of storm water to a rain garden, it requires a change in elevation or ground slope. It is best to construct rain gardens on sites with slopes of up to fifteen percent (although a lower rate of slope is adequate), where water is moving at a moderate rate. The use of four-inch perforated pipe will be required if a site is nearly flat. The pipe can be connected to downspouts or storm water sources and laid with a minimum two percent slope to transport water into the rain garden at a lower elevation (Woelfle-Erskine & Uncapher, 2012). The midway point of the elevation change is best for rain gardens designed on slopes. Excavate soil several inches deep (based on soil conditions) and build into a berm to retain water; thus stabilizing the lower end of the rain garden (Kraus & Spafford, 2009).

Rain gardens built on sites with slopes of up to thirty percent require more engineering and guidance. Sites with steep slopes may require the use of contour swales or terraced rain garden cells connected with pipes or cascading overflow channels (Woelfle-Erskine & Uncapher, 2012).

Overflow

Regardless of the slope on the site, a rain garden has to accommodate overflow situations. (A rain garden is not meant to treat major storm events, which occur multiple times a year in the Southern Piedmont region of the United States.) Managing overflow in residential rain gardens offers two options: surface drains or under drains/dry wells. Surfaces drains work well in flatter areas where water can flow out of the back of the rain garden in several areas (Hunt, 2001). In order to avoid erosion problems with surface drains, the overflow outlet areas feature stone, brick or dense vegetation to keep soil in tact (Woelfle-Erskine & Uncapher, 2012). In a situation where the soil has a slower infiltration rate or a site with physical limitations, then an under drain may be more appropriate (as seen in Figure 3-4.). An under drain is made of a drainpipe set in a gravel base below the rain garden. The pipe is set at a lower elevation than the inlet, allowing water to infiltrate into the soil and also flow to another location, via the drain pipe (Woelfle-Erskine & Uncapher, 2012). The pipes selected for the under drain must infiltrate water from the gravel layer considerably quicker than water entering from the above soil fill layer. The removal capacity of the under drain along with the peak inflow amount of the rain garden determines the appropriate pipes (Hunt, 2001). The required calculations require knowing the rain gardens dimensions, soil depth and infiltration rate. The latter option is the installation of a dry well, which is a deep pit below the rain garden filled with large stone or rubble. The large void spaces between the large pieces of rock offer additional water holding space (Woelfle-Erskine &

Uncapher, 2012). The dry well pit is topped with a layer of medium sized gravel, a layer of smaller gravel and then with a layer of well draining soil (Woelfle-Erskine & Uncapher, 2012).

Figure 3-4. Overflow pipes control rain garden flooding. (photo credit: UGA, Office of Sustainability)

General Guidelines

The location of a rain garden needs to be well thought out and the designer needs to take into account other factors including: local ordinances, setback laws, sun/shade conditions, existing infrastructure and views.

General construction guidelines indicate that rain gardens are to be built at least ten feet away from a building foundation; at least twenty-five feet from a septic system drain field; not within twenty-five feet of a well head; avoid underground utility lines; located in partial to full sun; not built in poorly draining depressions; away from trees that can not handle flooding; away from large mature trees where roots will limit excavation; on sites with a slopes no greater then fifteen percent; and where the water table is at least two feet below the soil surface (NC Cooperative Extension, 2013; University of Arkansas et al., 2010; Woelfle-Erskine & Uncapher, 2012).

Water Transportation and Pretreatment Areas

The transportation of water into a rain garden, or the water arrival method, is key to successful rain garden design. Water entering a rain garden must arrive at a velocity high enough to facilitate the movement of the water but slow enough to limit erosion. Directing storm water across elements such as grass, gravel, rocks or vegetation reduces its velocity (Kraus & Spafford, 2009). Sheet flow, vegetated diversion swale, rock-lined diversion swale, runnels or underground pipe transports water into rain gardens. (Woelfle-Erskine & Uncapher, 2012). Rain gardens use an individual or a combination of the methods above. The site location, slope, location of rain garden and other specific conditions will dictate the method of arrival.

Figure 3-5. Rain garden parking lot flow. (photo credit: UGA, Office of Sustainability)

Sheet flow is the least structural of all options of water transportation and refers to water moving over the ground surface at a shallow depth (as seen in Figure 3-5.). It is ideal in areas of gentle slope with even surfaces. The implementation of sheet flow transportation will reduce infiltration in the rain garden as some water will be lost in route (Woelfle-Erskine & Uncapher, 2012).

A vegetated diversion swale, also referred to as landscape swale, moves storm water runoff. The swales are shallow, long and eighteen to twenty-four inches wide (Woelfle-Erskine & Uncapher, 2012). The vegetated swale transports water opposed to infiltrating water, while limiting erosion with the use of dense low plantings.

A rock-lined swale uses the same concept as the vegetated swale but with gravel or stone instead of plants. Rock-lined swales can offer a better option if erosion is a site concern, or simply for aesthetic purposes.

The use of runnels to transport water has been around for hundreds of years beginning as early as the ninth century, in places such as the Patio de los Naranjos in Cordoba, Spain (Rogers, 2001). A runnel is a shallow depression or channel in the ground that is typically sealed, not allowing infiltration, and designed to direct water to a specific area. Runnels can be quite attractive and are best suited for areas with gentle slopes. Runnels engage the rain garden observer by demonstrating flow and movement.

Underground piping that directs water into rain gardens is installed for several reasons. Buried pipe can be connected directly to gutter downspouts allowing maximum capture of water without above ground disturbance; this allows for numerous design choices that add aesthetic value. Underground piping is beneficial in design situations with steep slope, where surface erosion is nearly unavoidable. For buried pipe to operate properly, a minimum slope of two percent is required for the movement of water. A French drain, (buried 4-inch perforated pipe, set in geotextile fabric) is another method of water transportation as indicated Figure 3-6.

Figure 3-6. A French drain brings water to a residential rain garden in Watkinsville, GA (photo credit: Thomas Peters)

Another consideration of rain garden design is the pretreatment area. This is the area of the rain garden where the transported water arrives prior to entering the actual rain garden. Many installed rain gardens function with one of the storm water control measures previously discussed in this thesis, such as vegetated filter strips or level spreaders. If a rain garden is designed without one of these storm water control measures, then the area where water arrives at the rain garden can be quite vital to the success of its functionality. If water arrives at a high velocity or in the form of concentrated flow from a pipe, then rocks or stones may need to be installed to dissipate that velocity at the location of the waters arrival as shown in Figure 3-7. (Hunt, 2001).

Figure 3-7. Rock and stone dissipates flow velocity. (photo credit: UGA, Office of Sustainability)

Another consideration of rain garden design is a forebay. If excess sediment is not filtered out prior to arriving at a rain garden, sediment has the potential to clog the soil and limit the rain garden's performance (DENR., 1997).

Sizing

Sizing the residential rain gardens properly is essential to ensuring effective function. Factors to consider include local weather conditions, catchment area of impervious surfaces, and soil conditions. The percentage of the drainage area that the rain garden should be sized will vary somewhat, according to different sources. In accordance with the state of Maryland, the percentage should be five to seven percent (Maryland Department of the Environment, 1998). Other sources note that the rain garden should be five to ten percent of the impervious area that drains into the rain garden.

One study looks at a numerical model relating to groundwater recharge. This study was conducted in Wisconsin during the non-snowfall season and indicates that high levels of groundwater recharge are possible through rain gardens. The study shows that a rain garden with a total area of about ten to twenty percent of its drainage area maximizes groundwater recharge potential. Rain gardens that are sized larger than the above percentage stand to lose storm water via evaporation before the storm water can be infiltrated (A. R. Dussaillant, Cuevas, & Potter, 2005; Alejandro R. Dussaillant, Wu, & Potter, 2004). Another method of sizing a rain garden is designing the garden to hold the first inch of rainfall in the catchment area as seen in the below table 3-2. (Hunt, 2001; Kraus & Spafford, 2009).

Table 3-2. Required rain garden size to capture one inch of rain. Adapted from (Hunt, 2001 and Kraus & Spafford, 2009)

Impermeable Surface Area	**Required Size of Rain Garden (6" deep)**	**Potential Rain Garden Dimensions (ft. x ft.)**	**Required Size of Rain Garden (3" deep)**	**Potential Rain Garden Dimensions (ft. x ft.)**
800 square ft.	40 square ft.	4 x 10, 5 x 8, 6 x 7	80 square ft.	7 x 12, 8 x 10, 9 x 9
1000 square ft.	50 square ft.	5 x 10, 6 x 8	100 square ft.	7 x 15, 10 x 10
1200 square ft.	60 square ft.	4 x 15, 5 x 12, 6 x 10, 8 x 8	120 square ft.	10 x 12, 8 x 15
1400 square ft.	70 square ft.	5 x 14, 7 x 10	140 square ft.	10 x 14, 7 x 20
1600 square ft.	80 square ft.	7 x 12, 8 x 10, 9 x 9	160 square ft.	8 x 20, 10 x 16
1800 square ft.	90 square ft.	6 x 15, 7 x 13, 8 x 12, 9 x 10	180 square ft.	9 x 20, 10 x 18, 12 x 15
2000 square ft.	100 square ft.	7 x 15, 10 x 10	200 square ft.	10 x 20, 14 x 15
2500 square ft.	125 square ft.	8 x 16, 10 x 13	250 square ft.	10 x 25, 13 x 20, 15 x 17
3000 square ft.	150 square ft.	10 x 15, 12 x 13	300 square ft.	10 x 30, 15 x 20
3500 square ft.	175 square ft.	9 x 20, 12 x 15	350 square ft.	14 x 25, 18 x 20
4000 square ft.	200 square ft.	10 x 20, 14 x 15	400 square ft.	16 x 25, 20 x 20
5000 square ft.	250 square ft.	10 x 25, 13 x 20, 15 x 17	500 square ft.	20 x 25

It is important to know the amount of total catchment area that will be draining into the rain garden with use of either method and to record how much of this area is impervious surface and how much is pervious. Based on these calculations, appropriate runoff coefficient numbers can be applied to the different types of areas. Grasses and vegetated areas typically have lower runoff coefficient numbers while impervious surfaces, such as concrete or roofs, have higher numbers. By applying these runoff coefficient numbers in the process of rain garden sizing, one is able to produce a more accurate design while possibly reducing unnecessary construction costs. Recommended runoff coefficient values from the Georgia Stormwater Management Manual can be seen in table 3-3. (Commission & Division, 2001)

Table 3-3. Recommended runoff coefficient values. Adapted from (Commission & Division, 2001)

Description of Area	**Runoff Coefficients**
Lawns, sandy soil, flat, 2%	0.10
Lawns, sandy soil, average, 2-7%	0.15
Lawns, sandy soil, steep, >7%	0.20
Lawns, clay soil, flat, 2%	0.17
Lawns, clay soil, average, 2-7%	0.22
Lawns, clay soil, steep, >7%	0.35
Unimproved area, forest	0.15
Business, neighborhood area	0.70
Business, downtown area	0.95
Residential, single-family areas	0.50
Residential, multi-units, detached	0.60
Residential, multi-units, attached	0.70
Residential, suburban	0.40
Residential, apartment dwelling areas	0.70
Industrial, light areas	0.70
Industrial, heavy areas	0.80
Parks, cemeteries	0.25
Playgrounds	0.35
Railroad yard areas	0.40
Streets, asphalt and concrete	0.95
Streets, brick	0.85
Drives, walks, roofs	0.95
Gravel areas	0.50
Graded or no plant cover, sandy soil, flat, 0-5%	0.30
Graded or no plant cover, sandy soil, flat, 5-10%	0.40
Graded or no plant cover, clayey soil, flat, 0-5%	0.50
Graded or no plant cover, clayey soil, average 5-10%	0.60

In order to determine the volume of water entering a rain garden, rainfall intensity must be identified. Rainfall intensity is the amount of rainfall over a period of time during the most intense part of a storm. This is a localized factor and many states will offer rainfall intensity numbers for specific cities or counties. The rainfall intensity number is typically given in inches per hour and correlated with storms of different magnitudes such as 1-year, 2-year, 5-year, 10-year, 25-year, 50-year or 100-year storm event. Residential rain gardens commonly are not designed to handle large storm events such as a 50-year storm event, but geographical location will dictate the rainfall intensity. Catchment area, runoff coefficient numbers and rainfall intensity are the three components needed to produce an accurate volume of storm water entering the rain garden.

Determining the depth is the next step in sizing a rain garden. This requires finding the soil texture and/or soil infiltration rate. The soil texture is the percentage of sand, clay and silt that compose the soil. These percentages will control the infiltration rate of the soil or how fast the water moves through the soil and are commonly measured in inches per hour. Infiltration rate can be analyzed by a number of methods in a laboratory using particle size distribution analysis (hydrometer, pipette method or texture-by-feel method). More commonly, in residential rain garden design, infiltration rate measurements are conducted on the site using the percolation or perk test (E. Gasparotto, 2003; Woelfle-Erskine & Uncapher, 2012).

By excavating a small hole in the soil and using a measuring stick, it is possible to calculate how quickly the water moves from the top of the hole to the bottom. Another method involves the use of an infiltrometer, which evaluates the soil capacity to percolate water (Steiner & Domm, 2012). Referring to the United States Department of Agricultural Soil Classification Chart will classify what type of soil exists on site such as a clay, sandy clay, silty clay, sandy clay loam, clay loam, silty clay loam, sandy loam, loam, silt loam, loamy sand, sand or silt. Each one of these classifications has an associated infiltration rate and rain garden installation recommendations. In general, sandy soils drain quickly while soils with high clay content drain slowly. If a soil is mainly composed of clay then it may be necessary to excavate or amend the soil with a medium containing a higher infiltration rate. Once the infiltration rate is identified it is possible to determine the desired depth of the rain garden, generally three to eight inches (NC Cooperative Extension, 2013; Prince George's County & Planning, 2002).

The two previously calculated variables, including water volume entering a rain garden and the known depth of the rain garden, will enable the designer to calculate the surface area required. Common rain gardens design choices include organic shapes based on the site and aesthetics. Planting selections based on different zones of vegetation within the rain garden (that require specific plant material) factor into the design process. Rain gardens feature several difference zones, classified based on soil moisture, referred to as saturation zones (Steiner & Domm, 2012).

In a simple rain garden design there are often three zones: the wettest zone, the sloped sides, and the berm. The lowest or wettest portion of a rain garden, commonly the center, takes on the most water for the longest period of time. This zone can be flooded for periods of forty-eight to seventy-two hours and will require plant species capable of surviving in the same inundation levels. Sloping up from the wettest zone of the garden is the next saturation zone, which gently slopes toward the previous zone. This saturation zone receives intermittent flooding for periods up to twenty-four hours, as well as periods of drought. Plant material in this area needs to handle large amount of water but also extended periods of dry soil. The final zone is the berm, the driest zone, which stabilizes the rain garden. The berm requires plant material that can survive with minimal irrigation and is capable of reinforcing the soil with root structure.

Many rain garden designs are complex and feature several additional zones constructed for aesthetic purposes or for the conditions of a specific plant species. A functional rain garden design will attempt to create at least three zones of different inundation levels. Creation of different saturation zones promotes diversity of plant material, proper functionality of the rain garden, and can encourage biodiversity within and around the rain garden. Specific plant material will be discussed in subsequent chapters.

Maintenance

As with any landscape design feature a certain amount of regular maintenance is required. Watering, erosion control, plant care and mulching will ensure proper function. Watering should occur on a regular basis to establish plants during the first year of the rain garden. This will aid in creating strong root systems (Woelfle-Erskine & Uncapher, 2012). Rain gardens should be inspected regularly for signs of erosion problems. Areas such as flow entrances, ponding areas and surface overflow areas all have potential to experience erosion issues (DENR., 1997). In some cases it may be necessary to replace soil, rocks or mulch. If erosion is a reoccurring issue, then it may be necessary to redesign portions of the rain garden.

The accretion of excess sediment may be another problem contributing to erosion. If this problem persists, it should be taken it to consideration upon re-design of the rain garden. Most of the plant material installed in the rain garden will require care such as removing weeds, cutting back plants in early spring, pruning shrubs, dividing plants, deadheading, dormant pruning or controlling tall plants (Steiner & Domm, 2012). Individual installed plant species require specific maintenance techniques. Organic mulch may also need reapplication based on how quickly existing mulch breaks down and decays (Steiner & Domm, 2012). Excess mulch placed for winter protection will hinder plant growth in spring and requires removal. After the first year of plant establishment, rain gardens do not require a great deal of maintenance compared to many other landscape installments, such as turf grass or ornamental plantings, that need fertilizing, pesticide control and regular irrigation (Steiner & Domm, 2012).

Understanding the functionality and components that make up residential rain gardens aid in comprehending the possibilities and limitations of phytoremedic rain garden installations in the Piedmont region of the Southeastern United States. Chapter Three looks at the design of rain gardens and construction guidelines. The physical design of rain gardens are limited by the site of installation. Steep slopes, heavily shaded area, soil with low infiltration rates are all factors that can limit the success of rain gardens. Chapter Four will look at phytoremediation and plant material that offer possibilities and limitations to phytoremedic rain gardens in the Piedmont region of the Southeastern United States

CHAPTER FOUR

PHYTOREMEDIATION IN RESIDENTIAL RAIN GARDENS

Phytoremediation Principles

Phytoremediation is the process of plants removing harmful pollutants from the ground as their roots take in water and nutrients from polluted soil, runoff and groundwater (United States Environmental Protection Agency (US EPA), 2012b). More specifically, phytoremediation includes the use of vascular and non-vascular plants to remove and control 'wastes'. The wastes controlled and/or removed by plant material include: heavy metals, metalloids, salts, excess nutrients, organic chemicals, sewage and air pollution (McCutcheon & Schnoor, 2004). In many cases of phytoremediation installments, photoautotrophic plants facilitate the pollutant removal process. A photoautotrophic plant is capable of synthesizing its own food from inorganic substances, using light as an energy source. Sun or solar power essentially powers phytoremediation. This makes phytoremediation a beneficial, sustainable practice (McCutcheon & Schnoor, 2004).

Rain Gardens and Target Pollutants

The intention of the design of a rain garden supports the concept of low-impact development. By doing this, rain gardens (if designed correctly) aid in mimicking the natural hydrology of a site. The rain garden will capture the storm water that otherwise would enter surface waterways or sewer systems, and the runoff will infiltrate into the soil of the rain garden.

By completing this sequence, multiple essential soil nutrients and other pollutants, such as heavy metals, enter rain gardens. Specific pollutants, such as excess nutrients and heavy metals, are targets of rain garden design and treat these pollutants as mentioned in previous chapters.

The essential mineral nutrients that that come from the soil are divided into two groups- macronutrients and micronutrients. The first group, macronutrients, further can be divided into two smaller groups: primary and secondary nutrients. The primary macronutrients are nitrogen (N), phosphorus (P) and potassium (K). These three nutrients are the main components of standard chemical fertilizers; plants require them for growth and survival. Fertilizers are chemicals that feed the plants roots directly. By doing this fertilizer inhibits much of the soils' microbiology and increases the demands of fertilizer reapplication (Lowenfels & Lewis, 2006). The secondary macronutrients are calcium (Ca), magnesium (Mg) and sulfur (S). These secondary macronutrients are also available in the form of chemical fertilizers but not used as frequently as the previous three primary macronutrients. Both calcium and magnesium are present in lime, which is a common fertilization treatment used to correct soil Ph balance. In addition to the macronutrients, there are several micronutrients found in soil. Plants require these trace elements, or minor elements, in small amounts. The micronutrients are boron (B), copper (Cu), iron (Fe), chloride (cl), manganese (Mn), molybdenum (Mo) and zinc (Zn). On residential properties over-application of chemical fertilizer is one of the most common causes of excess nutrients in soil. In run-off situations, these excess nutrients damage water quality in streams and rivers.

While excess chemical fertilizers and nutrients have the ability to alter and disrupt the natural hydrologic cycle, so do many other types of pollutants commonly found on residential properties. Three common hazardous pollutants found on residential sites are lead, arsenic and cadmium (Gromicko, 2006). Heavy metals, such as lead, can leach into the soil from roof shingles or improperly disposed hazardous materials (asbestos, asphalt). Another source of lead pollution on residential sites is old exterior house or deck paint. Paint residue will fall to ground surface as various forms of precipitation erode a homes' surface. Precipitation wearing away the paint/finish of a home creates a contaminated 'drip zone'. This drip zone typically extends six feet from the perimeter of a home and contains the highest amount of soil contamination (Gromicko, 2006). Actions such as power washing, acid washing or sandblasting can exacerbate contamination levels and increase the surface area of the drip zone. Even though the use of lead in paint has been outlawed since the environmental movement of the 1970's, residential sites still may contain lead in the soil from previous construction, renovation or demolition (Gromicko, 2006).

Storm water, which runs off of a driveway or parking area, can accrue a litany of chemicals from motor oil, to gasoline, to antifreeze and other automotive additives. Lead soil contamination is also commonly found along roadsides since automobile gasoline formally contained lead as an additive.

Arsenic or chromated copper arsenate (CCA) is recurrently found in residential soils. Arsenic was used in wood preservative to manufacture pressure-treated lumber. The lumber was typically used for the construction of children's playgrounds, walkways, gazebos and other exterior structures (Gromicko, 2006). This arsenic treated lumber was manufactured for approximately ten years from the mid- nineteen nineties to two thousand and four until it was banned by the Environmental Protection Agency. Although this lumber is no longer available for residential installations, it is still used in industrial construction (Shayler, McBride, & Harrison, 2009). The arsenic in these wood products does travel into adjacent soil but at a slow to moderate rate. Areas that receive high levels of precipitation and or contain longstanding abandoned structures are key suspects for arsenic soil contamination (Gromicko, 2006). In addition, arsenic has a long history of being used as a pesticide in the United States but has also been banned due to health concerns. Historic or older residential sites may contain arsenic soil contamination from antiquated farming or gardening practices.

Cadmium is another pollutant associated with residential sites. Cadmium soil contamination is a naturally occurring process as well as an anthropogenic activity. It can be introduced into the soil from the burning of fossil fuels and waste sludge (Gromicko, 2006). Fertilization practices formerly featured the use of cadmium but are no longer legal. Cadmium levels in the soil can be increased by the application of phosphate fertilizers, rich organic manure or treated sewage.

Another pollutant found in residential areas is zinc. Galvanized water pipes are pipes coated with zinc. Although considered safe to transport drinking water these pipes can omit zinc and other harmful agents if water within the pipes has a low pH or acid level (W. Wang & Zhu, 2010). The corrosive nature of acid can erode the galvanization and allow zinc to move into drinking water and ground water.

Rain Gardens and Bioretention Removal Studies

Many different studies analyze the effectiveness of rain gardens removing pollutants. One study shows the percentage of pollutants removed by rain gardens and associates them with common household amenities as seen in Table 4-1. (Kraus & Spafford, 2009; United States Environmental Protection Agency (US EPA), 2012b).

Table 4-1. Effectiveness of a rain garden in removing pollutants. Table adapted from (US EPA, 2012)

Pollutant	Source of Pollutant	% Removed by rain garden
Copper	Roof shingles, oil, grease, soil	43-97%
Lead	Roof shingles, oil, grease, soil	70-95%
Zinc	Roof shingles, oil, grease, soil	64-95%
Phosphorus	Detergents, fertilizers, pet waste	65-87%
Total nitrogen	Fertilizer, pet waste, organic matter	49-67%
Calcium	Fertilizer	27%

A field and laboratory analysis of rain gardens conducted in Maryland also indicated high levels of pollutant removal within biorentention areas. Rates of removal were approximately ninety-five percent for copper, ninety-eight percent for phosphorous and twenty percent for nitrate (A. Davis, M. Shokouhian, H. Sharma, and C. Henderson., 1997.). In addition to this study, another two biorentention facilities in Maryland exhibited high levels of nutrient and chemical removal as indicated in Table 4-2. (A. Davis, M. Shokouhian, H. Sharma, and C. Henderson., 1997.; United States Environmental Protection Agency (US EPA), 2012b).

Table 4-2. Pollutant removal effectiveness of two bioretention areas in Maryland. Table adapted from U.S. EPA report on National Pollutant Discharge Elimination System storm water program.

Pollutant	Pollutant Removal
Copper	43%-97%
Lead	70%-95%
Zinc	64%-95%
Phosphorus	65%-87%
Total Kjeldahl Nitrogen (TKN)	52%-67%
Ammonium	92%
Nitrate	15%-16%
Total Nitrogen	49%
Calcium	27%

One particular study analyzed the effectiveness of bioretention areas by removing relatively low levels of lead, copper and zinc from synthetic storm water runoff. The results of this study indicated that the bioretention areas were highly effective at removing the introduced metals. Based on concentrations and mass of the pollutants, the bioretention areas were able to remove almost one hundred percent of the metals. In order to ensure viable results, the runoff pH, duration, intensity and pollutant concentrations were all varied, showing little effect on the removal rates (A. P. Davis, Shokouhian, Sharma, Minami, & Winogradoff, 2003). Overall this study showed significant levels of heavy metal removal through bioretention infiltration. This study is of particular interest because the low levels of metals looked at in this study may be similar to the same low levels of metals found in storm water runoff in residential sites.

In Haddam, Connecticut during 2005 and 2006, two studies set out to provide results of rain garden pollutant removal capabilities on a smaller scale, comparable to residential sites. These studies analyzed rain gardens designed to capture storm water runoff from shingled roofs. Two experimental rain gardens were built and sized to capture the first one-inch of runoff. The study produced many interesting results including that the fact that levels of ammonia-nitrogen (NH3-N) was significantly lowered in both rain gardens and total nitrogen was significantly lowered in one of the rain gardens (M. E. Dietz & Clausen, 2006; Michael E. Dietz & Clausen, 2005).

Recent studies conducted by the International Stormwater Best Management Practices (BMP) Database analyzed volume reduction performance; in twenty separate bioretention cells in Pennsylvania, Massachusetts, North Carolina, Virginia, and Wisconsin. The result of the studies indicate an average relative volume reduction of sixty-six percent in the twenty bioretention cells (Clary et al., 2011).

Table 4-3. Relative volume reduction statistics for bioretention studies. Table adapted from (Clary et al., 2011).

Analysis Group	# studies	25th Pctl.	Median	75th Pctl.	Avg.
All Studies	20	42%	66%	98%	66%
No Underdrains	6	85%	99%	100%	89%
With Underdrains	14	33%	52%	73%	56%

Phytoremediation within Residential Rain Gardens

While many recent studies quantifiably measure the effectiveness of rain gardens, little work has been completed in the field of studying phytoremediation possibilities within residential rain gardens. In many cases the notion of phytoremediation is associated with storm water wetlands and the use of aquatic vegetation. For the residential landscape, the opportunity to create a phytoremedic rain garden exists. However, it may require the exploration of new plant material and new ideas. Plant species suited for both residential rain gardens and phytoremediation need to be highly functional and also aesthetically pleasing. The following is a selection of plant species suited for rain garden design and under review for phytoremedic capabilities.

Common annual sunflowers (*Helianthus annuus*) are species of interest. A 2011 study, investigated the capability of this plant to accumulate and endure high amounts of lead (Pb). The plants were studied in a hydroponic application but the study hoped to propose the plant for soil phytoremediation purposes. The study exposed the plants to a variety of lead levels and concluded that *Helianthus annuus* has the capability to accumulate significant levels of lead for phytoremediation purposes (Seth, Misra, Singh, & Zolla, 2011). This study is relevant for residential landscape design in several ways. The sunflower (*Helianthus annuus*) is a fast growing annual native Piedmont plant. It is member of the asteraceae family featuring rough, hairy, heart-shaped leaves and is one of the most commonly available species of sunflower (A.M. Armitage, 2001; Ellis, 1999). The plant is easy to cultivate and requires little more than sun and water in order to survive. Plants are vigorous, growing up to fifteen feet, yet most cultivars reach three to seven feet in height (A.M. Armitage, 2001; Ellis, 1999). This plant provides residential homeowners and designers an easy-to-grow planting option and phytoremedic possibility, especially if a site is known to have excess lead levels from a surface such a driveway or garage. Sunflowers can easily be grown each year and favor rain garden conditions as long as the area is located in full sun. The plants can be removed annually and replanted as necessary.

Castor bean plant (*Ricinus communis*) is another plant species that has been studied for its phytoremedic properties and has potential in residential design. A member of the Euphorbiaceae family, the castor bean plant is an eye-catching species and the only species in the *Ricinus* genus. The plant has both a commercial importance as well as the ability to make a stunning impact in landscape design. The plant is easily identifiable due to its large, glossy, palmately lobed leaves and impressive height which can reach fifteen feet (Ellis, 1999). The plant is commercially important for both the production of castor bean oil and the powerful toxin, ricin. Castor oil is used in the manufacture of varnishes, paints and lacquers. Typical plants reach heights of around twelve feet and a spread of six to eight feet (A.M. Armitage, 2001).

From a design standpoint, the large palmately shaped leaves exude a tropical feeling and can vary in color from dark green to blood red (A.M. Armitage, 2001). The plant, which has a rapid growth rate, is quite easy to grow from seed every year. The castor bean requires full sun and well draining soil to preform optimally and can be grown as a perennial in more southerly regions than the Piedmont. The species also has a variety of interesting cultivars, which adds to its ornamental value. These include: 'Carmencita', Carmencita Pink', Gibsonii', 'Impala', 'Laciniatus', 'Sanguineus', 'Scarlet Queen' and 'Zanzibarensis'. Castor bean also has appeal as a "heritage plant"; many rural Southerners traditionally used castor bean to help deter moles and voles, as its root system is extremely fibrous. A study conducted in 2012 investigated the potential use of the castor bean plant as a species to remediate metal-polluted sites. The study area contained high levels of copper (Cu), zinc (Zn), manganese (Mn), lead (Pb) and cadmium (Cd). The finding of the study indicated that the plants did not accumulate high levels of the heavy metals, but did show that *Ricinus communis* was well suitable for toxic conditions, could be used for soil remediation, for decreasing metal bioavailability, and phytostabilization (Ruiz Olivares, Carrillo-González, González-Chávez, & Soto Hernández, 2013). Phytostabilization refers to the holding of contaminated soils in place with the use of vegetation thus immobilizing pollutants in the soil. This can prevent further degradation of the surrounding areas (McCutcheon & Schnoor, 2004; Vangronsveld & Cunningham, 1998).

The castor bean plant is not always selected in residential landscape design but is a resilient plant that should not be overlooked. While the plant is considered to be an invasive species by the USDA in the states of Florida and California, the cold winter temperatures of the Piedmont region ensure the plant will not exponentially multiply to unhealthy or undesired levels.

Common Yarrow (*Achillea millefolium*) is also a versatile plant with possible benefits to rain gardens in the Piedmont. Considered an aggressive naturalized plant it can spread rapidly take over surrounding areas (A. M. Armitage, 1997). If chosen for rain garden installation in the Piedmont region this species will require careful management. It was used by early Native

Americans to remedy ailments such as toothache, earache and fever reduction. The plant was also noted for its medicinal properties throughout Europe prior to the advent of modern medicine. The plant itself is small, reaching heights and of spread two to three feet. The foliage is dark green with white to Cerise red blooms in summer months (A. M. Armitage, 1997). This plant is quite drought tolerant and well suited for installation on a berm in a rain garden. *Achillea millefolium* features dozens of cultivars and hybrids that contain a variety of color hues and different bloom colors. A study conducted in 2003 shows that Common Yarrow had the ability to uptake and accumulate the pollutant cadmium ((IERE), 2003). Another more recent study showed that *Achillea millefolium* grew quite well in cadmium-contaminated soil and may contain phytoremedic properties (Maryam Mashhoor Roodi, 2012). *Achillea millefolium* is common through the Piedmont region, attracts butterflies and could easily be incorporated into a rain garden.

Several studies have investigated the phytoremedic properties of the *Allium* genus. Some species within this genus have growth requirement characteristics that may not be best suited for the warm summers of the Piedmont region and are more prevalent in northern climates such as *Allium sphaerocephalum*. One study looks at several species in the Allium genus (*Allium sativum, Allium cepa, Allium porrum and Allium schoenoprasum*). Most of these plants are not typically grown for ornamental purposes but all plants in the study did indicate levels of cadmium uptake and accumulation (Soudek et al., 2009). Many plants of this genus can easily be grown from bulbs in residential gardens and many act as perennials, returning each spring. Alliums typically feature attractive blooms, that occur in early to late spring, prior to many other flowering plant species that are found in residential landscapes.

The *Solidago* genus (common name, Goldenrod) is a group of plants that are commonly installed in rain gardens. *Solidago canadensis* is one of the most common species of this genus in North America. It is a native herbaceous perennial plant that features brilliant yellow flowers in late summer to early fall. This genus is distributed throughout the United States and Canada, but is considered invasive in parts of Europe, Japan and China. These plants are installed in rain gardens due to their tough resilient nature and attractive flowers, although they are sometimes criticized for being too tall and dominating spaces (A. M. Armitage, 1997). This genus has also been shown to exhibit phytoremedic qualities. Solidago species have been used in studies to analyze metabolism of trichloroethylene (TCE), a hazardous chemical used to remove grease and used in textile production (McCutcheon & Schnoor, 2004). While TCE soil contamination may not be prevalent on residential areas, Solidago species have also been shown to accumulate heavy metals, specifically aluminum (McCutcheon & Schnoor, 2004). Goldenrod is an excellent choice for a residential rain garden based on its low maintenance needs and striking yellow flowers. Subsequently, in this thesis one cultivar of Solidago (*Solidago sphacelata 'Golden Fleece'*) will be further analyzed for its residential rain garden applicability.

In another recent study in Virginia, several species of common landscape plants were analyzed for possible phytoremedic properties. The study was divided into two sections, a modified hydroponic screening study and a landscape screening study. The modified hydroponic screening study looked at several species including: redtwig or redosier dogwood (*Cornus sericia),* buttonbush (Cephalanthus *occidentalis),* and deciduous holly or winterberry (Ilex *verticillata).* These plants were subjected to significantly high levels of nitrogen (N) and phosphorous (P). The plants were harvested, dried and weighed. The result indicated that all species grew to a larger size and accumulated higher levels of N and P in their tissue (Ruby &

Appleton, 2010). The second part of the study set out to compare the accumulation levels of nitrogen (N), phosphors (P), copper (Cu) and zinc (Zn) in woody shrubs. The study compared plants installed in standard soil with plants installed with a Filterra® Bioretention System. This study focused on several hollies (*Ilex sp.),* crape myrtle (*Lagerstroemia sp.)* and redtwig dogwood (*Cornus sericea*). The plants were installed in soil at multiple locations in Virginia, exposed to excess levels of the above nutrients and finally harvested. The results of the study indicated that all species of plants installed with the Filterra® Bioretention System showed higher levels of nutrient accumulation of all nutrients under review (N, P, Cu and Zn). The findings also suggests that these species may have potential to act as hyperaccumulators (Ruby & Appleton, 2010). Hyperaccumulation is a particular type of phytoextraction in which plants uptake and accumulate more then a tenth of a percent (by dry plant weight) of nickel, zinc, copper, chromium or other trace metals (Brooks, 1998; Brooks, J. Lee, R.D. Reeves, & Jaffre, 1977; McCutcheon & Schnoor, 2004).

A study conducted in 2012 investigated perennial ryegrass (*Lolium perenne*) and its phytoremedic properties of zinc accumulation. *Lolium perenne,* a loosely to densely tufted perennial, is widespread in Europe, Asia and Africa. It was introduced in North America, South America and Australia (Hubbard & Sampson, 1984). The study consisted of six applications of exponentially increasing levels of zinc to *Lolium perenne* grown both in sand and sandy loam (Zalewska, 2012). *Lolium perenne* grown in the sand showed visible signs of the toxic effect of zinc while *Lolium perenne* grown in sandy loam remain more resilient. The study concluded that zinc amounts in grass harvested during the study were at significant levels but the total uptake level was small in percentage, at one to two percent of the zinc introduced (Zalewska, 2012).

Lolium perenne is capable of accumulating high levels of zinc and tolerating sand and sandy loam with zinc in the soil (Zalewska, 2012).

The implementation of phytoremedic plants in residential rain gardens is a relatively new concept. Future studies evaluating specific plant species should prove noteworthy and informative. Based on the comparatively minimal amount of research that exists on residential landscape phytoremediation and compared to past horticulture science topics, many new species should emerge as candidates. It is also valid to consider that some phytoremedic species may not have the handsome foliage or appealing flowers desired for a residential landscape. It then becomes a subjective decision of the designer to either strictly consider attractive plant species in the design or to create an amalgam of functional phytoremedic plants and aesthetically pleasing species.

Plant Management and Maintenance

Based on the type of plant materiel installed in a phytoremedic rain garden mass of the vegetation will increase as growth develops. The type of phytoremediation will dictate the method of biomass removal (United States Environmental Protection Agency (US EPA), 2000). Species such as mature trees will not require periodic planned removal but annual species will need to be removed. Any phytoremediation system will eventually accumulate dead or diseased plants, fallen leaves, fallen limbs or pruned material that should be removed (United States Environmental Protection Agency (US EPA), 2000). As annual plant species die it is important to confirm they do not contain hazardous substances. If it is not possible to test or confirm plant species do not contain hazardous substances then they should be disposed of off-site (United

States Environmental Protection Agency (US EPA), 2000). Annual species can be replanted as needed to continue the phytoremediation process.

The removal of plants from phytoremedic rain gardens can be completed in several ways. First the contaminated plants must be harvested from the rain garden. The plants can then subjected to a pretreatment phase of compaction, composting or pyrolysis. After pretreatment the plants are commonly incinerated or disposed directly at a hazardous treatment facility (Sas-Nowosielska et al., 2004).

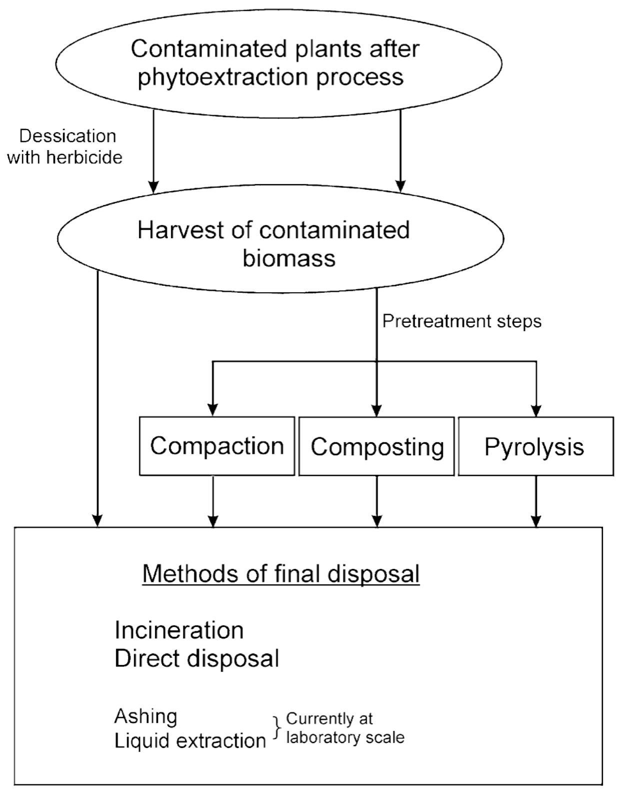

Figure 4-1. Phytoremediation harvest process (Adapted from Sas-Nowosielska et al., 2004)).

CHAPTER FIVE

AESTHETIC VALUE AND PLANT MATERIAL OF RESIDENTIAL RAIN GARDENS

Residential Rain Garden Benefits

The benefits of installing rain gardens in residential settings go far beyond the functionality of effectively and responsibly managing storm water. Creating a rain garden in a home landscape with plants that will cleanse the earth through phytoremediation does not even scratch the surface of all that rain gardens have to offer. Residential rain gardens can be skillfully designed and constructed to capture outstanding aesthetic qualities. Land with aesthetically attractive landscapes like rain gardens have a resale value twenty percent higher than traditional residential designs (Prince George's County & Planning, 2002).

Residential Rain Garden Planting Design Basics

The design of rain gardens is similar to the design of many other landscape features. When designing rain gardens on residential sites the intent of the feature and what it sets out to accomplish is paramount. If a rain garden is designed in the front yard of a residence, then the designer needs to consider neighboring properties and local city or county ordinances. Many municipalities have setback regulations the restrict construction projects near sidewalks, roads and other utilities. In addition, municipalities and homeowner associations may have specific restrictions on the size or type of landscape installations acceptable on residential properties. In February of 2013 the city of Atlanta, Georgia approved major changes to its ‘post-construction stormwater ordinance'. The changes state any new or re-development property site greater then five hundred square feet is required to treat the first inch of storm water runoff with BMPs (Hoffner, 2013). The BMPs can include rain gardens, porous paving, vegetated roofs and other acceptable low-impact development techniques. The changes also state new homes or large additions of one thousand square feet or more treat the first inch of storm water runoff with BMPs (Hoffner, 2013). Joel Bowman, owner B+C Studio, in Atlanta has completed five new residential rain gardens since the new regulations have been approved and expects to continue installations (Bowman, 2013).

The plants chosen for rain gardens provide the elements of design and their qualities contain different seasonal components. These plants do not necessarily limit the designer to choosing a certain design style or form. Many residential rain gardens are naturalistic, sinuous in shape and quite informal (Kraus & Spafford, 2009). Informal rain garden design typically embodies sweeping, gentle, curved, naturalistic and organic lines. Planting is grouped into asymmetrical patterns and can feature a mix of evergreen, deciduous and perennial plant species, not regularly intensely pruned into shapes (Kraus & Spafford, 2009). Comparatively formal rain garden design exemplifies many standard formal landscape architecture design choices. Formal rain garden deign can include straight or geometrically exact curved bed lines or bilaterally symmetrical planting (Booth & Hiss, 2004; Kraus & Spafford, 2009). In these rain gardens the use of clumping or non-spreading rhizomatous plants may be a valid choice (Steiner & Domm, 2012). Clumping plants offer an advantageous choice in formal or symmetrical garden design as these plants can be pruned and sculpted into desire shapes. Formal design often includes the use of key or focal plant species to draw attention to create important spaces and this can be accomplished in rain gardens with use of certain plant species.

The main concern of residential rain garden design besides the pure functionality of the rain garden is the need of the homeowner or client. If possible, the rain garden should be placed and designed in way such that the homeowner benefits the most from the sound, movement and effects of water (Van Sweden, 1995).

Planting Zones

Designing a rain garden requires the balance of plant moisture needs and aesthetic interest. A rain garden must be able to tolerate different soil moisture conditions; therefore, rain gardens are divided into different zones. The different 'saturation zones' allow the growth of a variety of plan species (Steiner & Domm, 2012). Rain gardens are divided into at least three zones of different flood tolerance. The bermed area or driest area (indicated as 'zone 1', in the tables below) of the rain garden should rarely flood. This zone is the driest and contains plants tolerant of drought. They also aid in stabilizing the rain garden with root structure (that taps into the water below). The sloped sides of the rain garden (indicated as 'zone 2', in the tables below) require plants that can handle brief flooding, for less then twenty-four hours. The lowest or wettest zone (indicated as 'zone 3', in the tables below) may receive flood conditions for up to forty-eight hours. Located in the center of the rain garden, this zone requires plants both capable of prolonged flooding, as well as drought conditions (Woelfle-Erskine & Uncapher, 2012).

Year-Round Interest

Many plant species ideal for rain garden have a large range of seasonal changes and interest. While a large amount of Piedmont plant species primarily bloom in the warm summer months, many do not, and can add year-round value and interest in a rain garden. It is invaluable to include the use of plants that bloom throughout the seasons so as not to limit the design or experience in different seasons. Many other plants have attractive berries that are persistent in winter months. The berries not only add in the color scheme of the garden but also provide wildlife benefits. Regional and migrating bird species and insects will be drawn to the garden. Three excellent plant choices that feature colorful winterberries that are pleasant to look at and benefit wildlife: red chokeberry *(Aronia arbutifolia*), black chokeberry *(Aronia melanocarpa*) and American beautyberry (*Callicarpa americana*) (Kraus & Spafford, 2009). These three plants are all native species to the Piedmont region. The berries remain on the plant in the cold months of winter and can be quite striking.

Sun and Shade

Appropriate sun exposure is one of the most critical factors when considering plant placement (Booth & Hiss, 2004). Sun availability is grouped into three categories: ‘Full Sun’, areas that receive at least six hours of direct sunlight a day; ‘Part Shade’, areas that receive bright sun for about half the day; and ‘Shade’, areas under a full canopy of tree out of direct sunlight (Booth & Hiss, 2004; Steiner & Domm, 2012). On residential sites, the house and existing vegetation will aid in creating four microclimates of sun exposure that relate to each side of the house. The south side of the house will have full sun exposure from afternoon until evening. The east side of the house will have morning sun and is conducive to plants that require part sun to shade. The north side is suited for plants needing shade and damp conditions. The west side will receive full afternoon sun and require plant capable of tolerating high temperatures and drought (Booth & Hiss, 2004). Plant selection methodology is based on the location of a rain garden in relationship to the residence.

Native Plants and Wildlife Attraction

Installing a rain garden with native plants will increase the amount of biodiversity and wildlife attraction on a residential site if replacing a paved surface or turf managed area (Dunnett & Clayden, 2007). These native plants offer advantages such as: providing food sources for animal species, serving as a genetic resource and requiring reduced amounts of water. While native plants are numerous and ideal for rain gardens in the Piedmont region of Southeastern United States, many state agencies and professionals accept the use of non-invasive, non-aggressive, non-natives as well (Dunnett & Clayden, 2007; NC Cooperative Extension, 2013; Steiner & Domm, 2012; Woelfle-Erskine & Uncapher, 2012). Native plants are usually better adapted to local climatic conditions, can resist disease/pests and have lower maintenance requirements (Steiner & Domm, 2012). Native plant species can be selected to attract specific species of songbirds, butterflies, caterpillars and hummingbirds.

Plant Height and Spread

Choosing plants with a variety of heights and spreads adds to the functionality and aesthetic value of a rain garden (Scott C. Scarfone, 2007). The variation of height will add to the interconnectedness of a planting scheme by staggering, overlapping and interlocking the plants vertically (Scott C. Scarfone, 2007). Factors that can affect plant height in rain gardens are sunlight, fertility levels and soil moisture. The use of differing zones will also affect height, plants placed in the wettest zones will appear shorter then if planted at ground level (Steiner & Domm, 2012).

Edging and Borders

Another element of rain garden design that should be considered in residential spaces is where the rain garden meets the yard or grass/turf. From a strictly aesthetic standpoint, edging can contribute to the desired form of garden and add a sense of enclosure. The functional structure of edging will limit the maintenance of the rain garden by keeping turf or grass from creeping into the garden, which will need to be removed. A raised edging choice such as brick or stone will also keep grass clippings from entering rain gardens. Residential grass clipping frequently contain high levels of nutrients which are not beneficial to rain gardens (Steiner & Domm, 2012). Inexpensive plastic edging typically does not last and hold up as well as sturdy metal edging or stone. The installation of durable edging can reduce maintenance cost and needs.

Piedmont Region Planting Lists

Choosing plants for rain gardens requires selecting species that contain specific characteristics based on soil moisture conditions. Plants shown the following tables (Table 5-1, Table 5-2, Table 5-3, Table 5-4) are all native to the Southeastern United States Piedmont and readily available in local nurseries. The plants are categorized by their flooding tolerance and drought tolerance. The zone classification is rated ‘1’, ‘2’ and ‘3’ and organized from driest to wettest. The plant lists below do not feature any cultivars, only straight species of plants. The plants shown below are not the only ones capable of growing in rain garden conditions but are recommended (Dunnett & Clayden, 2007; Hunt, 2001; Kraus & Spafford, 2009; NC Cooperative Extension, 2013; Steiner & Domm, 2012; Woelfle-Erskine & Uncapher, 2012).

Many plant nurseries in the Piedmont region sell some or all of the plants listed below. Theses nurseries include Goodness Grows, Inc., Woodlanders, Rock Spring Farm, Plant Delights Nursery, Inc., Niche Gardens, Nearly Native Nursery, Mellow Marsh Farm, EcoAddendum, Baker Environmental Nursery, Inc. and NorthCreek Nursurires.

Table 5-1. Trees for rain gardens, Piedmont region of the Southeast United States

Botanical Name	Common Name	Size (height)	Zone	Sun Conditions
Acer rubrum	Red Maple	40-70'	2	Full Sun to Part Shade
Aesculus flava	Yellow Buckeye	50-75'	2	Full Sun to Part Shade
Aesculus pavia	Red Buckeye	12-15'	2	Full Sun to Part Shade
Amelanchier canadensis	Serviceberry	25-30'	2	Full Sun to Part Shade
Betula nigra	River Birch	40-70'	1,3	Full Sun to Part Shade
Carpinus caroliniana	Ironwood	20-35'	1, 3	Part Shade to Full Shade
Celtis occidentalis	Hackberry	40-60'	2,3	Full Sun to Part Shade
Cercis canadensis	Redbud	20-30'	1, 2	Full Sun to Part Shade
Chionanthus virginicus	Fringe Tree	12-20'	2	Full Sun to Part Shade
Cladrastis kentukea	Kentucky Yellowwood	30-50'	2	Full Sun
Crataegus phaenopyrum	Washington Hawthorn	25-30'	3	Full Sun
Fraxinux pennsylvanica	Green Ash	50-70	3	Full Sun
Ilex decidua	Possumhaw	7-15'	1, 3	Full Sun to Part Shade
Ilex opaca	American Holly	15-30'	1, 2	Full Sun to Part Shade
Juniperus virginiana	Red Cedar	30-65'	1, 2	Full Sun
Magnolia grandiflora	Southern Magnolia	60-80'	1, 2	Full Sun to Part Shade
Magnolia virginiana	Sweetbay Magnolia	10-35'	2,3	Full Sun to Part Shade
Nyssa sylvatica	Black Gum	50-80'	2,3	Full Sun to Part Shade
Quercus bicolor	Swamp White Oak	50-60'	2,3	Full Sun
Quercus laurifolia	Swamp Laurel Oak	40-60'	3	Full Sun
Quercus nuttalii	Nutall Oak	50-80'	1, 2	Full Sun
Quercus phellos	Wilow Oak	40-75'	1,2	Full Sun
Robinia pseudoacacia	Black Locust	20-50'	1,2	Full Sun
Taxodium distichum	Bald Cypress	50-70'	3	Full Sun

Table 5-2. Shrubs for rain gardens, Piedmont region of the Southeast United States

Botanical Name	**Common Name**	**Size (height)**	**Zone**	**Sun Conditions**
Aronia arbutifolia	Chokeberry	6-10'	1, 3	Full Sun to Part Shade
Aronia melanocarpa	Black Chokeberry	2-3'	1, 2	Full Sun to Part Shade
Callicarpa americana	Beautyberry	3-6'	2	Full Sun to Part Shade
Calycanthus floridus	Sweet Shrub	6-10'	2	Full Sun to Part Shade
Cephalanthus occidentalis	Buttonbush	5-12'	3	Full Sun to Part Shade
Clethra alnifolia	Pepperbush	3-8'	2	Full Sun to Part Shade
Euonymus americanus	Strawberry Bush	2-3'	2	Part Shade to Full Shade
Hamamelis virginiana	Witchhazel	15-20'	2	Full Sun to Part Shade
Hydrangea quercifolia	Oakleaf Hydrangea	6-8'	2	Full Sun to Part Shade
Ilex glabra	Inkberry	5-8'	2	Full Sun
Ilex verticillata	Winterberry	3-12'	3	Full Sun to Part Shade
Itea virginica	Virginia Willow	3-5'	3	Full Sun to Part Shade
Lindera benzoin	Spicebush	6-12'	2	Full Sun to Part Shade
Myrica cerifera	Wax Myrtle	6-12'	1, 2	Full Sun
Vaccinium corymbosum	Highbush Blueberry	6-12'	1, 2	Full Sun to Part Shade
Viburnum dentatum	Arrowwood	6-10'	1, 2	Full Sun to Part Shade
Viburnum nudum	Possumhaw	5-12'	3	Full Sun

Table 5-3. Grasses for rain gardens, Piedmont region of the Southeast United States

Botanical Name	**Common Name**	**Size (height)**	**Zone**	**Sun Conditions**
Andropogon gerardii	Big Bluestem	4-6'	2,3	Full Sun
Carex crinita	Fringed Sedge	1-3'	3	Full Sun to Part Shade
Carex lurida	Lurid Sedge	1-3'	3	Full Sun to Part Shade
Chasmanthium latifolium	River Oats	3-4'	1, 3	Full Sun to Part Shade
Equisetum hyemale	Horsetail	2-4'	3	Full Sun to Part Shade
Helictotrichon sempervirens	Blue Oat Grass	2-3'	1	Full Sun
Juncus effusus	Common Rush	2-4'	2	Full Sun
Muhlenbergia capillaris	Muhly Grass	2-3'	1, 2	Full Sun to Part Shade
Panicum virgatum	Panic Grass	3-6'	1, 3	Full Sun to Part Shade
Rhynchospora latifolia	White-topped Sedge	1-2'	3	Full Sun to Part Shade
Schizachyrium scoparium	Little Bluestem	2-4'	1,2	Full Sun
Scirpus cyperinus	Woolgrass	4-5'	3	Full Sun to Part Shade
Sorghastrum nutans	Indiangrass	3-5'	1, 2	Full Sun
Sporobolus heterolepis	Prarie Dropseed	2-3'	1	Full Sun

Table 5-4. Perennials for rain gardens, Piedmont region of the Southeast United States

Botanical Name	**Common Name**	**Size (height)**	**Zone**	**Sun Conditions**
Actaea racemosa	Black Cohosh	4-6'	1, 2	Part Shade to Full Shade
Adiantum pedatum	Maidenhair Fern	1-2'	2	Part Shade to Full Shade
Allium cernuum	Nodding Wild Onion	1-2'	1	Full Sun to Part Shade
Amsonia tabernaemontana	Blue Star	2-3'	3	Full Sun to Part Shade
Aquilegia canadensis	Canada Columbine	2-3'	1, 2	Full Sun to Part Shade
Aruncus dioicus	Goat's Beard	4-6'	2	Full Sun to Part Shade
Asarum canadense	Wild Ginger	1/2-1'	1	Part Shade to Full Shade
Asclepias incarnata	Swamp Milkweed	4-5'	3	Full Sun
Asclepias tuberosa	Butterflyweed	1-3'	1	Full Sun
Aster carolinianus	Climbing Aster	2-5'	3	Full Sun to Part Sun
Athyrium filix-femina	Lady Fern	1-3'	2	Part Shade to Full Shade
Baptisia australis	fasle blue indigo	3-4'	1, 2	Full Sun to Part Shade
Boltonia asteroides	Boltonia	5-6'	3	Full Sun
Chelone glabra	Turtlehead	2-3'	3	Part Shade
Chrysogonum virginianum	Green and Gold	1/2-1'	2	Part Shade to Full Shade
Coreopsis auriculata	Mouse Ear Coreopsis	1-2'	2	Full Sun
Coreopsis lanceolata	Tickseed	1-2'	1, 2	Full Sun
Coreopsis rosea	Swamp Coreopsis	1-2'	2	Full Sun
Coreopsis verticillata	Threadleaf Tickseed	1-2'	1, 2	Full Sun
Echinacea purpurea	Purple Coneflower	2-5'	2	Full Sun to Part Shade
Eupatorium dubium	Joe Pye Weed	3-4'	3	Full Sun to Part Shade
Helianthus angustifolius	Swamp Sunflower	6-8'	3	Full Sun
Heliopsis helianthoides	Oxeye	3-6'	2, 3	Full Sun
Hibiscus coccineus	Texas Star	3-6'	3	Full Sun to Part Shade
Hibiscus moscheutos	Swamp Mallow	4-6'	3	Full Sun
Iris versicolor	Northern Blue Flag	2-3'	3	Full Sun to Part Shade
Iris virginica	Blue Flag Iris	1-3'	3	Full Sun
Liatris spicata	Dense Blazing Star	2-4'	2, 3	Full Sun to Part Shade
Lobelia cardinalis	Cardinal Flower	2-4'	3	Full Sun to Part Shade
Matteuccia struthiopteris	Ostrich Fern	3-6'	2, 3	Part Shade to Full Shade
Mertensia virginica	Virginia Bluebells	1-2'	1, 2	Part Shade to Full Shade
Monarda didyma	Bee Balm	2-4'	2, 3	Full Sun to Part Shade
Osmunda cinnamomea	Cinnamon Fern	2-3'	3	Part Shade to Full Shade
Osmunda regalis	Royal Fern	2-3'	3	Part Shade to Full Shade
Penstemon digitalis	Foxglove Beardtongue	3-5'	1, 2	Full Sun to Part Shade
Phlox paniculata	Garden Phlox	2-4'	2	Full Sun to Part Shade
Phlox subulata	Moss Pinks	1/4-1/2'	1,2	Full Sun
Physostegia virginiana	Obedient Plant	3-4'	2, 3	Full Sun
Polemonium reptans	Jacob's Ladder	1-2'	1	Full Sun to Part Shade
Polygonatum biflorum	Solomon's Seal	1-3'	2	Part Shade to Full Shade
Rudbeckia fulgida	Rudbeckia	2-3'	1,2	Full Sun
Rudbeckia laciniata	Green Headed Coneflower	2-9'	3	Full Sun to Part Shade
Rudbeckia pinnata	Gray-Headed Coneflower	3-5'	2	Full Sun
Silphium perfoliatum	Cup Plant	4-8'	2, 3	Full Sun
Solidago rugosa	Goldenrod	1-3'	3	Full Sun
Symphyotrichum novae-angliae	New England Aster	3-6'	2, 3	Full Sun
Tiarella cordifolia	Foamflower	1/2-1'	1	Part Shade to Full Shade
Tradescantia ohiensis	Spiderwort	2-3'	1, 2, 3	Full Sun to Part Shade
Vernonia noveboracensis	Ironweed	4-6'	3	Full Sun
Veronicastrum virginicum	Culver's Root	3-6'	3	Full Sun to Part Shade
Zizia aurea	Golden Alexanders	4-8'	1, 2	Full Sun to Part Shade

CHAPTER SIX

CONCLUSION

This thesis explored the possibilities and limitations of installing phytoremedic residential rain gardens in the Piedmont region of the South Eastern United States as a beneficial tool for homeowners to improve water quality. The thesis research was conducted in four particular areas: development of storm water control measures; rain garden design; phytoremediation; aesthetic purposes; and plant value. An experimental plant trial was then conducted using the research obtained to further study rain garden plants species shown in Appendix A.

The development of storm water control measures in the United States highlighted prominent events in the history of the United States that lead to the creation of rain gardens. As new bills and laws are passed, the future of rain gardens will change undoubtedly. The significant shift in legislation discussed in Chapter two, from the early nineteen seventies to present, indicates a progression in storm water control measures. Rain gardens were just one product of this change and as more municipalities and governments accept new measures rain gardens may become more prevalent. This innovation in storm water control management indicates a trend toward less disruption of the natural environment through low-impact development techniques.

The design of rain gardens investigated in in Chapter Three examined the functionality of managing non-point source pollution on residential properties. The methods of storm water quality and quantity control studied can be used to lessen the runoff problems associated with residential development. The design guidelines examined in Chapter Three can be used in the installation of residential rain gardens in the Piedmont region. These design and construction recommendations also provide a resource for residential tenets or homeowners to explore and encourage the implementation of rain gardens and to improve storm water control at the source.

The topics investigated in Chapter Four provided the main components of phytoremediation in the residential landscape. The target pollutants identified offer an overview of the harmful constituents that are found on residential areas. The different studies conducted on the pollutant removal capabilities of rain gardens indicate that they are effective and worthy of installation. The various specific plant species identified at the end of the chapter explored the possibilities of creating a residential garden with plants that are both attractive and phytoremedic. The sunflower (*Helianthus annuus*) was a specific plant of interest. A study concluded that *Helianthus annuus* has the capability to accumulate significant levels of lead for phytoremediation purposes, while offering strong aesthetic possibilities, producing large attractive leaves and striking flowers.

The aesthetic value of rain gardens and the plants placed with them is a subjective topic, but one of potential economic as well as practical application. Chapter Five examined rain garden design basics, unique planting zones, year round interest, sun exposure, native plant usage, height and spread, edging and borders and regional Piedmont plant lists. The majority of plants recommended for Piedmont rain garden design were native species. While native plants dominated the lists, many scholarly sources support the use of non-native, non-aggressive, non-invasive plants. The significance of this bolsters phytoremediation in residential landscapes as many plants studied for their phytoremedic properties are not native species. The analysis of perennial plants recommended for rain garden design provided the inspiration for the experimental plant trial design performed for this thesis.

The experimental plant trial design that is found in Appendix A was based on residential rain garden design guidelines and has generated some relevant inquiries. All cultivars in the trial are associated with a species that is suggested for rain garden design in the Piedmont region. The four plants selected for this experiment (*Boltonia asteroides 'Pink Beauty', Coreopsis pubescens 'Sunshine Superman', Solidago sphacelata 'Golden Fleece'* and *Symphyotrichum novae-angliae 'Purple Dome')* are all associated with minimal or no research relating to rain gardens. They were not selected for their phytoremedic potential but rather their aesthetic and functional qualities. While final results and conclusions of this plant trial not complete initial results indicate that*, Solidago sphacelata 'Golden Fleece'* and *Boltonia asteroides 'Pink Beauty'* are exhibiting the highest rate of die off than any other species in the trial.

The research presented in this thesis indicates that the concept of creating residential rain gardens in the Piedmont region of the United States is gaining momentum as many local municipalities accept the practices of low-impact development (Hoffner, 2013). As rain gardens have become more prevalent in residential landscapes, the plants required have also become more accessible and available to homeowners. While many plant species recommended for rain garden design have not been studied for phytoremedic properties, specific plants species have been studied. The acceptance and use of these species, some of which are listed in Chapter Four, is uncertain. Based on the research of this thesis, more plants are being studied for phytoremedic possibilities each year (*Helianthus annuus* and *Ricinus communis* in 2012). Ultimately the homeowner selects plants to install but research hints toward a trend of interest in phytoremedic residential rain gardens in the Piedmont region.

The investigation of the possibilities and limitations of phytoremedic rain gardens in the Piedmont region of the Southeastern United States have yielded multiple results. The possibilities grow as cities mandate rain garden installation and new phytoremedic research is conducted on specific plants. The limitations include availability of plants material, acceptability of rain garden use, homeowners' preferences and acceptance in the landscape architecture profession.

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APPENDICES

APPENDIX A: THE POTENTIAL USE OF FOUR PLANT SPECIES IN RAIN GARDEN INSTALLATIONS

THE POTENTIAL USE OF FOUR PLANT SPECIES IN RAIN GARDEN INSTALLATIONS

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ABSTRACT

Only limited research and in-depth analysis is available on the types of plant species commonly used in rain garden design in the Piedmont region of the United States. Many online publications and books offer recommended planting suggestions, but often lack performance data for individual species, especially cultivars. This study was conducted to provide a detailed analysis of four plant species and their potential performance in rain gardens based on levels of storm water inundation. The study examines four plant species: *Boltonia asteroides 'Pink*

Beauty', Coreopsis pubescens 'Sunshine Superman', Solidago sphacelata 'Golden Fleece' and *Symphyotrichum novae-angliae 'Purple Dome'*. These plant species were installed on a slope of a dry detention pond, in Athens, Georgia, that received regular storm water runoff. The plants were installed in a randomized block layout and each block monitored with soil moisture sensors. The results will correlate individual plant survivability to the volumetric water content of the soil. The recorded information will provide insight into the possibilities and limitations of using these four plants in Piedmont regional rain garden designs. This study is ongoing and data recording is set to conclude in August of 2013.

Keywords**:** Bioretention, Piedmont, Residential Rain Garden, Phytoremediation, Soil Moisture, Phytoremedic

INTRODUCTION

In an effort to expand the realm of rain garden plant material, gardeners, nurseries and academics offer recommendations of new species suited for installation. In some cases species that are recommended for rain gardens are selected based on only a few criteria and not trialed or closely studied in rain garden habitat. This study delves into four species of plants not commonly used in rain garden design and not adequately analyzed. Specifically, this study looks at four cultivated varieties or cultivars. A cultivar is a plant containing one or more traits that distinguish it from the straight species. Cultivars do not occur naturally and are maintained through cultivation (Steiner & Domm, 2012). However, publications that offer rain garden plant material suggestions promote the use of native plants. Using native plants offers a plethora of benefits that include, supporting wildlife, reducing the amount of invasive plants installed, beautiful foliage and flowers, promoting biodiversity and low maintenance costs (Dunnett & Clayden, 2007; Steiner & Domm, 2012; Woelfle-Erskine & Uncapher, 2012). The four plant species selected for this experiment are all native cultivars to the Piedmont region of the Southeast United States. The plants were trialed and studied at a dry detention pond, in Athens, Georgia, adjacent to the University of Georgia's Greenhouse facility/UGArden site. The species were installed at four different elevations in the dry detention pond and monitored with soil moisture sensors, which record soil volumetric water content. The research output hopes to produce a correlation between individual plant species survivability and soil moisture levels. This study will contribute to identifying plant species suited for rain gardens, which receive irregular inundations of storm water and periods of drought. Plants perform optimally in different saturation zones of rain gardens and this study will aid determining the proper installation zone. These plant species are all suited for residential rain garden applications based on their non-toxic/non-invasive nature, handsome foliage and attractive showy flowering habit.

MATERIALS AND METHODS

Study Area

The plant trial location is an existing dry detention pond located at the UGA Greenhouse Complex, on South Milledge Avenue, Athens, Georgia (Figure 6-1.). Designed in 2007, the existing dry detention pond was intended to capture the runoff from the surrounding greenhouses and adjacent area. The installing contractor originally left the pond barren, without any plant material. Since constrition the pond has transformed into a space that has received only periodic maintenance attention with marginal efforts to enhance the ponds interior. The trial area is next to the UGArden, an outdoor classroom where local fruits and vegetables are cultivated. Based on the observations of University of Georgia Greenhouse staff and UGArden faculty the dry detention pond is typically in a state of dry soil to moderately moist soil. It has never been observed to reach full capacity and large quantities of standing water is an infrequent occurrence in the pond. The pond has three methods of harvesting water. The first is from an 18" pipe on the east side of pond that collects water from the area surrounding the greenhouses via storm grates. The second method is from a 6" pipe on the west side of the pond that receives water from the interior of the greenhouse. The third method of water gathering is rainfall. The confluence is a dry detention pond that collects a variety of excess nutrients, pollutants and heavy metals comparable to a rain garden. The dry detention pond is larger in size than a typical residential rain garden yet provides other features that make the site worthy as a plant trial area. The pond was designed on its north side with a three-to-one sloped embankment. This sloped hill provides an example of grading common in rain garden design and an opportunity to install plants at different elevation points, which feature different soil moisture conditions. In addition to the preferred slope, the same area of the dry detention pond has a southerly orientation, making it ideal for plant species that require full sun. Full sun rain garden applications are common in residential landscape design and use plants that require full sun exposure.

Since construction of the pond, several species of plants have been introduced to the area. Numerous plants have 'volunteered' through anemochory (wind dispersal) and endozoochory (seed dispersal via animals). The two dominant species of plants currently in the pond are *Typha latifolia* (common cattail) and *Cyperus involucratus* (umbrella papyrus) (Figure 6-2).

In order to take advantage of this site for an experimental design plant trial, the sloped portion of the site was tilled and cleared of existing plants (Figure 6-3). The dimensions of the area of study were forty feet in length and twelve feet in width. The soil was tilled down to one and a half feet with the aid of a BCS walk-behind tractor/tiller. The tilled soil was then covered with Dewitt Natural Burlap set in place with landscape stakes in order reduce soil erosion (Figure 6-4). The area was allowed to settle for a period of two weeks before soil testing and soil moisture monitoring equipment installation.

Soil Sampling and Analysis

The soil of the trial area was tested to analyze texture, macronutrient and micronutrient content. The samples gathered for testing were taken from four central points in the test plot (Figure 6-5.). The four gathering areas contained samples from each of the four separate blocks and point touches, in order to ensure that each block was included in the analysis (Figure 6-6.). All samples were air dried over night and tested at the University of Georgia's Soil Physics Laboratory.

The texture of the soil was determined by the pipette method, which is a standard technique used to analyze soil texture (Keller & Gee, 2006). The method involves extracting a known volume of a suspension and dispersing solution to measure density of the suspension at a specific depth after the critical particle size fraction has settled to that depth in accordance with Stoke's Law. The procedure used follows:

1. Weigh out two samples of 10g of air-dry sieved (2mm) soil to the nearest 0.01 g in weighed beakers. Mark initials right on the beaker instead of using tape. Place one

sample in the oven at 1050 over night so that we can determine the oven-dry mass of the 10g air-dry sample.

2. Add 10 ml of dispersing agent (38g of sodium metaphosphate and 8g of Na2CO3 per liter) to soil and transfer to a mixer cup with care
3. The TA will determine the mass contribution in the sample due to dispersing agent by making a solution of 10 ml of dispersing agent and 990 ml of water. A 10 ml sample of this solution will be dried in a weighed beaker overnight and to get the mass of dispersing agent in 10 ml.
4. Add water to the soil in the mixer cup to make it about 3/4 full and mix for 15 minutes.
5. Remove the sand by washing the contents of the mixer cup through a three hundred mesh (0.05mm) screen held in place above a wide mouth funnel that empties into a 1000 ml sedimentation cylinder. Add more water to the residue in the mixer cup and pour this through the sieve. Wash the screen with water until the level in the sedimentation cylinder is a little below one thousand ml. Transfer all of the sand on the screen to a weighed beaker and dry this in the oven overnight and weigh to get dry mass of sand. Mark your initials right on the beaker instead of using tape
6. Fill the sedimentation cylinder up to one thousand ml volume by adding water. Mix the contents of the cylinder thoroughly with a mixing rod. Record the time when mixing is completed.
7. Sample by lowering the tip of a ten ml pipette into the suspension to a depth about three cm above the silt and remove ten ml of solution. This should be done slowly so that it takes about twelve seconds to fill the pipette. Carefully withdraw the pipette from suspension and empty the sample into a weighed fifty ml beaker. Immediately refill the

pipette with water and allow this to drain into the beaker to clear it out. Mark your initials right on the beaker instead of using tape. Dry the beaker and suspension in the oven overnight and weigh. Subtract the mass of the dispersing agent obtained in step four. This is then the mass of clay in 10 ml of solution.

8. Calculation of particle size percentages

The results of this process show that the percentage of sand, clay and silt for each of the four soil samples.

Sample 1: 63.4133% sand, 0.2458% clay, 36.3409% silt

Sample 2: 65.6221% sand, 0.3520% clay, 34.0259% silt

Sample3: 64.7572% sand, 0.3687% clay, 34.8741% silt

Sample 4: 58.9183% sand, 0.3668% clay, 40.7148% silt

Based on the sample percentage results and the United States Department of Agriculture particle-size classes for the fine-earth fraction at the family level, all four samples were classified as sandy loam soil (Figure 6-7). The organic matter was not removed from the soil samples prior to testing. It has been shown in recent studies that removing the organic matter when conducting the pipette method will increase the clay content by approximately five percent (E. Gasparotto, 2003). If the clay content of each sample was increased by five percent, the samples would all still remain classified as a sandy loam, thus, the amount of organic matter present in the samples can be assumed to be insignificant.

The nutrient analyze of the soil was conducted based on the previous four samples locations used in the soil texture analysis. The samples were taken by the same method, from the same central four locations, ensuring every block was included. The samples were collected and dried over night. The samples were then submitted to the University of Georgia Soil, Plant and

Water Laboratory at 2400 College Station Road, Athens, GA 30602. The results indicate high levels of macronutrients particularly both phosphorus and potassium (Figure 6-8.). The micronutrients found in the samples were at a moderate level (Figure 6-9). Sample locations one and two indicate higher levels of all nutrients than sample locations three and four.

Goal of Experiment

The goal of this experimental design plant trial is to analyze how the four plant species perform in different soil moisture levels, which are similar to rain garden soil inundation levels. The plants' performance refers to survivability (if the plant survives or dies). The study will investigate four plant species cultivars and if they survive or perish based on volumetric water content conditions of the soil.

Plant Selection Methodology

Plant selection is vital in the experimental design process. In order to be considered for this planting trial, species had to meet specific qualifying criteria. Plant species had to be native to the piedmont region of North America or an indigenous cultivar of the region. In order to create consistency with the plant material, species were selected based on core ecologic characteristics: herbaceous perennial growth duration, forb growth habit and native Piedmont status. Species were also selected by morphological and physiological factors including: active growing season, growth form, growth rate, showy characteristics and flowering habit. The next category of criteria for selection was based on growth requirements including: drought tolerance, soil texture adaptations, hardiness range and shade/sun tolerance.

The final selection requirement was commercial and retail availability in the nursery trade. Appropriate characteristics were searched for and filtered on the USDA's plants website (plants.usda.gov). Professionals and faculty members of the University Georgia College of Environment and Design, University of Georgia Department of Horticulture and the State Botanical Garden of Georgia further vetted results. Additionally, several prominent nurseries that supply the Piedmont region, were consulted as to regular plant availability. Many plant species met the qualifications for this plant trial but the species selected were the ones with the least amount of associated research or study. The following are the selection plant species submitted to trial.

Plant Species

Boltonia asteroides 'Pink Beauty'- false aster

Boltonia asteroides, a native to the Piedmont of North America, is a member of the Asteraceae family and has a reputation to be easy to cultivate. The plant flowers in late summer into fall and produces vast amounts of daisy-like white or purple flowers. The leaves are alternate, lanced-shaped and sessile (A. M. Armitage, 1997). *Boltonia asteroides* can reach heights of five to six feet and have a spread of about four feet. Many gardeners do not use this species in formal gardens due to its tall and lanky habit. The foliage of the plant is grayish-green and the flowers are typically three-quarters of an inch to one inch wide (Still, 1994). The plant prefers full sun and tolerates a variety of soil conditions, including moderately dry. The hardiness range of this plant is USDA zones four to eight (*USDA plant hardiness zone map [electronic resource] / mapping by Prism Climate Group, Oregon State University*, 2012). The cultivar being trialed in this experiment is *Boltonia asteroides 'Pink Beauty'*. This cultivar was discovered in North Carolina by plantsman, Edith Edelman, and has been offered under multiple names including *Boltona rosea* (A. M. Armitage, 1997). Notable features of *Boltonia asteroides 'Pink Beauty'* are its compact form of three to four feet in height and pale pink flowers.

Coreopsis pubescens 'Sunshine Superman'- star tickseed

Coreopsis pubescens is native herbaceous perennial to the Piedmont of North America. *Coreopsis pubescens* is a member of the Asteraceae family and is sometimes referred to as star tickseed or downy coreopsis. The leaves are cauline, entire, ternately or rarely pinnately dissected (Radford, Ahles, & Bell, 1968). It has an average height of twelve to eighteen inches and a spread of the same dimensions. The yellow flowers, which feature rays broadening upwardly from the base; bloom in late spring to late summer (Godfrey & Wooten, 1979). The species is commonly found in open or wooded banks of streams, stream beds, alluvial thickets, meadows, open woodlands and cliffs (Godfrey & Wooten, 1979). The hardiness range of *Coreopsis pubescens* is from USDA zones six to nine. *Coreopsis pubescens* grows successfully in natural low depressions that act as rain catchment areas in the North Carolina piedmont region (Nash, 2013). The cultivar being trialed here is *Coreopsis pubescens 'Sunshine Superman'*. This cultivated variety was introduced by North Creek Nurseries, in Pennsylvania. *Coreopsis pubescens 'Sunshine Superman'* is a compact plant with a height of ten to twelve inches. The flowers are yellow and are approximately two inches in diameter with yellow rays and orange disk centers. The overall growth habit of the plant is mounding.

Solidago sphacelata 'Golden Fleece'- goldenrod

Solidago sphacelata is a perennial and member of the Asteraceae family. The specific cultivar being used in this trial is Solidago sphacelata 'Golden Fleece'. This cultivar was introduced by Dick Lighty, of the Mount Cuba Center of Piedmont Flora in Greenville, Delaware (A. M. Armitage, 1997). Unlike many Solidago species this cultivar grows less then eighteen inches tall and has a spread of the same dimension. This compact cultivar has a spreading habit and alternate leaves that are linear-lanceolate to elliptic-lanceolate (Still, 1994). The plant flowers in mid-summer to late fall and produces bright yellow flowers borne in dense plume-like panicles. When not in flower, the foliage form, is low-growing and dark green creating the appearance of groundcover. This cultivar is hardy in USDA zones four to eight and can tolerate a variety of soil conditions.

Symphyotrichum novae-angliae 'Purple Dome'- New England aster

Formerly known as *Aster novae-angliae, Symphyotrichum novae-angliae* is a North American native perennial forb in the Asteraceae family. It can found in USDA hardiness zones four to eight and has alternate leaves with broad clasping bases and pointed tips. This species is a common wild flower but is rarely seen in retail nurseries, do to an wide variety of improved cultivars (A. M. Armitage, 1997). The cultivar being trialed is *Symphyotrichum novae-angliae* 'Purple Dome'. *Symphyotrichum novae-angliae* 'Purple Dome' is an introduction from the Mount Cuba Center of Piedmont Flora in Greenville, Delaware and typically grows to eighteen to twenty-four inches (A. M. Armitage, 1997). ‘Purple Dome’ maintains a mounding habit, grows thirty-six inches wide and produces a large number of semi-double one and a half inch wide deep blue flowers (Still, 1994). The plants season of bloom in the Piedmont is late summer to fall.

Experiment Layout

The study/planting area of the dry detention pond is set on a slope with a three-to-one ratio. The amount of elevation change from the bottom of the study area to the stop of the study area is three feet. In order to study the plants at different volumetric water content levels, four different elevations where surveyed and marked on the slope. The first elevation level was at the base of the pond and set at 0.0 feet; the second elevation level was set at 0.75 feet; the third elevation was set at 1.5 feet; and the final elevation was set at 2.25 feet. These sets of elevations along the slope were used for planting locations. The elevations were surrounded by a group of sixteen blocks as seen in previously in Figure 6-5. In order to create a valid experimental layout and design the University of Georgia, Department of Statistics created a randomized block layout planting plan to study the plants at different points of elevation in the dry detention pond. For each individual block in the experimental design, four plants were installed within each space, one of each species. The University of Georgia Department of Statistics created a randomized planting plan with the aid of a statistical randomizer. The result was a planting plan for each block that followed a randomized order (Figure 6-10.).

Monitoring Equipment and Installation

To adequately monitor the soil at the same elevation of the plants installation required the use of soil moisture sensors. Sensors were placed at the same elevation of the plants listed previously (Figure 6-11). A total of thirty-two sensors were installed, two sensors per each experimental block. The sensors measure the amount of water within the soil at the same elevation of the plants in each block. The sensors used in this study were Decagon Devices, 10HS Soil Moistures Sensors (Figure 6-12.). The sensors can measure volumetric water content by determining the dielectric constant of soil using capacitance/frequency domain technology. Each sensor was two-pronged device with the dimensions of 14.5cm by 3.3cm by 0.7 cm. The sensor itself was affixed to a five meter long cord with a 3.5mm stereo plug at the end. For the purposes of this experiment, each sensor was installed at six inches below the surface of the soil, the tip of the soil sensor is located six inches below the soil. The soil sensors were then connected to a Campbell Scientific AM25T Solid State Thermocouple Multiplexer. This multiplexer was the hub that connects to each individual soil moisture sensor. The multiplexer was then connected to a Campbell Scientific CR23X Micrologger®. This data logger is capable of recording the soil moisture measurements from each sensor. A specific software program allowed the data logger to record the soil moisture levels as frequently or infrequently as desired. In this experiment the data logger recorded each individual sensor reading every two hours. All of the monitoring equipment was powered by a marine style deep cranking battery and a UNI-SOLAR®, Solar Electric Module.

Plant Installation

All plant material for this experiment was ordered through NorthCreek Nurseries. The plants installed in the experiment were all in plug form, sized at two inches by two inches by two and a half inches. The plants were all installed on March 15th, 2013 (Figure 6-13.). Installed at the same depth of two and a half inches, the tops of each plug was even with the top of the soil. Once installed, the plants were all topped and surrounded by a two inches layer of cypress mulch. They were watered everyday for two weeks to ensure establishment with recycled rainwater.

RESULTS AND DISCUSSION

This experiment is currently underway and is expected to continue until August of 2013.

CONCLUSIONS

After one month of installment all plants are alive and recorded statistics are being cataloged in a tabular format.

ACKNOWLEDGEMENTS

This study could not have been made possible without the involvement of many individuals and thanks should graciously be given to all of them. Professor David Berle, of the UGA Department of Horticulture, Dr. Kimberley Love-Meyers of the UGA Department of Statistics, Dr. Mark van Iersel of the UGA Department of Horticulture, Sue Dove of the UGA College of Agricultural & Environmental Sciences, Katie Shepard of the UGA Department of Horticulture, Dr. James Affolter of the State Botanical Garden of Georgia, and Dr. Jon Calabria of the UGA College of Environment and Design.

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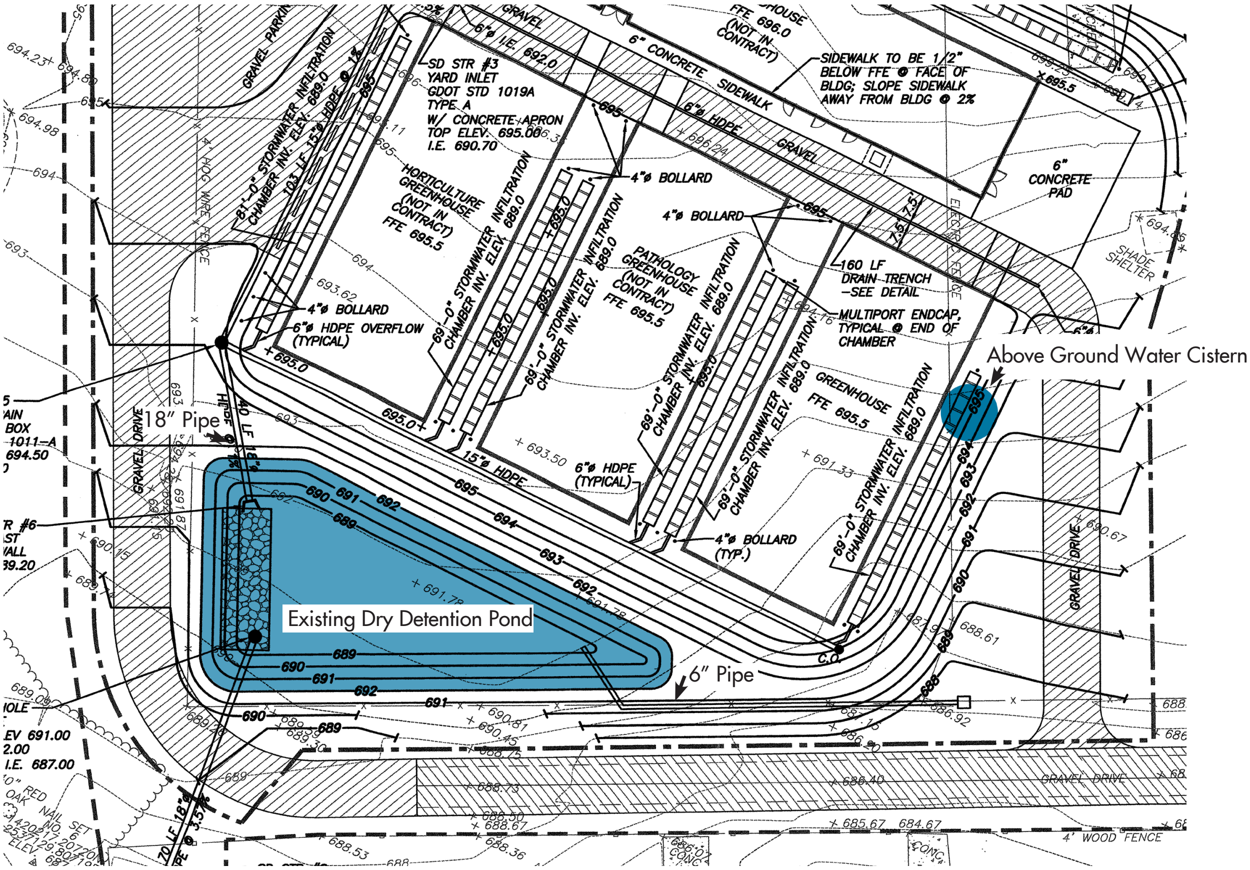

Figure 1-1. The location of dry detention pond at the UGA Greenhouse Facility.

Figure 1-2. Existing conditions in the summer of 2012. (photo credit: Jonathan Korman)

Figure 1-3. The sloped portion of the site tilled and cleared. (photo credit: Jonathan Korman)

Figure 1-4. The tilled soil covered with Dewitt Natural Burlap set in place with landscape stakes. (photo credit: Jonathan Korman)

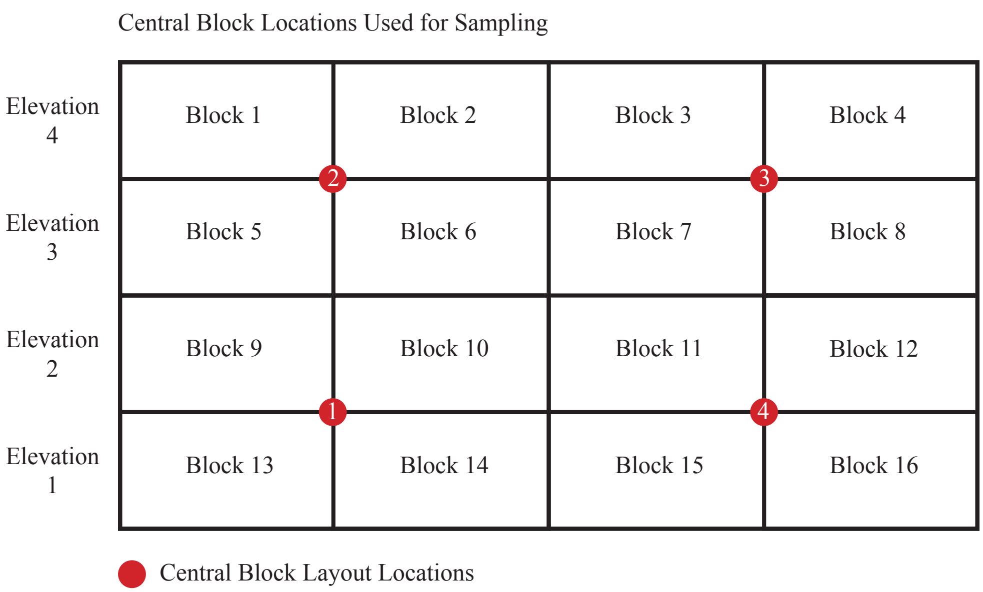

Figure 1-5. Central block locations used for soil sampling

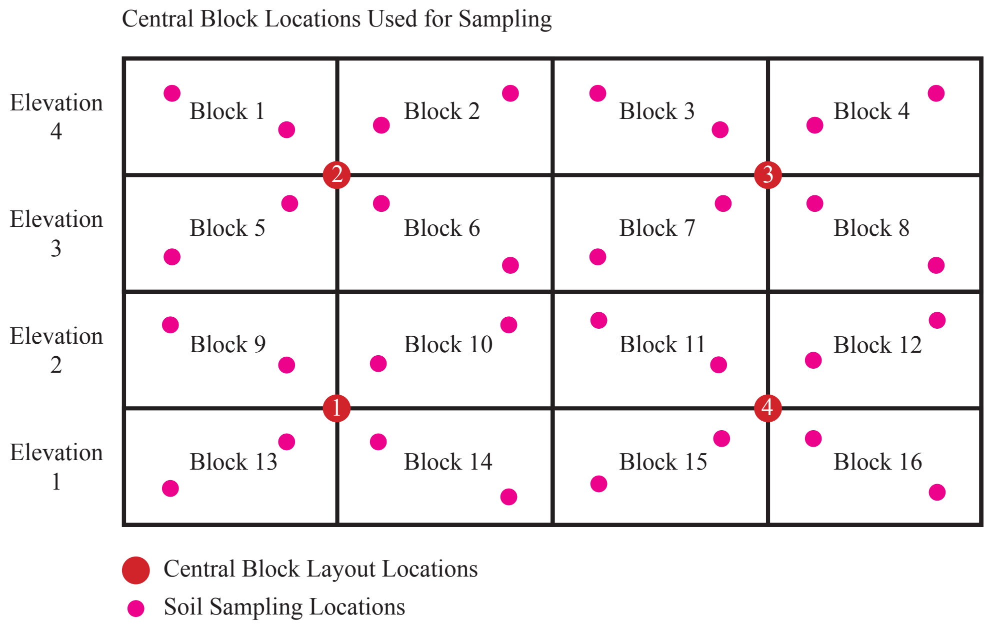

Figure 1-6. Soil sampling locations based on the central block locations. Every block touching a central point was included in that central point sample.

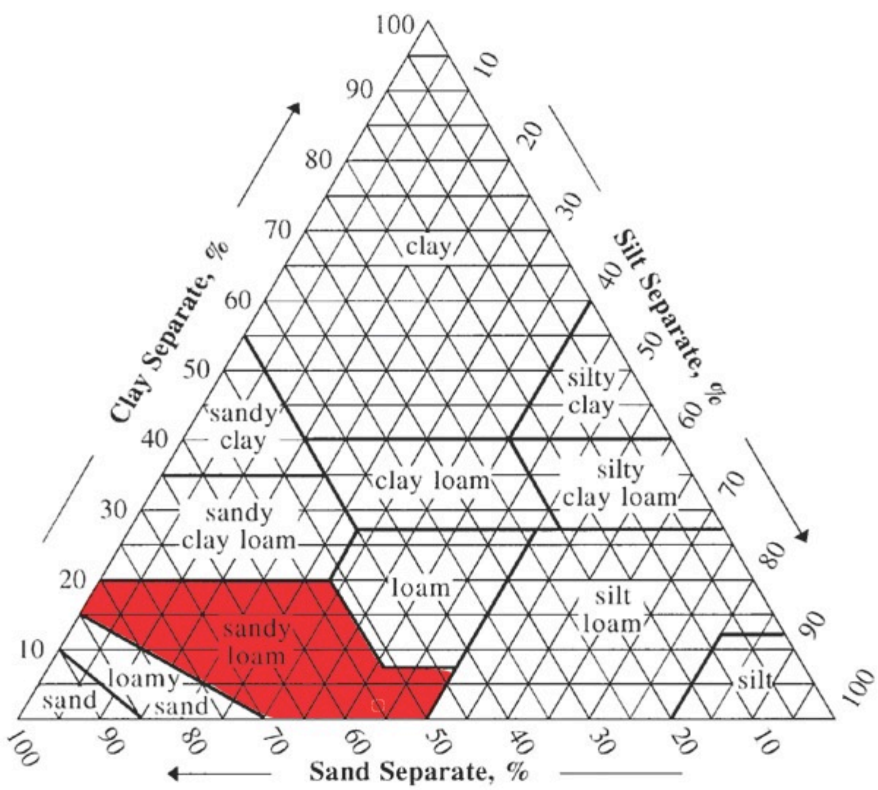

Figure 1-7. The US Department of Agriculture soil texture triangle indicates that each soil sample is classified as a sandy loam. (Source: soil.usda.gov)

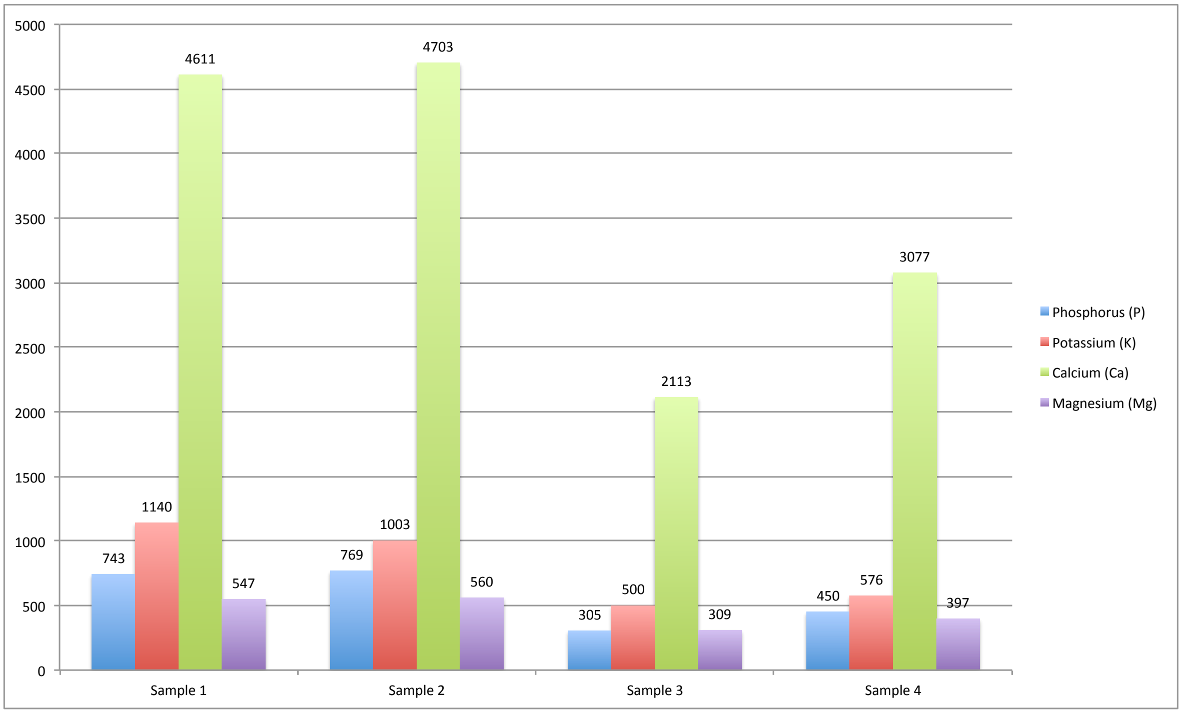

Figure 1-8. Macronutrient analysis from the (4) soil samples. Macronutrient levels are shown in pounds per acre. Samples were analyzed with the Mehlich I Extractant method.

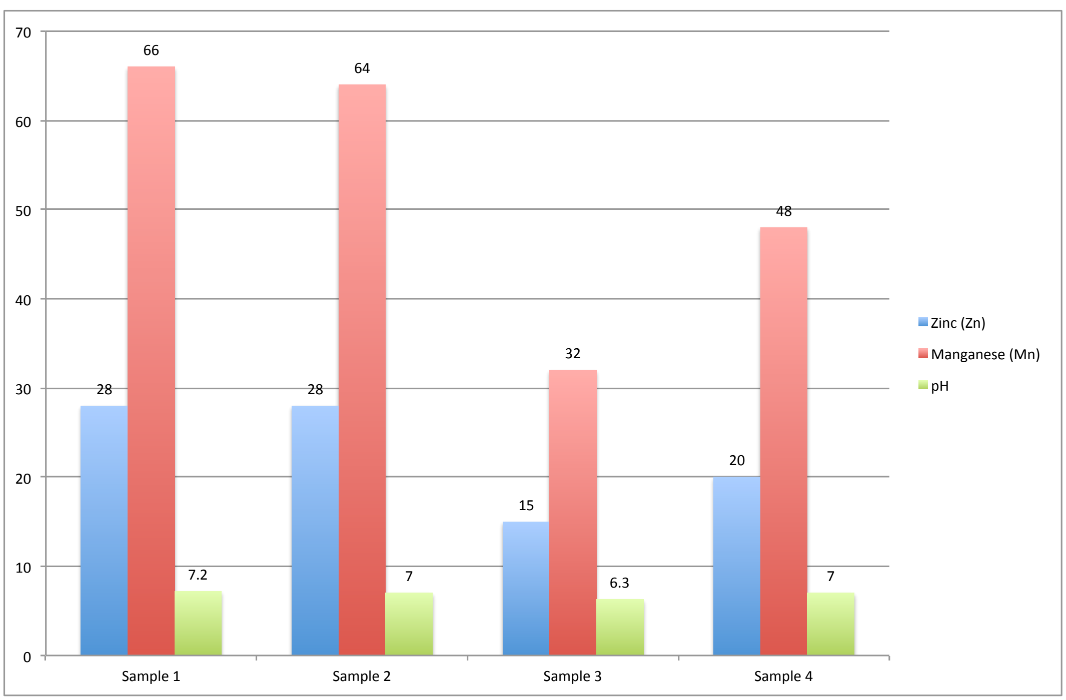

Figure 1-9. Micronutrient levels and pH from the (4) samples. Micronutrient levels are shown in pounds per acre.

Elevation 4	ABDC	BACD	CBDA	DACB
Elevation 3	DABC	ABDC	DABC	BDCA
Elevation 2	BCDA	ADBC	CBAD	DCAB
Elevation 1	DBCA	BCAD	BDAC	ADBC

A- Boltonia asteroides ‘Pink Beauty’

B- Coreopsis pubescens ‘Sunshine Superman’

C- Solidago sphacelata ‘Golden Fleece’

D- Symphyotrichum novae-angliae ‘Purple Dome’

Figure 1-10. The randomized planting design created by the University of Georgia, Department of Statistics. Each block is planted with one of each plant species in a randomized manner.

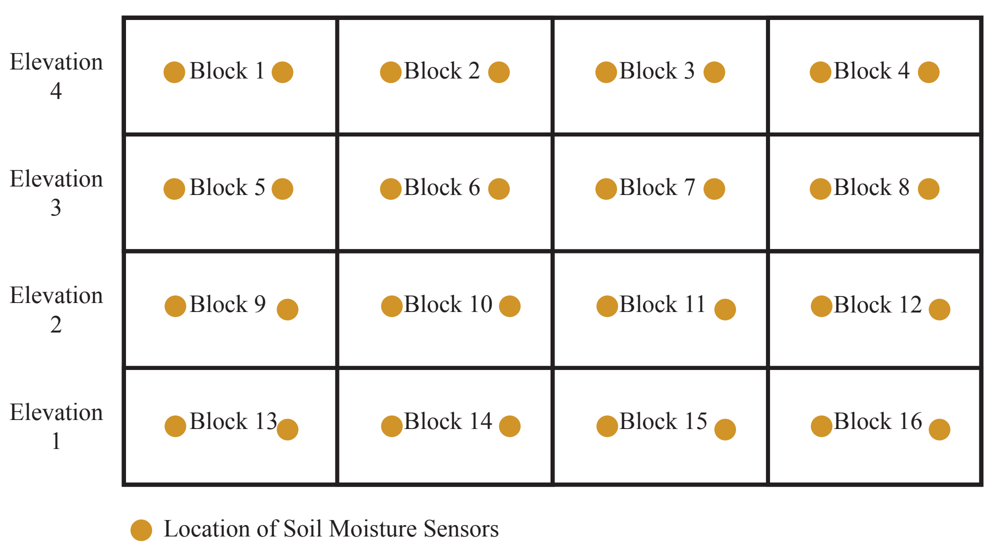

Figure 1-11. Soil moisture sensors were installed at the same elevation of the plants

Figure 1-12. Decagon Device 10HS soil moisture sensor. A total of thirty-two sensors were used in the experiment.

Figure 1-13. The plants installed on March 15th, 2013 (photo credit: Jonathan Korman)