In cooperation with the City of Madison and Wisconsin Department of Natural Resources


By William R. Selbig and Nicholas Balster
Scientific Investigations Report 2009-XXXX

U.S. Department of the Interior
U.S. Geological Survey

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### Conversion Factors and Abbreviations

#### Inch/Pound to SI

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#### SI to Inch/Pound

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Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8×°C) + 32

Horizontal coordinate information is referenced to the 1991 adjustment of the North American Datum of 1983 (NAD 83/91).

Water year in USGS reports is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends.

By William R. Selbig1 and Nicholas Balster2

Abstract

The U.S. Geological Survey, in cooperation with a consortium of nineteen cities, towns, and villages in Dane County, Wisconsin, undertook a study to compare rain gardens with different vegetative species and soil types at infiltrating stormwater runoff from the roof of an adjacent structure. Two rain gardens, one planted with turf grass and the other with native prairie species, were constructed side-by-side in 2003 at two locations of dominant soil type, sand or clay. Each rain garden was sized to a ratio of approximately 5:1 contributing to receiving area and a depth of 0.5 ft.

Each rain garden, regardless of vegetation or soil type, was capable of storing and infiltrating the majority of runoff over the 5-year study period. Both rain gardens in sand as well as the prairie rain garden in clay retained and infiltrated 100 percent of all precipitation and snowmelt

1 U.S. Geological Survey, Middleton, Wisconsin
2 University of Wisconsin, Madison, Wisconsin
events for water years 2004 – 2007. The turf rain garden in clay occasionally had runoff exceed its confining boundaries but was still able to retain 96 percent of all precipitation and snowmelt events over the same time period. Precipitation intensity and antecedent dry days were important variables influencing when the storage capacity of underlying soils would become saturated resulting in pooled water in the rain gardens.

Because the rooftop area draining runoff to each rain garden was approximately 5 times larger than the area of the rain garden itself, evapotranspiration was a small percentage of the annual water budget ranging from a maximum in water year 2005 of 19 to 25 percent of total influent volume for the prairie- and turf-sand rain gardens and 12 to 21 percent for the prairie- and turf-clay rain gardens, respectively. With little to no runoff leaving each rain garden as effluent and a small percentage of runoff returning to the atmosphere through evapotranspiration, the remainder was considered recharge. In water year 2005, recharge was 81 to 75 percent of total influent volume for the prairie- and turf-sand rain gardens and 87 to 78 percent for the prairie- and turf-clay rain gardens, respectively. Maximum recharge volumes ranged from 90 to 94 percent of the total influent volume in the turf- and prairie-sand rain gardens (water year 2004). Maximum recharge in the turf- and prairie-clay rain gardens ranged from 89 percent (water year 2007) to 98 percent (water year 2004), respectively.

Median infiltration rates were an order of magnitude greater for rain gardens planted in sand than those in clay, regardless of vegetation type. Under similar soil conditions, rain gardens planted with turf grass had lower median infiltration rates than those planted with prairie species. Median infiltration rates ranged from 0.28 and 0.88 in/hr to 2.5 and 4.2 in/hr in the turf and prairie rain gardens in clay and sand, respectively. In general, infiltration rates were greater during spring and summer months.
Of the six observed precipitation events exceeding the storage capacity of the turf-clay rain garden between the months of April through November 2004 – 2007, five were predicted using a combination of the normalized surface storage volume, median infiltration rate, and an estimate of specific yield for soils below the rain garden to a depth equal to the uppermost limiting layer. Using the same criteria, in water year 2008, when the contributing drainage area to the prairie-clay rain garden was doubled, all four observed precipitation events exceeding the total storage capacity were predicted. By measuring the appropriate soil properties, environmental managers and engineers may have greater confidence when tailoring design specifications of a rain garden to new or retrofitted areas.

An examination of soil structure and the root systems in the clay rain gardens revealed striking differences between turf and prairie vegetation. Soils under the prairie-vegetated rain garden, although possessing the remnants of a limiting clay layer, appeared well-drained, whereas the turf-clay rain garden showed marked evidence of a perched water table. While roots were present in all horizons sampled within prairie-clay soil, roots were limited to the upper A and Bt horizons within the turf-clay rain garden. Collectively, these differences point to greater pedoturbation and soil development in the prairie-clay rain garden relative to the rain garden planted with turf grass.

**Introduction**

The adverse impacts of urbanization on stormwater runoff quantity and quality have been well documented (U.S. Environmental Protection Agency, 1983, Bannerman and others, 1993). With increasing imperviousness, precipitation that previously infiltrated into surrounding soils is collected and conveyed by hard surfaces into nearby receiving water bodies. Collectively, impervious areas introduced by traditional urban landscapes lead to more diverse pollutants,
reduced pollutant removal during overland flow, and reduced infiltration (Davis, 2005). By reducing the volume of runoff that would percolate into underlying soils under natural conditions, urban development can reduce the supply of groundwater that is beneficial for wetlands, streams, and lakes and vital for human consumption (Simmons and Reynolds, 1982, as cited in Brander and others, 2004). Traditional stormwater management has focused primarily on detention ponds in order to reduce flood peaks and prevent localized flooding. While these practices have been successful in reducing episodic localized flooding and improve the quality of runoff, they fail to address groundwater recharge issues or other aspects of altered streamflow that negatively impact stream ecosystems and human uses (House, 1993; Pettersson, 1998; Winer, 2000; Marlin and others, 2002).

As development continues to push further into our nation’s landscape, controlling nonpoint sources of contamination, replenishing groundwater supplies, and protecting natural waterways has become a major focus for the regulatory community. Environmental managers must develop new strategies that promote a balance between existing and expanding urban areas and the environmental challenges they impose. To this end, the Wisconsin Department of Natural Resources (WDNR) promulgated a series of performance standards and prohibitions with regard to nonpoint stormwater sources (Wisconsin Administrative Code NR 151, 2002). These standards are intended to be minimum benchmarks of performance necessary to achieve water quantity and quality goals. Specifically, new residential areas must infiltrate 90 percent of pre-development infiltration volume for an average rainfall year. Commercial and other non-residential land uses must infiltrate 60 percent of pre-development infiltration volume (Wisconsin Administrative Code NR 151.12, 2002).
Recent trends in urban runoff mitigation have resulted in a number of technologies that focus on infiltration. One such technology, known as a rain garden, is a shallow depression that gathers runoff generated from nearby impervious surfaces and infiltrates that runoff into the ground. In addition to reducing or limiting the quantity of stormwater runoff, rain gardens provide some level of water-quality benefit by settling, filtration, adsorption, decomposition, ion exchange, and volatilization (Prince George’s County, 1993). Rain gardens are commonly used to retrofit existing urban areas where land requirements often preclude larger structures. Although the use of rain gardens is increasing, there appears to be no clear consensus on how soils at the site might limit the use of an infiltration device. In the state of Wisconsin, an exemption is granted to those who fall under the purview of infiltration technical standards if the infiltration rate of the soil is less than 0.6 in/hr (Wisconsin Administrative Code NR151, 2002). This exemption limits the use of infiltration in many areas in Wisconsin. In order to expand the use of rain gardens and other infiltration devices, more needs to known about soil amendments and sizing criteria that will reduce the uncertainty of requiring infiltration in soils with lower infiltration rates.

Previous studies have attempted to evaluate the infiltrative and water-quality benefits of rain gardens under various soil types. Results of these studies suggest rain gardens can be an effective way to infiltrate stormwater runoff from localized sources (Dietz and Clausen, 2005; Dietz and Clausen, 2006; Smith and Hunt, 2007). However, most of these studies may not have adequately represented true field conditions since they often installed underground impermeable membranes to seal the rain garden. This was done in order to capture all percolated water ensuring accurate volumetric mass balance calculations; it also disturbed the native soil structure in the process. Furthermore, many rain garden manuals recommend planting vegetation that is native to the hydrologic regime and do not consider a more commonly accepted ground cover such as turf grass.
Native prairie vegetation has been associated with a dense root structure capable of growing to significant depths below the ground surface. This type of vegetation is assumed to promote runoff interception and infiltration; however, few studies have verified this claim and none have examined the rooting character of these vegetation types within urban rain gardens. This inadequate understanding of belowground processes has arguably limited our ability to predict the contribution of rain gardens to stormwater management (Eissenstat and others, 2006). Other studies have shown that turf grasses can also limit overland runoff (Kussow, 1995). Steinke and others (2007) measured significantly lower runoff volumes from an experimental buffer strip planted with turf grass than an adjacent plot planted with emergent prairie vegetation. This option may be more suitable to homeowners due to cost and maintenance concerns. However, little is known about the interactions between the soil and variety of plant species used in rain garden design. This absence of data is understandable given the difficulty of assessing in situ root dynamics and morphology without destructive sampling. However, it limits our understanding of plant-soil dynamics in rain gardens including the cycling of carbon and minerals, root-water relationships, and the thus long-term functionality of these bioengineered systems (Asseng et al. 1997).

For these reasons, the U.S Geological Survey, in cooperation with a consortium of nineteen cities, towns, and villages in Dane County, Wisconsin, undertook a study to evaluate the effectiveness of rain gardens with different soil types and vegetative species at infiltrating stormwater runoff. Two rain gardens, one planted with turf grass and the other with native prairie species, were constructed side-by-side in two locations of dominant soil type, sand or clay. Instruments were installed to measure the volumetric mass balance of each rain garden from late
2003 through 2008. This study supports an ongoing effort to identify existing and new methods to reduce the loss of recharge to ground water from urban areas.

**Purpose and Scope**

This report describes the methods used in and the results from an evaluation of two rain gardens with different vegetative species and underlying soil types. The objective of the study was to determine whether soil type and (or) vegetative species in a rain garden had an effect on the rate of infiltration of stormwater runoff. Two geographic areas were selected in Madison, Wis. to represent different soil conditions. The first location had predominantly sandy soils while the second contained more clay and silt. Two rain gardens were constructed side-by-side at each location in June 2003. Each rain garden received approximately equal amounts of runoff from the roof of a nearby structure. One rain garden was planted with turf grass while the adjacent rain garden was planted with native prairie vegetation. Estimates of evapotranspiration were computed to characterize the volume of water lost to the atmosphere. Although soils at each rain garden location are variable in texture, each was primarily dominated by soils that could be generalized as sand or clay and were therefore was assigned a single soil type to simplify discussion. Furthermore, to clarify reference to vegetation, each rain garden will be referred to by vegetative species followed by the soil type in which it was located. The resulting rain gardens are subsequently labeled as turf-sand, prairie-sand, turf-clay, and prairie-clay.

Comparisons of volumetric inputs and outputs for each rain garden were made from December 2003 through September 2008 within and between geographic locations to estimate the effects of vegetation and (or) underlying soil lithology on infiltration and evapotranspiration. At the conclusion of the study, a portion of the prairie-clay rain garden was excavated to facilitate documentation of root mass development given the presence of a limiting clay layer.
Description of Study Area

Madison, Wis. has a population of 208,054 (based on the 2000 census). The climate is typical of interior North America, with a large annual temperature range and frequent short-period temperature changes. Nearly 60 percent of the annual precipitation falls in May through September, with annual precipitation averaging 31.7 in. (National Oceanic and Atmospheric Administration, 2005). Both rain garden study areas were located approximately 2 mi apart near the western boundaries of the city (fig. 1).

FIGURE 1 NEAR HERE

Methods

Rain Garden Construction

The City of Madison constructed the rain gardens using equipment typically available to homeowners and landscaping crews. Skid loaders excavated all parent material and assisted in forming earthen berms around the rain garden boundaries to assure that no runoff from areas other than the roof entered the rain garden. Approximately 4 to 6 in. of screened compost from the Dane County compost facility was mixed into parent material at the bottom of each rain garden using a roto-tiller. A uniform, level surface was approximated by use of survey equipment. Turf rain gardens were seeded with a grass mix of red fescue, Kentucky bluegrass, and perennial rye grass, then fertilized and matted whereas the prairie rain gardens were planted using dormant plugs spaced approximately 1 ft apart, then fertilized (fig. 2). Table 1 details the diversity of species planted in each prairie rain garden.

FIGURE 2 NEAR HERE
TABLE 1 NEAR HERE

Construction of each rain garden was completed in June 2003; however, an extended drought during the summer of 2003 inhibited root growth in the turf rain gardens. However, by the following spring (2004) the grass was well established in both turf gardens. The prairie rain gardens did not experience the same retardation of vegetative growth and appeared well established by fall 2003. This may be a result of using dormant plantings rather than seed.

Rain gardens in sand were built next to a municipal maintenance garage located in the Owen Conservation Park, a hummocky area on the west side of Madison (fig 1). Surficial deposits in this area consist of silt loam, sandy clay loam, and sandy loam (NRCS, 2009). The parent material of soils in this area consists of till typical of unconsolidated glacial deposits of drumlins created during the Wisconsin glaciation (Mickelson, 2007). Each rain garden received runoff from the roof of the maintenance garage. The total area of the roof was 1,026 ft² and was constructed using asphalt composite shingles commonly found on residential dwellings. One-half of the total roof area (513 ft²) was directed into one of two downspouts draining into the turf grass or prairie rain gardens. Each rain garden was sized to approximately 100 ft², or, one-fifth the size of the roof area draining to it. Water was allowed to pond up to a depth of approximately 6 in. before leaving the rain garden as discharge.

Rain gardens in clay were built next to a municipal water supply pump house approximately two miles west of the sand rain gardens (fig. 1). Similar to the sand rain garden location, surficial deposits in this area range from a sandy loam to a clay loam (NRCS, 2009). The parent material of soils in this area consists of a sand-based matrix of glacial outwash and till typical of unconsolidated glacial deposits of the Milton end moraine during the last part of the Wisconsin glaciation (Mickelson, 2007). However, excavations from urban development over the last decade
disturbed the native landscape resulting in post-construction soils that were heavily compacted prior to rain garden construction. Each rain garden received runoff from the roof of the municipal well house. The total area of the flat, rubber roof was 3,080 ft² and was designed to drain equally (1,540 ft²) into one of two downspouts. Similar to the rain gardens in sand, the area of turf- and prairie-clay rain gardens was approximately one-fifth and one-fourth the size of the roof area draining to it (354 and 403 ft²), respectively. Water was allowed to pond up to a depth of approximately 6 in. before leaving the rain garden as discharge.

**Hydrologic Measurements**

Stormwater runoff was measured from downspouts leading to each rain garden (figs 3 and 4). Locations of the monitoring stations are shown in figure 1. Each monitoring station was equipped to measure water level, precipitation, subsurface soil moisture content, and reference evapotranspiration Measurement, control, and storage of data were done by way of electronic dataloggers. Data were automatically retrieved twice daily with telephone modems. Storm event characteristics for runoff events at each rain garden location are detailed in appendix tables 1-1 and 1-2.

**FIGURE 3 NEAR HERE**

**FIGURE 4 NEAR HERE**

**Precipitation**

Continuous precipitation data were collected at each rain garden location by use of tipping-bucket rain gages calibrated to 0.01 in (fig 5). Although these rain gages were not designed to measure snowfall, there were several runoff events during winter months where precipitation was in the form of rain instead of snow. Monthly precipitation totals during winter months (December
through March) were estimated from the National Oceanic and Atmospheric Administration (NOAA) weather station at the Dane County Regional Airport in Madison, Wis. (National Oceanic and Atmospheric Administration, 2003 – 2007). Summaries of precipitation data from the clay and sand rain gardens are presented in appendix tables 1-1 and 1-2, respectively.

**FIGURE 5 NEAR HERE**

Evapotranspiration

To calculate reference evapotranspiration (ET₀), solar radiation, air temperature, relative humidity, and wind speed were collected by use of a pyranometer, platinum resistance temperature detector, capacitive relative humidity sensor, and anemometer, respectively (fig. 5). Reference evapotranspiration, in millimeters, was computed every 5 min. using the Penman-Monteith equation (Monteith and Unsworth, 1990; Allen and others, 1998) then summed into hourly and daily totals. A reference surface closely resembles a green, well-watered grass of uniform height, actively growing and completely shading the ground (Allen and others, 1998). Both rain gardens planted with turf grass closely resemble a reference surface. A landscape coefficient of 0.95 was applied to the reference evapotranspiration in the turf rain gardens based on published values for cool season grasses (Allen and others, 1998).

Many of the vegetative properties, such as ground cover, canopy, and aerodynamic resistance in the rain garden planted with prairie vegetation were likely different than those found in the reference turf rain gardens. Estimates of evapotranspiration in the prairie rain gardens were based on a range of published landscape coefficients for a variety of vegetative species commonly used in the landscaping industry. The landscape coefficient uses species type, density, and microclimate to estimate a correction factor to reference evapotranspiration (Costello and others, 2000). Average landscape coefficients representing “low” and “high” evapotranspiration were
calculated for many of the species found in the prairie rain gardens. A landscape coefficient ($K_L$) for a specific vegetative species was determined using the following formula:

$$K_L = K_s \times K_d \times K_{mc}$$ (1)

where

$K_s$ is the species factor;

$K_d$ is the density factor; and

$K_{mc}$ is the microclimate factor.

$K_L$ is then multiplied by the reference evapotranspiration to determine the final evapotranspiration for a specific vegetative species. A weighted average was used to more accurately represent the abundance of each species identified in each rain garden.

**Water Influent and Effluent**

**Influent**

Stormwater runoff influent at the turf- and prairie-clay rain gardens was measured by means of a pre-rated H-flume and shaft encoder (fig. 3). Rooftop runoff first traveled through the downspout dedicated to each rain garden into a buffer tank to prevent turbulent flow conditions. Water levels in the buffer tank would raise or lower a float and counterweight system connected to a shaft encoder, calibrated to the nearest 0.01 ft. The shaft encoder’s point of zero flow was coincident with the invert of a 0.8 ft H-flume. Water levels in the buffer tank were used to compute an instantaneous discharge using the known H-flume rating. Storm-runoff volumes were computed by summing the 1-minute-interval instantaneous discharge over the runoff duration.
Stormwater runoff influent at the turf- and prairie-sand rain gardens was measured by means of a tipping bucket and magnetic reed switch (fig. 4). Rooftop runoff first traveled through the downspout dedicated to each rain garden into a buffer tank. A small funnel was attached to the bottom of the buffer tank to focus water into the tipping bucket. Each tip of the bucket represented a known volume of water. Once passing through the tipping bucket, runoff would flow into a drain tube leading into the rain garden.

**Effluent**

Water level in excess of 6 in. in each rain garden was discharged as effluent. A 0.6 ft pre-rated H-flume was used to control the rate of flow (figs. 3 and 4). Water levels in each rain garden were measured by means of a submersible pressure transducer, calibrated to 0.01 ft, placed inside a small-diameter pvc tube, illustrated in figures 3 and 4. Water level was measured in 0.01 ft increments above the rain garden floor. Since the invert of the 0.6 ft H-flume was at a known elevation above the rain garden floor, water levels above the flume invert were converted to an instantaneous discharge using the known H-flume rating. Storm-runoff volumes were computed by summing the 1-minute-interval instantaneous discharge over the runoff duration.

**Data Analysis**

Classification and regression trees (CART) were used to visualize a relationship between a dependent variable to a set of independent variables (Breiman and others, 1984). CART analysis was done on each rain garden to understand what climatologic and hydrologic variables might determine when the rain garden would pool with water. The dependent variable was qualitatively termed “wet” or “dry” to describe whether a rain garden did or did not pool with water during a discharge event. Quantitative independent variables including precipitation depth, total event...
volume, antecedent dry days, and 15-, 30-, and 60-minute precipitation intensities were used to describe the hydrologic and climatologic conditions.

During “wet” periods, an estimate of the rate of infiltration was computed using a simplified falling head technique. Consistent with Darcy’s Law, infiltration rates varied with depth (or head) of water in the rain gardens. In order to determine whether infiltration rates were changing over the duration of the study period, a fixed water depth was used in the computational process. This also provided a consistent basis for which to evaluate each rain garden. After cessation of rainfall, infiltration rates were estimated based on the rate of falling head in the rain garden from a depth of approximately 0.1 ft to when the rain garden was no longer covered by water. Figure 6 shows an example of determining an estimate of infiltration rates in the clay rain gardens. In some cases, an estimate of infiltration rate was not possible because of additional influent prior to or during recession of pooled water in the rain garden. Estimates of infiltration rates were compared between soil types and vegetative species for seasonal and temporal changes. Seasonal differences were determined using the nonparametric Mann-Whitney statistical test for two groups (Helsel and Hirsch, 1992). Limited sample populations precluded an evaluation of winter and fall infiltration rates in the prairie- and turf-sand, and prairie-clay rain gardens. Therefore, use of the Mann-Whitney test was limited to a comparison of spring and summer infiltration rates. Comparison of all four seasons in the turf-clay rain garden was done by use of the nonparametric Kruskall-Wallis and Dunn’s statistical tests for multiple groups (Dunn, 1964; Helsel and Hirsch, 1992).

FIGURE 6 NEAR HERE
Characterization of Soils and Vegetation

Texture and Other Soil Properties

Selection of each study location was based upon the presence of either sand or clay as the dominant soil texture. Prior to rain garden construction, a hand-powered soil auger was used to identify soil texture to a depth of approximately 1 ft at each study location. Additionally, regional soils maps were reviewed to verify soil classification at depth (NRCS, 2009). Finally, infiltration rates at each location were determined using a double-ring infiltrometer. The resulting infiltration rates were then compared to published values typical for sand and clay soils (Rawls, 1998). In 2003, after construction of each rain garden was complete, a core was extracted from the prairie-clay and turf- and prairie-sand rain gardens to a depth of approximately 20 ft by use of a Geoprobe to help provide a depth profile of texture changes. Additional soil cores were taken in 2008 at multiple locations in both the turf- and prairie-clay rain gardens to a depth of approximately 10 ft in order to further characterize the substrate by minimizing the large amount of spatial variability in soil texture. All cores were taken during winter months when soils were frozen and less prone to compaction from heavy equipment.

Sand Site

Figure 7 shows a cross-section of surficial deposits based on the turf and prairie rain garden cores down to 20 ft. The upper 4 ft of soil in the prairie rain garden generally contained a greater amount of clay than the turf rain garden and was described as a loam to clay loam rather than a sand loam. A thin clay layer was found in the prairie rain garden core at a depth of approximately 4.5 ft. This same clay layer was not found in the turf rain garden. Both gardens had sand loam with occasional layers of clay loam below 5 ft. The upper 4 ft of soil in the prairie rain garden showed the majority of sediments to be classified as sandy loam with some gravel (fig 7). The dissimilarity
between soil profiles may be due, in part, to rain garden construction practices. Because the turf rain garden was located on a hill slope, a greater amount of material was excavated in order to achieve a level surface. This likely removed some of the surficial deposits that were found in the prairie rain garden. A level surface was more easily achieved with minimal excavation in the prairie rain garden. The elevation of the turf grass rain garden (post-construction) was 0.77 ft lower than that of the prairie rain garden.

**FIGURE 7 NEAR HERE**

Craig (2007) investigated soil and botanical characteristics of both the turf- and prairie-sand rain gardens and their relationship with microbial community composition. The results were then compared to those determined from 50 additional rain gardens surveyed around Dane County, Wis. and are presented in table 2. Average soil composition from three test plots in the turf-sand rain garden had a higher percentage of organic matter than other surveyed lawns in Dane County. Similarly, porosity was higher than other Dane County lawns which may have been a function of the high sand content and low bulk density (table 2).

**TABLE 2 NEAR HERE**

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Figure 8 shows a cross-section of two cores from the clay rain gardens. The prairie and turf cores were taken in 2003 and 2008, respectively. The turf and prairie gardens had variable thicknesses of sand, sand loam, clay, and silty clay deposits. The uppermost limiting clay layer was generally at shallower depths in the turf rain garden at approximately 1.5 ft below the soil surface compared to approximately 3.0 ft in the prairie rain garden. A continuous clay layer of variable thickness was distributed across both rain gardens at a depth of 3 ft. The upper 4 ft of soil in the
turf-clay rain garden showed the majority of sediments to be classified as sandy clay, clay loam, and clay with some fine layers of sand and gravel (fig 8).

**FIGURE 8 NEAR HERE**

Similar to the sand rain gardens, an examination of soil and botanical characteristics was done on the clay rain gardens then compared to 50 additional rain garden surveys around Dane County, Wis. (Craig, 2007). The results are presented in table 2. Average soil composition from three test plots in the prairie-sand rain garden had a higher percentage of organic matter than other surveyed lawns in Dane County. Similarly, porosity was higher than other Dane County rain gardens which may have been a function of the high sand content and low bulk density (table 2).

**Soil Moisture**

Within each rain garden, volumetric soil-moisture profiles were measured by use of vertically oriented soil moisture sensors (fig. 9). Soil moisture was measured at 20 cm increments to a depth of 4 ft below the rain garden. One sensor and its protective access tube was installed in each rain garden following methods described by the manufacturer (Sentek Party Ltd, 1999). Proper installation of soil moisture sensors and access tubes results in no air pockets along the length of the access tube and causes minimal disturbance of the adjacent soil profile (Graczyk and Greb, 2006). Soil moisture was measured at 15 cm, 35 cm, 55 cm, 75 cm, 95 cm, and 115 cm below the land surface in the turf-clay, prairie-clay, and prairie-sand rain gardens. Soil moisture in the turf-sand rain garden was measured at 5 cm, 15 cm, 25 cm, 35 cm, and 45 cm below the land surface. Measurements of soil moisture were collected at 15 min increments from October 2003 to January 2006 and 5 min. increments from February 2006 to September, 2008.
Each soil moisture sensor was periodically calibrated using methods described by the manufacturer (Sentek Party Ltd, 1999). Calibration was limited to 100 percent (water) and 0 percent (air) saturation. Each sensor can be calibrated to measure the absolute volumetric moisture content of a specific soil type if the physical properties of that soil are known across a range of moisture conditions. However, given the destructive nature of the calibration process to determine absolute soil moisture values, a generalized algorithm, developed by the manufacturer to represent sands, loams, and clay loams, was used in this study. Therefore, in-situ soil moisture conditions were considered a relative, rather than absolute, value.

**FIGURE 9 NEAR HERE**

**Root Morphology**

In October 2008, a 4.25 ft wide by 10 ft long observation trench was excavated through the approximate center of the prairie- and turf-clay rain gardens. The trench in the prairie-clay rain garden was dug to a depth of 5 ft, while the turf-clay trench was excavated to only 4 ft due to standing water at depth; no standing water was observed in the prairie-clay trench. These trenches provided profile walls to describe the physical characteristics of each soil and quantify rooting dynamics within each rain garden. The south wall of each trench was prepared by hand for soil profile descriptions, sub-sampling, and additional *in situ* root measurements; care was taken to avoid smearing of soil surfaces.

Soil descriptions were performed according to standard protocol for field observation (NRCS, 2002). Measurements included master and subordinate horizons, any changes in parent material, texture class, rooting depth, color, structure, and presence of mottling. Following the profile descriptions, six discrete soil cores were extracted horizontally from the approximate midpoint of each horizon along the length of the trench by use of a 5.6 in$^3$ cylinder driven into
random locations along the trench wall (within each horizon) with a hammer-core sampler (Blake and Hartge, 2002). These samples were bagged and transported to the University of Wisconsin soils lab for measurements of bulk density and root morphology. An additional sample was taken with a hand trowel from each horizon for determination of soil texture.

Two of the six soil cores per horizon were used to quantify bulk density and soil organic matter (SOM). In the laboratory, the soil cores were dried at 105°C for 24 hours and weighed. Bulk density was then calculated to the nearest 0.01 g. Soil textures were determined with a hydrometer using samples pretreated with Calgon© solution (Gee and Or, 2002). This analysis was performed at 30°C on samples from each horizon with the exception of O and A due to their variable proportions of organics. Soil organic matter contents were determined by loss on ignition, using 10 g of oven-dried soil heated at 550°C for three hours in an Isotemp muffle furnace (Heiri and others, 2001).

Root dynamics were quantified in the lab from the remaining four core samples per horizon. Calculations of root length density (RLD), specific root length (SRL), root dry mass, and total length were done for each horizon. Each core was first soaked in distilled water for 48 hours at which point the cores began to naturally disperse. The cores were then lightly agitated by hand to liberate the roots from the soil. All visible roots were extracted from the soil slurry on a 0.05 mm soil sieve, and cleaned with distilled water. The soil slurry was run through the sieving process a second time to ensure all roots were extracted from the core samples. The roots were then patted dry on a paper towel at which point the length of each root was measured and then dried at 70°C for 48 hours in a convection oven for dry weight determination.
Comparison of Rain Gardens

Hydrologic, soil, and vegetation characteristics were compared for the turf-clay, prairie-clay, turf-sand, and prairie-sand rain gardens from December 2003 to September 2008. During the five year monitoring period, the sand and clay gardens received runoff from over 380 and 275 precipitation and snowmelt events, respectively (appendix tables 1-1 and 1-2). Measurements of runoff volume (both influent and effluent), precipitation, and reference evapotranspiration were used part of a water balance used to estimate recharge at each rain garden. Water depth in each rain garden was measured to estimate infiltration rates. Infiltration rates were compared for differences between vegetative species and soil type as well as seasonal and temporal trend.

Water Influent and Effluent

The main sources of influent to the rain gardens are rainfall and snowmelt runoff from the roof surfaces and rainfall falling directly on to the gardens. The water equivalent for snow falling directly over the rain garden was not included in the computation of influent since actual snow depths were not recorded at the field site. Over the 5-yr monitoring period, the annual precipitation ranged from 24 percent below the 30-yr normal of 32.95 in. in 2005 to 35 percent above in 2008 (fig. 10). Monitored storms during the period ranged in precipitation depth from less than 0.05 in, the amount typically required to generate rooftop runoff, to 4.0 in. Sixty-minute precipitation intensities ranged from 0.01 to 1.29 in/hr.

FIGURE 10 NEAR HERE

Sand Site

Annual rainfall-runoff volumes into the turf-sand and prairie-sand rain gardens were nearly equal during each study year with a 5 percent or less difference in influent for all years (table 3). In
general, the prairie-sand rain garden received slightly more influent volume than the turf-sand rain garden. Some of the added volume can be attributed to preferential rainfall patterns as well as a disproportionate amount of snowmelt to the prairie-sand rain garden due to the roof’s orientation to the sun. Annual influent volumes were slightly less in water year 2004 than in 2007 despite having a greater annual precipitation depth. Much of this discrepancy is due to the estimated water equivalency of snowmelt during winter months. Excluding months of the year where precipitation was estimated using data from the NOAA weather station (December through March), total precipitation in water year 2007 was, in fact, greater than in 2004.

There were no monitored events during the initial phase (2004 – 2007) of the study that exceeded the storage capacity of either the turf-sand or prairie-sand rain gardens; therefore all runoff was infiltrated and stored, lost to the atmosphere through evapotranspiration, or recharged. In water year 2008, all runoff was directed to only the turf-sand rain garden. Despite doubling the contributing drainage area, only a single event on June 8, 2008 produced measurable effluent in the turf-sand rain garden (table 3). Some events prior to June 8 had similar precipitation depths and intensities but did not result in effluent discharge. The inter-event period for these storms was long enough to allow soils to drain. Therefore, the June 8 event was likely due to a combination of not only high precipitation intensity and depth but also saturated soil conditions from previous events. Rainfall occurred on consecutive days from June 5 through June 8 totaling over 5 inches.

TABLE 3 NEAR HERE

Clay Site

Annual runoff volumes into the turf-clay rain garden were approximately 20 percent greater than the prairie-clay rain garden for all but one study year (table 3). It is unclear why more rooftop runoff was measured in the turf-clay rain garden. One possible explanation is the buildup of
precipitation due to prevailing winds. Despite the fact that each downspout drained an equal amount of rooftop area, prevailing westerly winds had the potential to push some water from the area draining to the prairie-clay rain garden over to the area draining the turf-clay rain garden. Differences in measured annual influent volumes could also be attributed to the downspout design. Each downspout had an open face which allowed runoff to occasionally escape the channel walls. This small amount of runoff was not collected or measured by the H-flumes and thus was unaccounted for. This phenomenon was more pronounced during winter months when the downspout channel would fill with ice (fig. 11). Much of the water from melting ice was not contained within the downspout channel walls. Though each downspout had this design limitation, it may have been more pronounced in the downspout draining to the prairie-clay rain garden.

The turf-clay rain garden had one or more precipitation and (or) snowmelt events result in a measureable volume of runoff leaving the rain garden during each study year (table 3). In most instances, effluent volume was a result of high precipitation intensity and (or) depth. Nearly ½ of all effluent volume measured from the turf-clay rain garden was the result of two storm events in May 2004 that produced 4.7 in. of rain within 48 hours (appendix table 1-2). There were no monitored events during the initial phase (2004 – 2007) of the study that exceeded the storage capacity of the prairie-clay rain garden; therefore all runoff was infiltrated and stored, lost to the atmosphere through evapotranspiration, or recharged. In water year 2008, all runoff was directed to only the prairie-clay rain garden thereby doubling the contributing drainage area. All effluent volume measured during this period was a result of 4 precipitation events, each with precipitation depths in excess of 2.5 in. (appendix table 1-2).

**FIGURE 11 NEAR HERE**
Evapotranspiration

In general, reference evapotranspiration followed a seasonal pattern with highest monthly totals occurring during the warmer summer months of June and July then gradually decreasing with the onset of plant senescence in late fall (fig. 12). Since the turf grass evaluated as part of this study closely resembled that of a reference surface, estimated evapotranspiration values were only slightly modified (Allen and others, 1998). Several species identified in the prairie rain gardens were given a landscape coefficient ranging from “low” to “high”. Regardless of soil type, resulting correction coefficients for prairie vegetation were lower than that of turf grass; therefore, estimates of evapotranspiration were also lower.

Annual evapotranspiration for turf grass ranged from 21 to 26 in. in the sand and clay rain gardens for water years 2004 and 2005, respectively (table 4). This accounts for more than one-half of direct annual precipitation. Evapotranspiration was greater than direct precipitation in 2005; a result of below normal precipitation. Steuer and Hunt (2001) reported similar average annual evapotranspiration amounts (23.9 in) for the watershed in which this study was located based on hydrologic model simulations from 1993 to 1998. Because the contributing drainage area to each rain garden was approximately 5 times greater than the receiving area, the percentage of turf grass evapotranspiration, when compared to direct precipitation plus influent, ranged from a low of 9 and 11 percent in water year 2004 to a high of 21 and 25 percent in water year 2005 in the clay and sand rain gardens, respectively, (table 4). The percentage of evapotranspiration was reduced to 7 percent in water year 2008 when the contributing drainage area to the turf-sand rain garden was doubled to approximately 10 times the receiving area (table 4).

FIGURE 12 NEAR HERE

TABLE 4 NEAR HERE
Differences in leaf anatomy, stomatal characteristics, density, and aerodynamic properties of vegetation can cause differences in evapotranspiration (Allen and others, 1998). Microclimate can also be important. Table 5 lists several species of vegetation identified by Craig (2007) in the prairie rain gardens and estimates a correction coefficient to reference evapotranspiration based on species, density, and microclimate. Bare ground was the largest percentage of ground cover (or lack thereof) in the prairie-sand rain garden. Water loss from soil evaporation may occur when ground shading is less than 100 percent. Consequently, the reference evapotranspiration rate for bare soils was increased by 10 to 20 percent (Costello and others, 2000). The weighted average landscape coefficient, $K_L$, for all identified species ranged from 0.5 to 0.7 for the prairie-sand garden to 0.2 to 0.5 for the prairie-clay garden. These values agree with similar landscape coefficients for prairie vegetation recorded by Pitt and others (2008). Using this range of landscape coefficients, annual evapotranspiration for prairie rain gardens ranged from a low of 2 and 11 percent in water year 2004 to a high of 12 and 19 percent in water year 2005 in the clay and sand rain gardens, respectively (table 4). The percentage of evapotranspiration in the prairie-clay rain garden decreased in water year 2008, ranging from 1 to 4 percent, when the contributing drainage area was doubled to approximately 8 times the receiving area (table 4).

**TABLE 5 NEAR HERE**

**Recharge, Infiltration, and Storage**

Recharge was estimated using the water balance formula:

$$R = P + V_i - V_o - ET$$  \hspace{1cm} (2)

where

- $R$ is recharge, in inches;
P is precipitation, in inches;

\( V_i \) is the volume of runoff into the rain garden, in inches;

\( V_o \) is the volume of runoff out of the rain garden, in inches; and

ET is evapotranspiration, in inches.

Table 4 shows the amount of water for each variable described in the formula above as well as the relative percentage of water outputs to inputs. For comparison, volumes in Table 4 were normalized by rain garden area. Rain gardens planted with prairie vegetation are expressed in terms of a range of low to high recharge to coincide with a similar range in evapotranspiration. At both the sand and clay study sites, the rain garden planted with turf grass received slightly more annual influent than did the rain garden planted with prairie vegetation. Despite having more water available for recharge in the turf grass rain gardens, the overall percentage of annual recharge was slightly less than in the prairie rain gardens. This is largely due to a much smaller amount of evapotranspiration estimated for prairie species. If rooftop runoff were equally distributed between the turf grass and prairie rain gardens, the difference in percent recharge between turf grass and prairie vegetation would become even greater.

Differences in annual recharge between the turf grass and prairie rain gardens in clay were slightly greater than differences between vegetative species in sand. The average difference between percent annual recharge in the turf grass and prairie rain gardens in clay was 7 percent compared to 4 percent in sand (using the lower estimate of annual percent recharge for the prairie rain gardens). Differences in vegetation may therefore have a more pronounced effect on recharge given different soil structure.

In general, each rain garden, regardless of vegetation or soil type, was capable of storing and infiltrating the majority of runoff over the 5-year study period. This might suggest use of a
specific vegetative species in a rain garden has no bearing on the overall performance. However, the robust design of the rain gardens tested in this study may have been the primary reason for their success. A simple calculation was done to characterize the approximate size of storm required to exceed the storage capacity of each rain garden. Assuming zero infiltration, the minimum depth of precipitation required to fill the turf- and prairie-clay rain gardens would be approximately 1.4 and 1.6 in, respectively. Both rain gardens in sand would require approximately 1.2 in. From figure 13, total storm precipitation (excluding snowfall) exceeded these thresholds approximately 10 percent of the time over 4 years in both the clay and sand rain gardens. A 5 to 1 ratio of contributing to receiving area (4 to 1 for the prairie-clay rain garden) was, therefore, fully capable of retaining approximately 90 percent of all precipitation events. However, since the water retaining capacity of a rain garden is both a function of above and below ground storage of runoff from a source area as well as simultaneous infiltration of runoff, the capacity to store runoff from a precipitation and (or) snowmelt event is beyond that suggested by ponding depth alone. With infiltration, an even greater amount of precipitation would likely be retained and infiltrated over time if the precipitation intensity was equal to or less than the median infiltration rates listed in table 6. Only 3 and 13 out of all precipitation events measured over the period April through November 2004 – 2007 had 60-minute precipitation intensities greater than the median infiltration rate as well as precipitation depths greater than the minimum depth required to exceed rain garden storage capacity (assuming zero infiltration) in the prairie- and turf-clay rain gardens, respectively. There were no precipitation events in the sand rain gardens that satisfied the same criteria.

**FIGURE 13 NEAR HERE**

Additional runoff volume can also be temporarily stored by the soils below a rain garden to a depth equal to the uppermost limiting layer. The volume of these void spaces in the soil, the
drainable porosity (or specific yield), in addition to the infiltration rate may have more influence on a rain garden’s ability to recharge runoff than ponding depth. The specific yield is the ratio of the volume of water that drains from a saturated soil owing to the attraction of gravity to the total volume of the soil (Fetter, 2001). Using the same calculations previously described, an estimate of the volume of water needed to saturate the soils below the turf- and prairie-clay rain gardens was determined. The volume, after normalizing by rain garden and contributing rooftop area, was then compared to individual precipitation events that equaled or exceeded the soil volume and resulted in pooled water. The approximate depth of soil down to the uppermost limiting layer, based on soil core descriptions, was 1.5 and 3 ft for the turf- and prairie-clay rain gardens, respectively (fig 8). Soils down to these respective depths ranged from sand to sandy clay. An average soil texture of silt was selected to approximate the full range of specific yield found in the gardens. Specific yield for unconsolidated silt deposits was estimated to be 18 percent based on published values (Johnson, 1967). Using these parameters, the volume of runoff from the rooftop as well as direct precipitation required to saturate the turf- and prairie-clay rain garden was 0.61 and 1.34 in., respectively. The number of precipitation events equal to or exceeding these thresholds was summed over the months of April through November 2004 – 2007. Forty-six of the 62 precipitation events equal to or exceeding 0.61 in. resulted in pooled water in the turf-clay rain garden. In the prairie-clay rain garden, 11 out of 17 precipitation events equal to or exceeding 1.34 in. resulted in pooled water. The total storage capacity of each rain garden would be a sum of storage both above and below ground. Table 6 details the quantities of each variable used to predict when the total storage capacity of the turf- and prairie-clay rain gardens would be exceeded and compares to the observed number over the months of April through November 2004 – 2007. Of the 6 observed precipitation events exceeding the turf-clay rain garden total storage capacity, 5 were predicted using the values
Similarly, a single precipitation event was predicted to exceed the total storage capacity of the prairie-clay rain garden when none were observed. The criteria used to create table 6 were then applied to the prairie-clay rain garden in water year 2008 when the contributing drainage area was doubled. Four out of 4 predicted precipitation events exceeding the total storage capacity of the prairie-clay rain garden were observed.

**TABLE 6 NEAR HERE**

Many design manuals promote the area of a rain garden as an important variable for accepting runoff, emphasizing the ratio of draining to receiving area. Oftentimes, those space requirements cannot be met or poor soil conditions preclude location of a rain garden in an area where space may be available. If surficial area is unavailable, then storage of runoff can be created by excavating to a greater depth, even in the presence of clay. Using the prairie-clay rain garden as an example, the time required to go from saturated to pre-event soil moisture conditions could range from approximately 7 to 34 hours, well below the 48 hours commonly prescribed as a design specification for standing water. This estimate assumes an infiltration rate in the limiting clay layer of 0.04 to 0.20 in/hr (Hillel, 1982). Sixty-eight percent of all precipitation events measured over the months of April through November 2004 – 2007 had an antecedent dry period greater than 34 hours. By measuring the appropriate soil properties, environmental managers and engineers may have greater confidence when tailoring design specifications of a rain garden to new or retrofitted areas.

**Effects of Antecedent Conditions and Precipitation Intensity on Storage**

The lack of appreciable effluent from the turf and prairie vegetated rain gardens is a function of both the above and below ground storage capacity of the rain garden and the infiltration
rate of the underlying soils. If the supply rate of water to the rain garden is greater than the infiltration rate, excess water will accumulate in the rain garden and eventually become runoff once the level of water exceeds the rain garden berm. Although effluent discharge was rare, there were multiple times when influent exceeded infiltration into underlying soils resulting in pooled water.

Results from the CART analysis of climatologic variables and presence of pooled water indicated that 60-minute precipitation intensity largely determined whether water would pool in both the turf- and prairie-sand rain gardens (fig 14a). The majority of discharge events producing “wet” conditions were from high intensity precipitation events (greater than 0.24 in/hr). This is likely due to the high saturated hydraulic conductivity of sand allowing water to infiltrate quickly oftentimes exceeding the rate at which water would discharge into the rain garden. However, as the rate of water influent to the rain garden exceeded the infiltration rate, water would be stored above ground within the rain garden boundaries. Of the few discharge events producing “wet” conditions from low intensity events, all were a result of saturated soils from recent events.

Similar to the sand rain gardens, both precipitation intensity and the number of antecedent dry days between precipitation events were important factors controlling when water would pool in the turf-clay and prairie-clay rain gardens (fig 14b). As with the sand rain gardens, results of the CART analysis were similar for both vegetation types. The low saturated hydraulic conductivity of clay would require considerably more time between precipitation events to drain than sand. Subsequently, the majority of “wet” conditions in both the turf-clay and prairie-clay rain gardens were a result of precipitation occurring within the last 5 days. Similarly, Ishtok and Boersma (1986) concluded that antecedent moisture is more important than the magnitude or intensity of rainfall in controlling the occurrence of runoff. Pitt and others (1999) found infiltration rates in clay were affected by a strong interaction of compaction and moisture. Antecedent moisture could act as a
surrogate for antecedent dry days since soil moisture would decrease with increasing time between precipitation events. Secondary to antecedent dry days was precipitation intensity. All “wet” conditions in the prairie-clay rain garden were a result of not only a short amount of time between precipitation events but also precipitation intensity greater than approximately 0.3 in/hr. This condition was also true in the turf-clay rain garden although not quite as strong.

FIGURES 14A AND B NEAR HERE

Seasonal and Temporal Changes to Infiltration Rates

Infiltration rates were estimated at each rain garden using a simplified falling head technique. Estimates of infiltration rates were compared between soil types and vegetative species for seasonal and temporal changes. Median infiltration rates in sand rain gardens were greater than those in clay, regardless of vegetative species. Furthermore, in both sand and clay, prairie rain gardens had higher median infiltration rates than turf rain gardens. In general, higher infiltration rates were measured during spring and summer for all rain gardens.

Sand Site

Table 7 shows the number of discharge events producing pooled water during each water year as well as a statistical summary of estimated infiltration rates over the study period. Median infiltration rates in the prairie-sand rain garden are greater than in the turf-sand rain garden at 4.2 and 2.5 inches/hour, respectively. The large standard deviation in the prairie-sand rain garden suggests greater variability, covering a wide range of infiltration rates (fig. 15). At the beginning of the study, the prairie-sand rain garden had a greater number of discharge events that resulted in pooled water than did turf-sand rain garden (table 7). This may be a function of the both the soil structure and immature root development of the prairie vegetation shortly after planting. The upper
4.5 ft of soil in the prairie-sand rain garden contained greater amounts of clay and silt than found in
the turf-sand rain garden. Destruction of the natural soil matrix as well as removal of mature
vegetation during rain garden construction in the sand study area may have influenced infiltration
rates during the first study year. In later years, as the prairie root system matured, perturbation of
the soils may have allowed more rapid infiltration and thus fewer “wet” conditions. Improvements
to soil structure and infiltration rates in the prairie-sand rain garden may have been more prevalent
than in the turf-sand rain garden because of the abundance of sand directly beneath the turf-sand
rain garden. Evidence of improved infiltration rates in the prairie-sand rain garden are illustrated in
figure 15. Median values for estimated infiltration rates in the prairie-sand rain garden steadily
increased from 2004 through 2006. A slight drop in 2007 may be a result of when the discharge
events occurred. Five discharge events resulted in pooled water in the prairie-sand rain garden in
2007, three of which occurred in summer (August). Comparatively, in 2006, 3 of the 4 discharge
events producing “wet” conditions occurred in spring (May). Spring in this case is defined as the
months of March through May and summer defined as the months of June through August. Despite
results of the Mann-Whitney test indicating no difference in infiltration rate in the prairie-sand rain
garden between spring and summer (at the 5 percent significance level), many of the estimated
infiltration rates in the prairie-sand rain garden were greater in spring than in summer, especially
during 2006 and 2007 (fig. 16). Diamond and others (1998) found a similar seasonal pattern when
assessing the spatial and temporal variability of infiltration capacity of major soil types in Ireland.
This pattern was not reproduced in the turf-sand rain garden which showed a similar range in
infiltration rates in the summer and spring. Unlike the prairie-sand rain garden, infiltration rates in
the turf-sand rain garden remained relatively consistent, ranging from 2 to 4 in/hr, except in 2005
when a single infiltration rate of nearly 10 in/hr was estimated. It is unclear why this single event is
much larger than all others but was included when comparing changes to infiltration rates over time and season in the turf-sand rain garden.

Winter and fall were excluded from statistical tests due to a limited sample population. Water pooled in the prairie-sand rain garden only twice during winter, February 2004 and January 2005, resulting in an estimated infiltration rate of 0.75 and 2.28 inches/hour, respectively. There were no pooled water events during winter in the turf-sand rain garden. Muthanna and others (2006) found the hydraulic performance of an experimental rain garden in Norway was not impacted by the climatic factors experienced during the cold season. Given the paucity of pooled water conditions in the sand rain gardens during winter months, it is likely their hydraulic function was not appreciably altered by frozen soils.

**TABLE 7 NEAR HERE**

**FIGURE 15 NEAR HERE**

**FIGURE 16 NEAR HERE**

Clay Site

*Table* 7 shows the number of discharge events producing pooled water during each water year as well as a statistical summary of estimated infiltration rates over the study period in the clay rain gardens. Median infiltration rates in the prairie-clay rain garden are more than three times greater than in the turf-clay rain garden at 0.88 and 0.28 inches/hour, respectively. Despite the disparity between overall median infiltration rates, the turf-clay rain garden exhibited a general increase in annual median infiltration rates from 2004 through 2007 ranging from less than 0.2 in/hr in 2004 and 2005 to over 0.4 in/hr in 2006 and 2007 (*fig.* 17). Although the increase in infiltration rates appears modest, they represent an appreciable improvement over those measured prior to rain.
garden construction. Infiltration rates of approximately 0.1 in/hr were measured by use of a double-ring infiltrometer at the clay rain garden site prior to rain garden construction. Destruction of the natural soil matrix by excavation and compaction can decrease hydraulic conductivity (Pitt and others, 1999; Legg and others, 1996). Considering the soil structure prior to this study was likely degraded from construction activities, it would not be unusual to see an increase in infiltration rates regardless of vegetation type. Hino and Shutto (1987) found the growth of grass altered the structure of soils within 2 months of establishment and measured increases in saturated hydraulic conductivity from 0.24 in/hr in bare soil to nearly 4.0 in/hr for grass-covered soil. Despite annual differences in median infiltration rates, seasonal differences were not as apparent. Comparison of seasonal infiltration rates using a combination of the Kruskal-Wallis test for multiple groups and Dunn’s test suggested infiltration rates in the turf garden were greatest during summer months at the 5 percent significance level. Winter infiltration rates in the turf-clay rain garden were the lowest of all seasons with a median value of 0.11 inch/hour; the same as the infiltration rate measured prior to rain garden construction. Furthermore, infiltration rates increased by season with winter being the lowest, then spring, fall and finally, summer the highest (fig. 18).

Similar to the turf-clay rain garden, an increase in annual median infiltration rates was also measured in the prairie-clay rain garden (fig. 17). Rates ranged from 0.6 in/hr to more than 1.0 in/hr in 2004 and 2008, respectively. As with turf, prairie vegetation can improve hydraulic conductivity by creating and (or) improving macropores from extensive root growth (Beven and Germann, 1982). Under favorable circumstances, macropore systems can be developed in as little as 1 to 2 years (Beven and Germann, 1982). Little can be inferred as to the direction of median infiltration rates in 2005 and 2006 due to the lack of data. However, fewer rather than more data points in figure 17 qualitatively suggest a greater infiltration rate. Since a lack of pooled water would
preclude estimation of an infiltration rate, as was often the case in the prairie-clay rain garden, the rate at which water infiltrated into the soil was likely greater than the rate of water influent to the rain garden. Results of the Mann-Whitney test indicate no difference between spring and summer infiltration rates at the 5 percent significance level for the prairie-clay rain garden. Due to the lack of “wet” conditions in the prairie-clay rain garden during fall and winter months, an evaluation of seasonal differences was limited to only spring and summer.

FIGURE 17 NEAR HERE

FIGURE 18 NEAR HERE

Vegetative Effects on Soil-Moisture

Analysis of the temporal variation of soil moisture can be qualitatively useful in estimating the timing, depth and duration of recharge events (Delin and Herkelrath, 1999). Interpretation of fluctuations in soil moisture in the unsaturated zone is based on the premise that water in the soil above the vegetative rooting depth travels upward in response to evapotranspiration. Water below that depth drains downward to the water table as recharge. This evapotranspiration/drainage boundary is further described by Delin and others (2000) when using soil moisture as a means to compute a volumetric mass balance of the unsaturated zone.

Visual observation of time-lapse imagery in conjunction with the vertical soil moisture profile illustrates the combined effect of root systems and evapotranspiration on soil moisture in the prairie-clay rain garden during an extended dry period in 2005 (fig. 19a). From figure 19a, a diurnal fluctuation in soil moisture with increasing depth becomes more evident from May through August 2005. Multiple days with no precipitation forces the prairie root system to tap into deeper sources of soil moisture. The development of root systems into deeper soil depths may increase the
infiltrative capacity of a rain garden by creating macropores and other fissures that allow for more rapid water movement. This might also explain in part the larger median infiltration rate measured in the prairie-clay rain garden compared to the turf-clay rain garden (table 7). The diurnal fluctuation in soil moisture over the same time period is not as prominent in the turf-clay rain garden (fig. 19b). This is likely due to the shallow root depth of turf grass. Only the uppermost soil layer (0.5 feet below land surface) showed appreciable decline in soil moisture.

**Figures 19a and b near here**

In September 2008, an effort was made to track the temporal changes in soil moisture after artificially flooding the prairie-clay rain garden. Because there was evidence of a limiting clay layer approximately 3 ft below the land surface (fig. 8), water was expected to pool and accumulate at or near this depth. However, if the prairie root system was capable of penetrating through the limiting layer then water could slowly percolate downward. Soil moisture was measured vertically by use of a neutron logger at four intervals: before flooding, 1 hour after flooding, and 3 and 6 days after flooding. As expected, soil moisture rapidly increased in the uppermost soil layers shortly after flooding of the rain garden began (fig. 20). After 1 hr, modest increases in moisture levels continued down to a depth of approximately 8 ft, 5 ft below the demarcation of the upper limiting layer. Soil moisture returned to before flooding levels down to approximately 6 ft after 3 days; however, moisture from 6 to 8 ft remained high even after 6 days. It is likely a second, thinner layer at approximately 8 to 9 ft was limiting the downward movement of water causing a perching effect, and thus elevated moisture levels above 8 ft for an extended period of time. Despite the presence of a lower limiting layer, water still advanced downward as recharge as is evident by the increase in soil moisture after 3 and 6 days after rain garden flooding below 10 ft. An increase in soil moisture in the upper limiting layer, while small, might indicate perturbation of the soil by
prairie roots. The clay rain gardens were excavated shortly after the flood test to verify the extent of soil structure and root morphology. The results are discussed later in this report.

**FIGURE 20 NEAR HERE**

Additional evidence of deep penetrating prairie root systems is further illustrated in the prairie-sand rain garden (fig. 21). In 2005, there was little change in soil moisture levels after extended periods of no precipitation in both the turf- and prairie-sand rain gardens at 1.6 and 2.6 feet below land surface, respectively. In 2007, however, soil moisture in the prairie-sand rain garden began to display a diurnal fluctuation during extended dry periods; an indication of the effect of evapotranspiration. In contrast, the turf-sand moisture levels showed a steady decline in soil moisture levels. This is more likely a function of evaporation and drainage than the water needs of a root system.

**FIGURE 21 NEAR HERE**

**Comparison of Soil Properties and Root Morphology**

In October 2008, five years after planting, an observation trench was excavated through the approximate center of the prairie- and turf-clay rain gardens to characterize differences in soil properties and rooting between vegetation types. Although the turf- and prairie-clay rain gardens had similar soil textures and soil horizon designations, there were striking differences in soil characteristics between the two clay gardens. Table 8 details physical characteristics of the soil profiles in the turf- and prairie-clay rain gardens.

The differences in soil properties were associated with water and air movement within the two rain gardens. The soil under the prairie-vegetated rain garden, although possessing the remnants of a limiting clay layer, appeared well-drained. At no time during field sampling did
water enter the prairie-clay trench from the profile wall or its bottom. Conversely, there was clear evidence of a perched water table at approximately 0.7-1.0 ft below the surface of the turf-planted rain garden. Water not only seeped into the turf-clay trench during sampling, but a strongly gleyed horizon was present from 1.05-2.95 ft indicative of an anaerobic, saturated environment; a weakly gleyed horizon in the prairie-clay garden (0.66 ft in thickness) ended at 1.51 ft below the surface. Oxidized mottles and other redox features within the master B horizon of the turf-clay rain garden further indicated the presence of a fluctuating perched water table. Moreover, the Bt horizon above the gleyed layer in the turf-clay soil possessed a higher clay fraction such that it was classified as a silt loam relative to the Bt horizon in the prairie-clay soil. This observation may indicate a hydrologic transfer of the finer clay fraction to lower horizons in the prairie-clay profile. Finally, a substantial clay fraction was found in the lower B horizons of both rain gardens evidenced by an angular blocky to somewhat platey structure, as well as the laboratory particle size classification of silty clay loams.

The 2008 soil profile descriptions also indicated differences in flora and fauna activity between the prairie- and turf-clay rain gardens (table 8). Many fine roots were found from the surface down to 0.46 ft in the turf-clay rain garden, while the prairie-clay rain garden had roots extending to a depth of 4.7 ft (absolute rooting depth in the turf-clay garden was 0.56 ft). Moreover, many roots were found within the Btg horizon of the prairie-clay garden relative to an absence of roots in the Btg horizon of the turf-clay rain garden. The greater amount and depth of rooting in the prairie-clay rain garden coincided with greater macrofauna activity, as many earthworms were found, along with many abandoned worms channels and cavities once occupied with roots. These channels were either lined with organic matter or redox features indicating the movement of water and air into lower horizons of the prairie-clay rain garden. Conversely, there was little evidence of
macrofauna activity in the soil under the turf. This biological activity was also evident in the horizon boundaries, as the prairie-clay soil had horizon transitions that were wavy, irregular, and clear, while the horizon boundaries of the turf-clay soil were largely smooth and abrupt. Collectively, these differences in soil properties point to greater pedoturbation in the prairie-clay rain garden relative to the turf-clay rain garden.

**TABLE 8 NEAR HERE**

Although the absolute values of dry root mass were low relative to mature turf and prairie systems, differences were evident between the prairie-clay and turf-clay gardens (table 8). The root number and dry mass in each rain garden (prairie-clay garden being greater) mirrored the differences of organic matter throughout each profile. While both soils possessed an Oi and A horizon, the organic accumulation of the prairie-clay rain garden was 0.4 in thicker in the Oi horizon and 4 percent greater in the A horizon relative to the turf-clay soil. This percent difference in organic matter between gardens carried into the B horizons with the prairie soil averaging one percent greater organic matter compared to the turf-clay garden. These biotic-derived differences appear to also correlate with differences in soil bulk density between the two rain gardens. Both rain gardens displayed the typical increase in bulk density with depth; however, the soil of the prairie-clay rain garden was less dense overall, particularly in the A and Btg horizons relative to the turf-clay soil.

Similar to the differences in dry root mass, rooting behavior also varied between the prairie-and turf-clay rain gardens. Whereas roots were present in all horizons sampled within the prairie-clay soil (absolute rooting depth to 4.7 ft), roots were only found in the A and Bt horizons within the turf-clay rain garden. The absence of roots below 1.05 ft in the turf-clay soil may be explained by the interaction between the shallow-rooting turf grass and the saturated, anaerobic character of
the thick Btg horizon. Conversely, the prairie species appeared to penetrate the “limiting layer” and encouraged mixing of surface organics, macrofauna, water, and air deeper into the profile.

There were marked differences in rooting morphology (e.g. length, density, amount) between the prairie- and turf-clay rain gardens (table 9). The mean dry root mass per volume of soil within the A horizon of the prairie-clay rain garden was almost double that of the turf-clay rain garden; root mass within the Bt was similar between rain gardens. The SRL was 23 percent lower and 14 percent greater in the A and Bt horizon, respectively, of the prairie-clay soil relative to the turf-clay soil. Conversely, the RLD was 75 percent greater in the A horizon of the prairie-clay rain garden relative to the turf-clay soil, while the RLD in the Bt horizon was similar between rain gardens. These differences in rooting morphology concurred with the differences in SOM and bulk density between the two rain gardens where greater root mass equated with higher SOM and lower bulk density. Moreover, these quantitative measures capture the interaction between vegetation types and soil that controls rain garden function.

The length of a plant’s root system largely controls its acquisition of water and nutrients, as well as the development of soil structure. Although species vary widely in their specific root length, the relative differences observed between the two rain gardens studied here helps explain the differences observed in soil development (Fitter, 1985). Species with a relatively small investment in root biomass per unit root length, high SRL, may possess an advantage for exploiting pulses of water in the soil by quickly increasing root length (Eissenstat and Caldwell, 1989; Chapin, 1989). Moreover, a lower energy cost per unit length of root may facilitate soil development, as the plant can afford to explore a greater volume of soil and typically turnover roots at higher rates (Grime and others, 1986). In a study of 13 year-old orange trees grown in disturbed soil, rootstocks with
higher SRL and greater RLD were able to extract water more rapidly than those with lower SRL (Eissenstat, 1991).

This interaction between roots and soil may explain the greater soil development in the prairie-clay rain garden. Within the A horizon, the prairie roots not only had a greater mass of roots per volume of soil, but also a lower mass investment per length of root such that there was almost double the rooting length per volume of soil in the prairie-clay rain garden relative to the turf-clay rain garden. This trend between rain gardens carried into the Bt horizon although the differences were much less pronounced. Therefore the ability of the prairie to build an energetically less expensive root system may have facilitated higher rates of root proliferation leading to greater soil development and improved infiltration for water and air. The 2008 profile observations in table 8 support this hypothesis.

Finally, the absolute values of root mass, SRL, and RLD for these rain gardens were low relative to published values for grasses. The relative immaturity of these systems and our one-time sampling late in the growing season may help explain this difference. Moreover, the differences in soil development reported here are based on two rain gardens. Sequential coring and additional treatment replication would increase the reproducibility of these data.

TABLE 9 NEAR HERE

Conclusion

Recent trends in urban runoff mitigation have resulted in a number of technologies that focus on infiltration. One such technology, known as a rain garden, is a shallow depression that accepts runoff generated from nearby impervious surfaces and infiltrates that runoff back into the underlying soil. Additionally, rain gardens may provide some level of water-quality benefit by
settling, filtration, adsorption, decomposition, ion exchange, and volatilization. Rain gardens range in size but are commonly used as a way to retrofit existing urban areas where land requirements often preclude larger structures. Although the use of rain gardens is increasing, there appears to be no clear consensus on how soils at the site might limit the use of an infiltration device. In order to expand the use of rain gardens and other infiltration devices, more needs to be known about soil amendments and sizing criteria that will reduce the uncertainty of requiring infiltration in soils with lower infiltration rates.

To that end, the U.S Geological Survey, in cooperation with a consortium of nineteen cities, towns, and villages in Dane County, Wisconsin, undertook a study to evaluate the effectiveness of rain gardens with different soil types and vegetative species for stormwater infiltration. Two rain gardens, one planted with turf grass and the other with native prairie species, were constructed side-by-side in two locations of different soil types, sand and clay. Instruments were installed to measure the volumetric mass balance of each rain garden from late 2003 through 2008. Root morphology, soil texture and other subsurface properties were characterized to understand differences in storage capacity and infiltration rates between vegetation and soil type.

Results of the study show that each rain garden, regardless of vegetation or soil type, was capable of storing and infiltrating the majority of runoff over the 5-year study period. Median infiltration rates for rain gardens in sand were greater than those in clay. Within each soil type, rain gardens with prairie vegetation had greater median infiltration rates than those with turf. Infiltration was generally highest during spring and summer months and lowest during winter. Despite reduced infiltration rates during months when soils were likely frozen, the hydraulic function of the rain gardens did not appear to be appreciably altered.
The success of the rain gardens was primarily because the 5 to 1 ratio of contributing to receiving area (4 to 1 for the prairie-clay rain garden) and 0.5 ft depth were fully capable of storing and infiltrating nearly all the stormwater. Even when the contributing area was doubled to 10 to 1 in the turf-sand rain garden and 8 to 1 in the prairie-clay rain garden, only a limited amount of outflow was generated. Approximately 90 percent of all precipitation events measured over the 4 year study were capable of being stored in the gardens (assuming an infiltration rate of zero). The percentage of precipitation events fully retained by each rain garden increased to nearly 100 percent when factoring in the median infiltration rate and specific yield of subsurface soils. Precipitation intensity and antecedent dry days were the dominant secondary controlling factors when determining when the storage capacity of a rain garden might be exceeded resulting in pooled water above ground.

Because of the large area of rooftop contributing runoff to each rain garden, evapotranspiration was a small percentage of the overall water balance. Therefore, the majority of annual runoff volume influent to each rain garden was recharged back into groundwater, regardless of vegetation or soil type; however, differences in annual recharge between the turf grass and prairie rain gardens in clay were slightly greater than differences between vegetative species in sand. This is largely due to a much smaller amount of evapotranspiration estimated for prairie species than for turf grass.

Examination of soil development and root morphology in the clay rain gardens 5 years after planting clearly showed greater biological activity of both flora and fauna in the prairie-clay rain garden compared to the turf-clay rain garden. Roots in the prairie-clay garden were found to a depth of 4.7 ft compared to 0.46 ft in the turf-clay rain garden. The greater amount and depth of rooting in the prairie-clay rain garden coincided with greater earthworm activity along abandoned
worms channels and cavities once occupied with roots. These channels were either lined with organic matter or redox features indicating the movement of water and air into lower horizons within the prairie-clay rain garden. Moreover, the prairie roots had a lower mass investment per length of root such that there was almost double the rooting length per volume of soil in the prairie-clay soil relative to the turf-clay soil. Collectively, these differences point to greater pedoturbation and soil development in the prairie-clay rain garden relative to the rain garden planted in turf grass which may result in greater capacity to store and infiltrate stormwater.

By measuring the appropriate soil properties, environmental managers and engineers may have greater confidence when tailoring design specifications of a rain garden to new or retrofitted areas. If surficial area is unavailable, then storage of runoff can be created by excavating to a greater depth, even in the presence of clay.

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