IMPACTS OF BIOTA ON BIORETENTION CELL FUNCTION DURING ESTABLISHMENT IN THE MIDWEST

by

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Abstract

To understand the region-specific effects of biota on function of bioretention cells, a lysimeter study was conducted at Kansas State University to determine how earthworms and native Kansas grasses impact runoff treatment and hydraulic function of a bioretention cell. This study also employed the Comprehensive Bioretention Cell (BRC) model to demonstrate how three seasons of growth could impact bioretention cell function. The model results of the first season of growth were then compared to field data. Results indicate that the interaction of plant roots and soil macrofauna over one growing season improved several aspects of bioretention cell function. The greatest increase in saturated hydraulic conductivity was in the treatment that included both plants and macrofauna. The presence of vegetation reduced ponding effects and increased water storage. Earthworm treatments had a lesser ability to store water. All treatments were effective in reducing the concentration of P in effluent. A large amount of N was released during all events from all treatments probably because of a high initial N content of the bioretention media. No treatment performed significantly better in improving water quality, indicating that macropore flow in the earthworm treatments did not induce a higher rate of pollutant transport.

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CHAPTER 1 - Introduction

Urban stormwater management is receiving increased attention as a result of the National Pollutant Discharge Elimination System (NPDES) Permit Program and growing awareness of stormwater runoff impacts on surface and groundwater source quality and quantity. Many existing stormwater structures convey runoff from impervious urban areas over concrete channels and directly into water resources, bypassing opportunities for natural treatment and aquifer recharge. The result is eroded stream channels and potential flooding in downstream areas with pollutants from parking lots, roads, and lawns transported to the nearest lake or river.

To alleviate stormwater impacts on receiving waters, a number of Stormwater Best Management Practices (BMPs) have been developed. BMPs can be used in conjunction with, or as an alternative to, traditional stormwater practices and facilitate water treatment through natural processes. A bioretention cell is a recessed area of vegetation designed to accept and treat stormwater runoff through infiltration into layers of plant roots and growing medium, and is just one example of a BMP. The conventional design has been found to significantly reduce concentrations of heavy metals (copper, lead, and zinc), oils and grease, Total Kjeldahl Nitrogen (TKN), ammonium, and total phosphorus from stormwater runoff (Davis et al. 2001, 2003; Sharkley and Hunt, 2005). However, design limitations arise from the lack of understanding of the influence of ecological factors on the function and longevity of bioretention cells.

Previous bioretention research has focused on engineering the cell for hydraulic properties and has thus neglected the important role that plants and belowground processes play in improving infiltration and pollutant removal. Bioretention cell research has also primarily been conducted on the east and west coasts of North America, leaving few applicable standards for other regions. Having national bioretention cell design standards that suggest use of coastal plants have caused several Midwestern cells to fail. People are losing faith in the idea of so-called *Best* Management Practices and thus knowledge and research on the region-specific function of Bioretention cells is necessary. To encourage use of BMPs in the Midwest this research is focused on the region-specific function and design of bioretention cells.

CHAPTER 2 - Literature Review

Urban Stormwater Management

Since the implementation of the Clean Water Act (CWA) of 1972 and the National Pollutant Discharge Elimination System (NPDES) by the United States Environmental Protection Agency (EPA), the quality of America's surface waters has vastly improved. This is due to the issuance of over 65,000 permits to industrial and wastewater facilities to control point source pollution (Swietlik, 1997). However, the impairment of surface water quality due to stormwater runoff is difficult to address under similar jurisdiction.

Stormwater runoff is excess water from any precipitation event not intercepted or retained by vegetation and results in overland flow (Davis, 2005). Existing urban stormwater structures convey runoff from impervious areas over concrete channels and directly into water sources, bypassing opportunities for energy reduction and treatment by natural processes. Runoff, when managed by traditional systems, adversely impacts surface water quality in two ways: through the introduction of nonpoint source (NPS) pollutants and by altering the hydrologic cycle.

NPS pollutants are defined as pollutants that are derived from many different sources and are distributed intermittently, usually linked with precipitation (Carpenter et al. 1998). These pollutants are very difficult to control due to their high variability and diffuse nature; they do not come from one exact source. In the urban environment, debris and pollutants are carried over impervious areas during precipitation events.

Nearly 40% of NPS pollution comes from urban sectors, where the combination of concentrated populations and impervious surfaces contribute to more pollution and higher volumes of stormwater runoff (EPA, 1997). NPS contaminants commonly found in urban runoff include sediment, suspended solids, nutrients, heavy metals, pathogens, toxins, and oxygen-demanding substances (Swietlik, 1997). The result is eroded stream channels and potential flooding in downstream areas.

The Clean Water Act and NPDES Permitting

There are two main sections of the Clean Water Act (CWA), the first part allocates funding for municipal sewage treatment plants and the second regulates discharge from municipal and industrial sites. The primary focus of the CWA before 1987 was on point sources of pollution. Amendments (section 319) in that year recognized that nonpoint sources of pollution (NPS) accounted for 50% of our Nation's water quality problems and directed states to implement NPS pollution programs and pursue groundwater protection (EPA, 2002).

The CWA was founded around the concept that "all discharges into the Nation's waters are unlawful, unless specifically authorized by a permit". This was achieved in part through the establishment of the National Pollution Discharge Elimination System (NPDES) program. The NPDES program requires municipalities and local entities to meet technology based effluent limitations and attain a 5-year renewable permit. Current evaluation criteria are established for 115 pollutants that recommend ambient pollutant concentration limitations (EPA, 1999).

Stormwater management has recently received increased attention due to implementation of Phase II of the NPDES Permit Program. Phase I required operators of large and medium municipal separate storm sewer systems (MS4's) to pursue stormwater programs that protect water quality and reduce discharge of pollutants from new and re-developed areas (EPA, 2005). Starting in 1999, Phase II required smaller municipalities to undergo similar jurisdiction. Thus, the need for research on Best Management Practices (BMPs) and urban diffuse pollution control strategies is essential for timely adoption of NPDES permitting in smaller cities, as well as improvement of existing BMPs in larger cities.

Best Management Practices

To alleviate stormwater impacts on receiving waters, a number of stormwater Best Management Practices (BMPs) have been developed. BMPs can be used in conjunction with, or as an alternative to, traditional stormwater practices to facilitate water treatment through natural processes. Bioretention cells are one BMP that have developed (Figure 2.1). A bioretention cell is a recessed area of vegetation designed to accept and treat stormwater runoff through infiltration into layers of plant roots and growing medium. The conventional bioretention cell design has been found to significantly reduce concentrations of heavy metals (copper, lead, zinc),

oils and grease, Total Kjeldahl Nitrogen (TKN), ammonium, and total phosphorus (TP) from stormwater runoff (Davis et al. 2001, 2003; Sharkley and Hunt, 2005).

Figure 2.1 Conventional bioretention cell from NRCS website (www.ia.nrcs.usda.org)

However, design limitations arise from the lack of understanding of the influence of biology on bioretention cell function and longevity. A larger emphasis must be placed on selecting vegetation and may require in-depth knowledge of the ecosystem in which the cell is built.

Evolution of Bioretention Cell

The majority of design guidance for bioretention cells has been provided by the Environmental Protection Agency (EPA) and research conducted at the University of Maryland and the North Carolina State University (Davis et al. 2001, Davis et al. 2003, Hsieh and Davis, 2004, Sharkley and Hunt, 2005, Hunt et al. 2006, Davis, 2007). Guidelines suggest that a bioretention cell must infiltrate and retain the “first flush”, or the first inch (25.3 mm) of runoff from paved areas that contain a majority of the solids and pollutants (EPA, 2004, Hunt et al.

2006). To capture the first flush, bioretention cells are typically sized at about 5 to 10% of the contributing watershed (Chavez et al. 2006, NCDNER, 2007). Any runoff ponded on the cell surface must drain through the soil profile within 24 to 48 hours (NCDNER, 2007). This standard eliminates health risks associated with standing water and mosquitoes. Bioretention cells must also have an overflow system to prevent inundation from large storm events.

Bioretention media can be "engineered" to allow for adequate water movement and is usually made up of sands and fines (clays) mixed and layered to allow for sufficient permeability (Davis et al. 2001, Hseih and Davis, 2005). A study by the University of Maryland assessed different combinations of bioretention media. The use of a uniform, moderately permeable organic top soil layer facilitates plant growth and temporary storage of runoff, allowing sorption by organic matter or degradation by microorganisms. However, during large storm events, the permeability was insufficient for drainage. The use of a coarse sand and sandy loam mixture allowed for high pollutant mass removal and an infiltration rate of 1.2-5.4 cm hr^{-1}, or 4-6 times faster than the sandy loam top soil. The soil ratio in the second configuration ranged from 20-70% by mass depending on vegetation requirements (Hseih and Davis, 2005), but may not have sufficient organic matter content to support growth and longevity of vegetation. Other studies have found that uniformly mixed sandy loam soils with a mulch top layer remove significant amounts of heavy metals and moderate levels of TKN, TP, and ammonium. Particularly, studies have noted the impact of the mulch top layer in metal binding and removal (Davis et al. 2001, Sharkley and Hunt, 2005). The role of soil media pH cannot be ignored as soil acidity dictates the adsorption of metals (Hseih and Davis, 2005; Sharkley and Hunt, 2005).

The conventional bioretention cell is basically an enhanced infiltration basin that allows for plant growth in the top 0.7-2.0 m of soil media underlain by a drain and gravel envelope (Hunt et al. 2006) and has been an effective method for runoff reduction and pollutant removal from stormwater runoff. With a soil-mulch-plant based bioretention cell, Davis et al. (2001) reported a large decrease in copper, lead, and zinc (>92%), moderate decreases in phosphorus (80%), TKN (65-75%), and ammonium (60-80%). The removal of nitrate, however, was minimal and very inconsistent.

To increase nitrate removal in a bioretention cell, Hunt et al. (2006) suggested the addition of an anaerobic zone. This 18 cm deep zone was located at the bioretention cell base and provided an electron donor source to encourage denitrification. The results showed that there was

still a minimal removal of nitrogen, this may be due to the continual "flushing" of new rainwater and dissolved oxygen through the cell. This created an aerobic environment which is unsuitable for denitrification.

Conventional bioretention cell design also neglects the importance of biology in the management of stormwater. A functioning bioretention design must mimic a natural, functioning ecosystem. Thus, this "ecosystem" must be regionally appropriate and site-specific. By incorporating native vegetation and fauna, a bioretention cell will establish more rapidly and be more stable during changes in runoff volumes and pollutant concentrations.

Ecological Aspects of Bioretention Cell Design

The ability of a bioretention cell to manage stormwater is dependent upon the ability of the designer to mimic a natural, functioning ecosystem. This study focuses on the Midwestern region and more specifically the region previously covered by the tallgrass prairie. The tallgrass prairie includes the Konza Prairie, a Long Term Ecological Research (LTER) site known for large populations of warm-season grasses that are distinguished by extensive root systems.

Soil and Bioretention Media

The hydraulic properties of soil dictate how much water a system can retain. Water retention is especially important for stormwater management in urban areas in order to control the high energy and volumes of urban runoff. The ability of a soil to conduct or retain water is controlled by the pore structure, which is *a* function of mineralogical composition, age, organic matter content, water content, transport processes, weather, plant roots, soil organisms, and management (Kodesova et al. 2006).

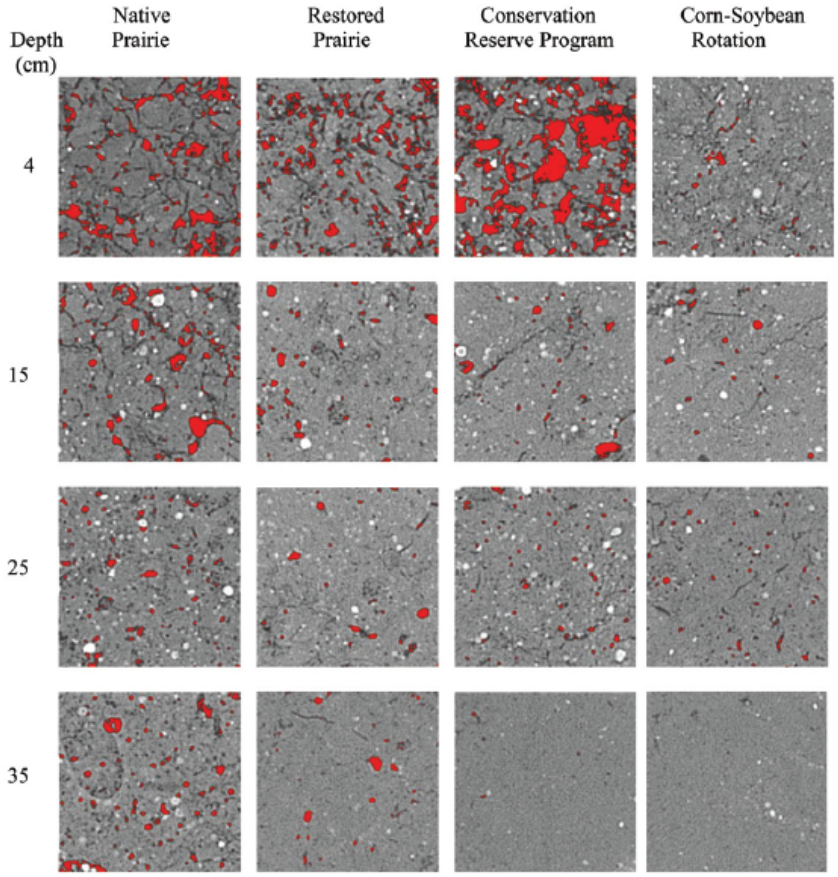
Macropores are defined as large, continuous pores within soil where water is not restricted by capillary forces (Beven and Germann, 1982) and are ideal for bioretention cell function. Macropores constitute a small proportion of total soil volume, but can facilitate preferential water flow (Beven and Germann, 1982; Chen and Wagenet, 1992; Ela et al. 1992; Wang et al. 1994; Weiler and Naef, 2003; Helman-Dodds, 2006; Jarvis, 2007). Preferential flow describes the rapid water flow occurring at localized points of saturation as water near atmospheric pressure bypasses the soil matrix by way of the macropore (Jarvis, 2007).

These voids are created by plant root growth, soil fauna burrows, cracks from wetting cycles, and natural erosive action within the soil profile. Reported macropore size varies widely between 30 μm to 5 mm (Chen and Wagenet, 1992), but conventionally the minimum pore size must be greater than 0.3 mm to effectively transmit water (Jarvis, 2007)..

Bioretention media typically is "engineered" to permit adequate infiltration and is generally made up of sands and fines (clays) mixed and layered (Davis et al. 2001, Hseih and Davis, 2005). However, engineering soil specific for infiltration properties may require a financial investment and may not yield much if any improvement over using native soils. Engineered soil also may not have the structure to support a healthy and native ecosystem of plants and soil fauna, so it may be beneficial to let the biology engineer the soil and make an environment suitable for the improved nutrient, wetting, and drying cycles of a healthy ecosystem. A designer must look to native ecosystems in their region and try to replicate the soils, plants, and microfauna in a bioretention cell.

For example, Kansas has very distinct wet and dry seasons. A sand soil matrix would not provide the water retention necessary to hold water from the wet season to support vegetation during the dry season. The system would not be sustainable due to the frequent irrigation inputs required to maintain the soil moisture necessary for plant growth. As shown in Figure 2.2 from Udawatta et al. (2008), the native prairie and restored prairie soils are made up of pores of varying sizes, while the tilled/disturbed soil hardly has any noticeable pores at all. Thus, the desired infiltration rates will be developed with the growth and formation of roots and macropores.

Figure 2.2 A 2500 mm^2 scan of soils showing air-filled pores in red (Udawatta et al. 2008)



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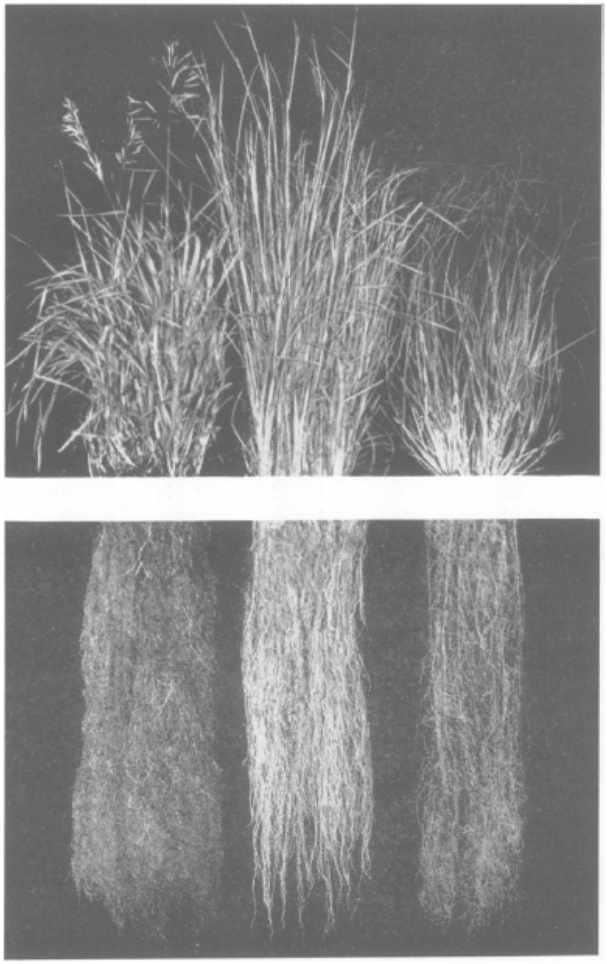
Native Tallgrass Prairie

Native tallgrass prairie plant species are believed to improve soil physical and chemical processes in a Midwestern bioretention cell. Tallgrass species are associated with exceptionally productive soil systems (Helman-Dodds, 2006); their growth encourages mychorrizhal and microbial activity, nutrient cycling, and the uptake and storage of carbon (Rice et al. 1998). Studies on the Konza Prairie in eastern Kansas have found that grass roots may constitute two to four times the amount of aboveground biomass, or 859 to 1086 g m^{-2} in the top 30 cm of soil (Rice et al. 1998). The dense root structure (see Figure 2.2) allows these grasses to withstand the climatic variability typical of the Midwest in which 75% of precipitation falls during the growing season with heavy, intense thunderstorms, followed by periods of drought during hot summer months (Hayden and Davis, 1998).

The season of activity for prairie grasses begins in mid-April and continues into the late summer with grasses reaching their maximum stalk height in late June or early July (Weaver and Rowland, 1952). Grasses can rapidly reestablish themselves after a disturbance such as fire (Weaver and Zink, 1947) and vigorous growth can continue well into September (Weaver and Zink, 1946). Root densities fluctuate seasonally with changing patterns of rainfall and temperature (Dahlman and Kucera, 1965; Hayes and Seastedt, 1987). The seasonal maximum density of roots occurs in the top four centimeters of soil in early July, and later in deeper soil layers (Dahlman and Kucera, 1965).

Figure 2.3 The a) tops and b) roots of *Bromus inermis*, *Schizachyrium scoparium*, and *Stipa spartea* at the conclusion of one season of growth from seed (Weaver and Zink, 1946)



Roots enhance soil physical properties and increase soil porosity by forming aggregates and macropores. Living roots either create new macropores with growth or utilize existing root or worm channels. Empty macropores elicit water movement as roots decay (Fuentes et al. 2004). Aggregates are created through the root's synthesis of organic matter into humus and also through the mechanical act of root formation (Weaver and Zink, 1946). It is important to understand that root growth does not disturb the presence of soil micropores, or the "fine structure" of soil. This allows the soil to maintain moisture capacity in addition to being highly conductive (Hino et al. 1987).

The preservation of "fine structure" with root growth was illustrated in a study on infiltration and runoff processes in grassed lysimeters by Hino et al. 1987. A little more than half (60%) of the runoff from the control (bare soil) lysimeter occurred as overland flow, while the

grassed lysimeter produced very little overland flow. This result was attributed to improved soil conductivity (from 6 to 100 mm/hr), increased evapotranspiration rates, and also the reallocation of soil moisture. In the grassed lysimeter, water was stored in soil pores near roots to restore the moisture deficit from evapotranspiration, and so soil moisture near the surface remained more constant. Runoff was accepted into this cell more readily for plant water uptake. In contrast, water in the bare soil lysimeter was not readily transmitted through the profile and water not lost as overland runoff became groundwater recharge without treatment by plant uptake and filtration through root pores (Hino et al. 1987).

Maximum root growth for most tallgrass species, including *Schizachyrium scoparium* (little bluestem) and *Bouteloua gracilis* (blue gama) occurs after the second growing season (Weaver and Zink, 1946), and in the third growing season for *Andropogon gerardii* (big bluestem). Root productivity decreases in all soil layers over the winter season (Hayes and Seastedt, 1987) and roots in the upper soil layers die, while deep roots are buffered from seasonal change and retained to initiate growth the following spring (Weaver and Zink, 1947).

Lumbricus terrestris

Appropriately dubbed “Intestines of the Earth” by Aristotle, earthworms improve soil structure through burrowing and casting (Lee and Foster, 1991). Earthworms have also been shown to influence soil productivity and nutrient cycling (Edwards and Fletcher, 1988; James, 1991; Lee and Foster, 1991). Thus, earthworms may have an interesting impact on plant growth (Brown, 1995) and soil physical properties in a bioretention cell. This may especially be true in a bioretention cell modeled after the tallgrass prairie ecosystem where earthworms constitute the largest portion of soil invertebrates by biomass (James, 1991, Rice et al. 1998).

Burrows are formed through the ingestion and excretion of soil particles and also through the lateral pressure created by the earthworm body on soil. The result is a hardened burrow wall, or drilosphere, which can be 1-10 mm thick and remain intact under disturbance (Edwards et al. 1990, Linden et al. 1991). The excretions from earthworms can account for 4-6% of the mass in the top 15 cm of soil, and for 2-35% of the annual organic matter production in the tallgrass prairie (James, 1991).

Earthworms improve soil productivity by mineralizing organic matter and enabling further degradation through microbial activity or uptake by plants. In a study on soil and nutrient processing in the tallgrass prairie, earthworms were found to mineralize 10-12% of the N and 50% of the TP taken up by prairie plants on an annual scale (James, 1991). Earthworms also indirectly encourage microbial activity and pollutant degradation through the organic-rich drilosphere of earthworm burrows (Edwards et al. 1992, 2004). Edwards et al. (1992) also reported that earthworm burrows induced an 88 and 82% decrease in the concentrations of Alachlor and Atrazine, respectively. This reduction was attributed to sorption of the chemicals to the organic material in the burrow wall.

Earthworm burrows may also stimulate plant growth. Roots tend to grow in earthworm burrows due the increased amounts of oxygen and water and lack of mechanical resistance (Kirkham, 1982). In a study on earthworm inoculation, the presence of earthworms had minimal effect on plant growth in the first year, but total yield increased by 25 and 49% in the second and third years, respectively (Baker et al. 2006). A restoration project by Blanchart et al. (1992) found that plants played the dominate role in the restoration of soil physical properties, but that earthworms stabilized 200-500 µm aggregates. This is supported by results from Binet and

Curmi (1992) that showed initial changes in porosity occurred only near the soil surface, where the *L. terrestris* were actively coming to the surface to feed.

Canadian nightcrawlers (*Lumbricus terrestris*) are classified as "anecic". Anecic species are surface-feeding earthworms that live in semi-permanent, vertical burrows open to the surface (Lee and Foster, 1991), which makes *L. terrestris* particularly important for infiltration (Figure 2.4). A study by Shipitalo et al. (1994) found that *L. terrestris* burrows were 2.7 times more conductive than the bulk soil material in a fine particle field site. *L. terrestris* channels can increase infiltration rates by more than 100 mm yr^{-1} (Edwards et al. 1990) and are generally *Y* shaped. Several surface entrances can lead to a single channel within the soil profile and can convey substantial amounts of water (Edwards et al. 2004).

Binet and Curmi (1992) found that the burrowing activity of *L. terrestris* creates a circular, compacted zone 0.5-1 cm thick. This reduced the connectivity of the earthworm burrow to the soil matrix and restricted fluid and air movement to microporous exchange. Consequently, the formation of earthworm burrows had little impact on overall porosity, but reallocated soil pores within the profile so that water was more readily infiltrated. Edwards et al. (1992) reported similar findings, but recognized that the burrow connectivity to other burrows and also to the surface decreased the overall soil bulk density and moisture-holding capacity.

Figure 2.4 An adult *Lumbricus terrestris* inside its burrow near the soil surface (art.com)

Modeling Ecological Parameters

A number of models exist that could be used to assess functional components of a bioretention cell independently. The Soil and Water Assessment Tool (SWAT) and Better Assessments Science Integrating Point and Nonpoint Sources (BASINS) are typically used for BMP design applications and were developed by the government agencies. However, there are currently no systems with the capability to model ecological parameters. Thus, no existing models can simulate complete bioretention cell function.

SWAT is a model that stems from research and modeling efforts of the Agricultural Research Service of the United States Department of Agriculture (Benaman et al. 2006). The model is physically-based and is typically applied at the watershed scale. The purpose of SWAT is to determine how management impacts stormwater runoff and consequent sediment and pollutant loads (Gassman et al. 2005). The model requires numerous data and parameter inputs (Benaman et al. 2006) and thus requires an extensive knowledge of the area being modeled. The model has been shown to be an effective tool for modeling large-scale BMP's, but SWAT does not effectively model localized practices due to the limited spatial capability at the sub-watershed level (Benaman et al. 2006).

BASINS was developed by the EPA's Office of Water for watershed and water quality based environmental assessments. The model includes a user-friendly Windows interface and has Geographic Information Systems (GIS) spatial mapping capabilities. Based on EPA literature, BASINS can be adapted to model environmental processes on a variety of scales and for different types of pollutants (EPA, 2006).

Due to the inability of SWAT and BASINS to function at the scale that many bioretention cells operate, the Comprehensive Bioretention Cell (BRC) model can be manipulated to reflect changes in biology. The BRC model was created at Oklahoma State University to predict how a BRC will function under a single storm event. The model is a compilation of basic principles behind existing infiltration models that can be adapted to study water movement in bioretention cells such as DRAINMOD, CREAMS, and SPAW. Input parameters for the BRC model include site-specific characteristics such as soil properties, drainage basin area, climate, and pollutant loads. The model uses the Green-Ampt infiltration equation and the Freundlich sorption principals to demonstrate infiltration, metal sorption, and

organic compound degradation within the bioretention cell (Christianson et al. 2006, Christianson et al. 2004).

Objectives

A lysimeter study was conducted on the Agronomy Research farm at Kansas State University to assess the impacts of vegetation and microfauna, particularly a native Tallgrass Prairie mixture and Lumbricus terrestris (Canadian nightcrawlers), on the pollutant removal and hydraulic function in a bioretention cell. The objectives of this lysimeter study were; (1) to quantify overall water quality improvements, (2) to quantify overall changes in runoff quantity, (3) to quantify how earthworms and plants influence infiltration rates, and (4) to employ a model showing impacts of earthworms and soil fauna on soil macroporosity, and compare results to field data. By conducting research in the Midwest utilizing native plants, fauna, and soil, the results of this study will contribute to a growing pool of information from which developers, planners, and consultants can guide effective BMP design.

CHAPTER 3 - Methods and Materials

Site Description

This study examined the effect of earthworms and native Kansas grasses on bioretention cell function through assessment of the performance of twelve lysimeter cells (75 cm wide, 230 cm long, and 230 cm deep) located on the Kansas State University North Agronomy Research farm. The North Agronomy Research farm is located northwest of the Kansas State University campus at -96.35 degrees longitude and 39.12 degrees latitude. The average high temperature range is from 4-32°C and the average low temperature ranges from -10-20°C. The mean annual precipitation is 835 mm (LTER, 2008). Three-fourths of the annual precipitation falls during the growing season from April-June with intense thunderstorms. This is followed by periods of drought during hot summer months (Hayden and Davis, 1998).

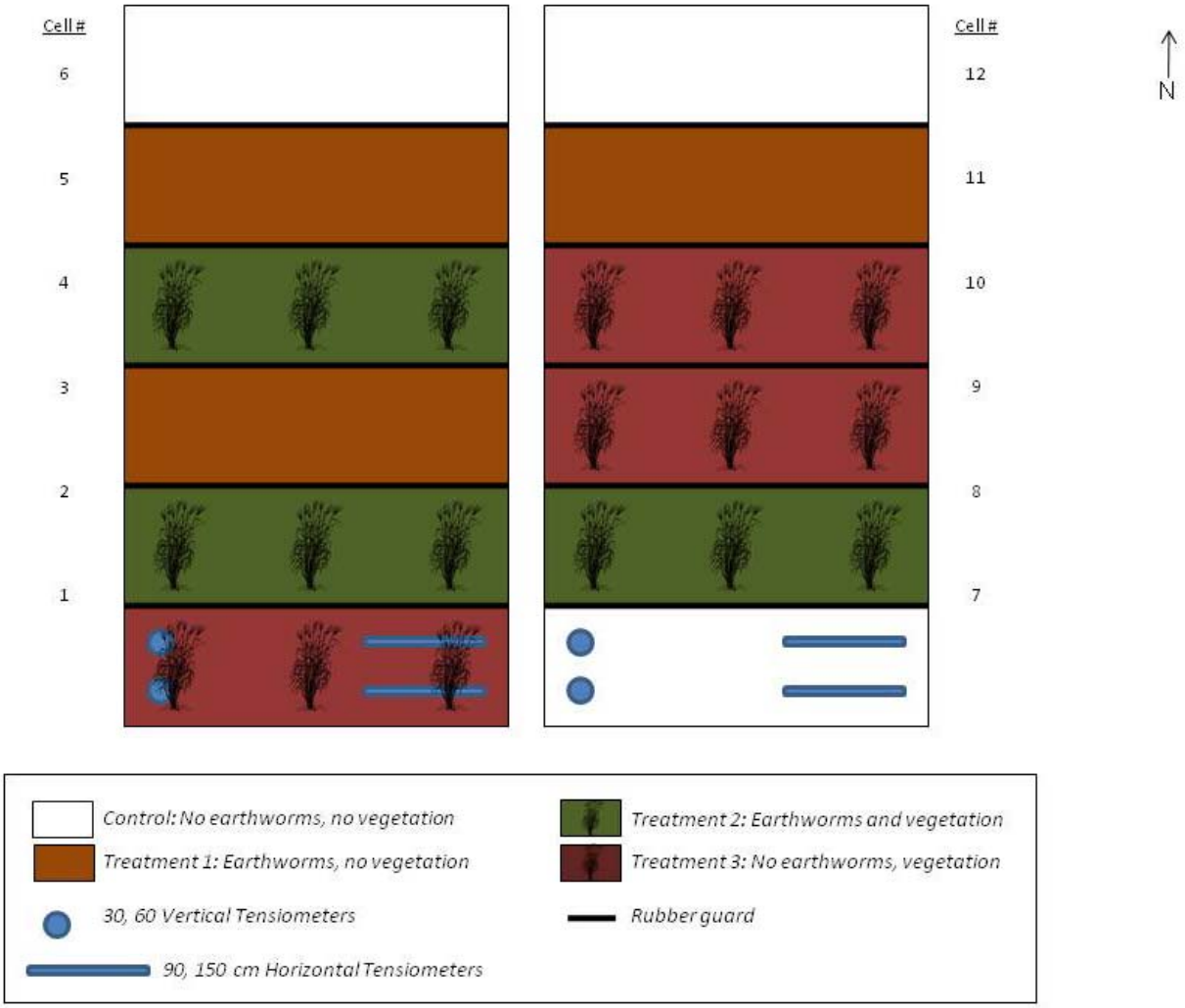
Experimental Design

The study consisted of four treatments in a completely randomized design. As depicted in Figure 3.1, the treatments were; (1) earthworms only, (2) vegetation only, (3) earthworms and vegetation, and (4) control. The cells were installed belowground and each unit has a 5 cm drainage pipe located on the bottom to allow water to drain from the cell. The lysimeter cells were used for previous water quality and irrigation studies and were left with a 1 m layer of silt-loam soil. The remaining 100 cm were filled with a similar silt-loam soil (48% sand, 43.5% silt, 8.5% clay) on October 24, 2007. Compost from the Beef Cattle Research center was tilled into the top 15-20 cm of soil on November 2, 2007, leaving 30 cm of freeboard for plant growth and ponding water.

To track changes in nutrient and metal content, five 30 cm (1 ft) deep soil cores were taken in March 2008 after weathering over the winter and after the conclusion of the growing season in October 2008. Soil samples were analyzed for pH, Mehlich-3 P, NH_4-N, NO_3-N, Total N, Total P as well as for exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}). Samples were analyzed according to the Recommended Chemical Soil Test Procedures for the North Central Region (University of Missouri, 1998) by the Kansas State University Soils Testing Laboratory. In brief, soil samples were dried overnight in a 260°C oven, then ground to pass through a 2mm sieve. To

prevent bacterial conversion of nitrogen, soil samples were dried immediately. Soil pH was measured directly using a 1:1 slurry of 5 or 10 g of prepared soil with deionized water with an automated system, Mehlich-3 P was measured with a universal extractant that removes a wide range of elements, total nitrogen and phosphorus were measured with a modified Kjeldahl digestion where the diluted digest was analyzed for nitrogen and phosphorous in separate colorimetric reactions using a flow analyzer, and Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} are extracted with 1 M ammonium acetate, adjusted to pH 7.0 and analyzed by Flame Atomic Absorption or ICP Spectrometry (University of Missouri, 1998).

Figure 3.1 The lysimeter cells arranged in a completely randomized design



Synthetic stormwater and irrigation water was applied via a gravity-fed PVC pipe system (Figure 3.2). The chemicals used for the synthetic stormwater were mixed with potable water from the North Farm in 100 gallon tanks that drained into the PVC pipe system. To measure the volume of outflow, water was piped from the cell outlet through a 1363 L/hr (360 gph) bilge pump (Rule 360, Rule Industries) and into an analog flowmeter that measures to the nearest liter (Kent Industries).

Figure 3.2 Irrigation and stormwater application apparatus

On April 15, 2008 lysimeters cells 2, 3, 4, 8, and 10 (see Figure 3.1) were planted at rates of 8 g/m^2 of *S. scoparium (*little bluestem), 18 g/m^2 of *Tripsacum dactyloides* (Eastern grama grass), 20 g/m^2 of *Sorghastrum nutans* (Yellow Indiangrass), and 14 g *Bouteloua curtipendula* (Sideoats grama) from Sharps Brothers Seed company in Healy, KS (S. Bear, personal communication, February 21, 2008). These grasses were chosen because of their dense root structure and their ability to withstand the climatic variability typical of the Midwest. The root formation provides paths for water to flow into the soil, and thus may increase the storage

capacity of a bioretention cell. Plant growth was monitored throughout the season and biomass was measured at the conclusion of the season by removing all aboveground biomass 5 cm above ground level. Roughly 10% (by weight) of removed biomass was dried overnight at 105°C and weighed to determine the dry-weight of aboveground biomass.

Figure 3.3 The a) introduction and b) dispersal of Canadian Nightcrawlers in cells

On April 1, 2008, 72 Canadian Nightcrawlers (*Lumbricus terrestris*, Figure 3.3) from Derick's Bait and Tackle (of unknown origin) in Manhattan, KS were introduced to cells 2, 5, 8, 9, 10, and 11 (see Figure 3.1). The 30 cm freeboard and rubber separators (circular rubber tube split on one side to slip over cell edge) prevented earthworm movement between cells. The burrowing activity of earthworms creates networks of macropores that facilitate water movement via macropore flow. *L. terrestris* form vertical burrows that can be up 2.4 m deep (Shipitalo and Butt, 1999) that remain intact in an undisturbed soil system. The presence of earthworm burrows was confirmed at the conclusion of the growing season in October 2008 by fully saturating cells 2, 5, 8, 9, 10, and 11 and recording the number of earthworms that surfaced for oxygen.

Synthetic Stormwater Tests

Each cell received natural precipitation as well as synthetic stormwater treatments. Synthetic stormwater was mixed based on regional urban water quality data taken from two residential sites in Lenexa, KS and a similar site in Mission, KS. The Mission, KS site drains a mature 170 acre residential and commercial watershed and data was taken after each storm event from 1/27/2007-10/20/2007 and 6/7/2008-7/3/2008.

The minimum, maximum, median, and average of all measurements of total nitrogen, total phosphorus, and total suspended solids (TSS) from Lenexa and Mission were compared to determine a representative stormwater solution. This information was also compared to synthetic stormwater mixtures used in previous experiments (Ramirez, 2006 and Davis, 2006). Table 3.1 shows the components of the synthetic stormwater.

Table 3.1 Components of the synthetic stormwater solution

Pollutant Source	Mass (mg $10L^{-1}$)	Pollutant	Conc. (mg L^{-1})
Cupric Sulfate $CuSO_4 \cdot 5H_2O$	0.8	Copper	0.13
Sieved Soil	1.0	Total Suspended Solids	100.0
DAP $(NH_4)_2 \cdot HPO_4$	26.0	Total Phosphorus	1.20
		Nitrogen	0.47
Urea $(NH_2)_2 \cdot CO$	63.0	Nitrogen	2.83
		Total Nitrogen	3.30

Two different types of synthetic stormwater treatments were applied to the lysimeter cells. The first type of treatment, TREAT1, consisted of the water quality volume (WQv) generated from a representative watershed of 11.7 m^2, which is based on the EPA design criteria for bioretention cell dimensions (EPA, 1999). The WQv is defined as 90 percent of the average annual stormwater runoff volume (MARC, 2008). The WQv for this watershed area was calculated based on methods described in the Mid-America Regional Council Manual of Stormwater Best Management Practices (MARC, 2008). Based on this procedure, 0.38 m^3 (100 gal.) of synthetic stormwater was applied to each cell for TREAT1. In the second treatment, TREAT2, 1.5 m^3 (400 gal.) of synthetic stormwater was applied to each cell. TREAT2 allowed us to assess the effect of a larger runoff load on cell performance. This load could be derived from either a large storm event from the 11.7 m^2 watershed area or the WQv from a larger drainage area. Information from the second treatment provided insight into cell design criteria, particularly to the minimum size required for a bioretention cell to effectively treat an area. The synthetic stromwater tests conducted on August 25, 2008 (Day 238) and on September 4, 2008 (Day 248) were TREAT 1 type. The test on September 9, 2008 (Day 253) was TREAT 2 type.

All stormwater treatments were applied within 48 hours of each significant (> 13 mm) natural rainfall event from August to October 2008. For each test, all outflow valves were opened prior to stormwater application and closed 48 hours after application. After 48 hours, there was little to no flow exiting the system. There were no synthetic stormwater applications prior to August 2008 to demonstrate a potential bioretention cell management technique: the routing of stormwater runoff away from the cell during the establishment period so that nascent grasses and earthworms are not affected by an inundation of water.

Water samples were collected for quality analysis either during synthetic stormwater application or at 48 hours after application, depending on the storm duration. Effluent collected immediately following synthetic stormwater application was not exposed to anaerobic conditions due to minimal ponding. However, water pooled at the cell bottom for 48 hours may induce anaerobic conditions, and thus may impact nitrate removal through denitrification.

To determine significant differences between treatments, analysis of variance (ANOVA) and least significant difference were used in evaluation of water sample data (See Appendices B-D). Water samples were analyzed by the Kansas State University Soils Testing Laboratory for Total N, Total P, Total Suspended Solids, Total Dissolved Solids, Ortho phosphate, NH_4-N and

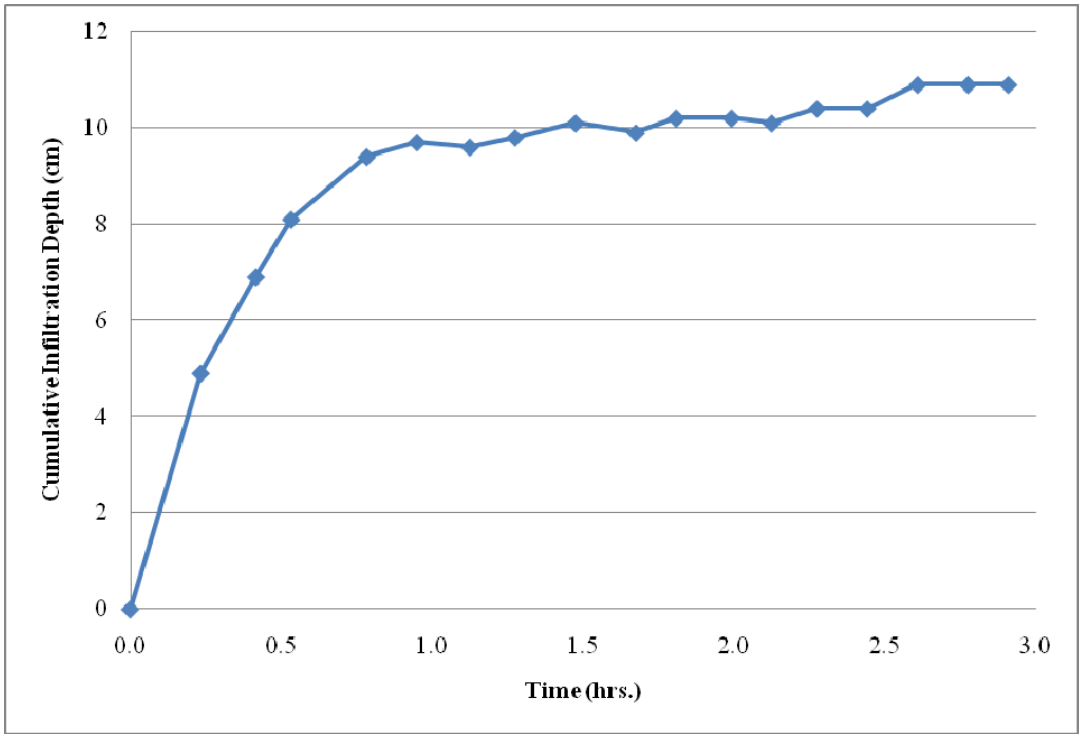
NO_3-N according to the Recommended Chemical Soil Test Procedures for the North Central Region (Missouri Agricultural Experiment Station, 1998).

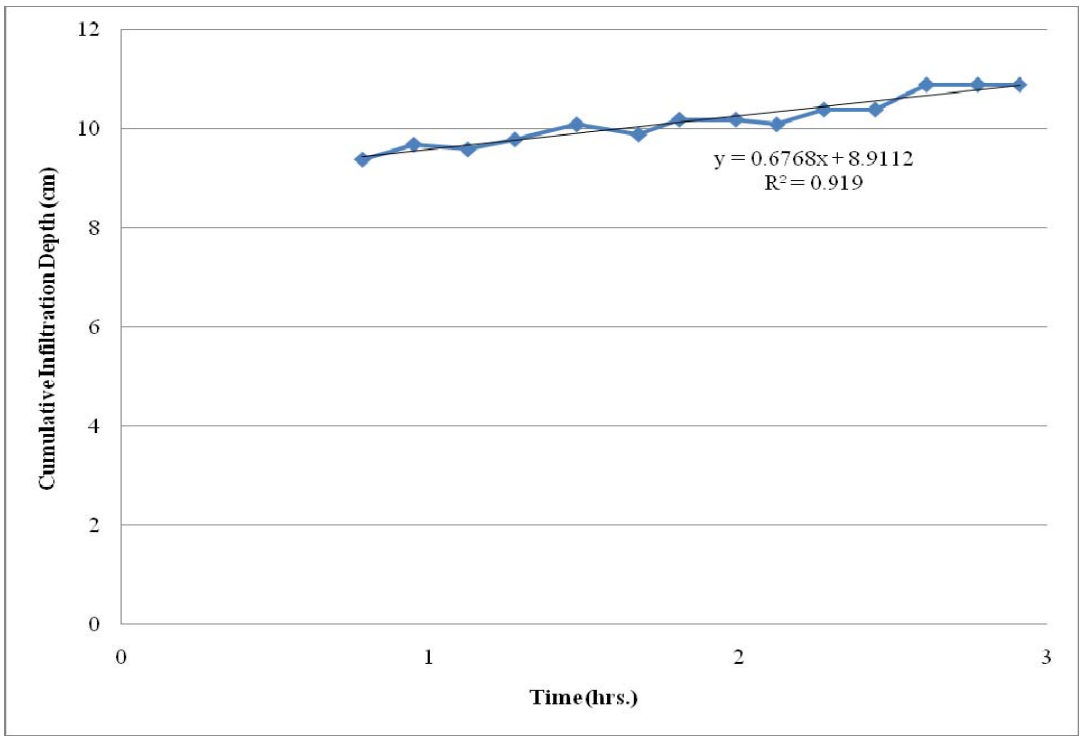
Infiltration Measurements

Cell soil moisture was measured prior to synthetic stormwater applications using vertical tensiometers located at 30 and 60 cm depths to note the impact of soil moisture on infiltration. Cell soil moisture was recorded weekly from August to October 2008 to note fluctuations in moisture. Infiltration rates were measured using a double ring infiltrometer prior to planting in March and again in October at the completion of this study. Infiltration during synthetic stormwater application was measured by noting the difference in time between whole-cell application and complete infiltration of the water front.

The saturated conductivity was determined from infiltrometer measurements by plotting the cumulative infiltration depth versus time. At steady state, the rate of increase of cumulative depth becomes constant with time and the line takes on a linear shape. The saturated conductivity is the slope of the linear portion of the graph and is determined from linear regression analysis. Figure 3.5 provides an example of this procedure.

Figure 3.4 An example of the linear regression analysis procedure used to determine the saturated hydraulic conductivity from cell 3 where a) is the complete curve and b) is the isolated linear portion of the complete curve



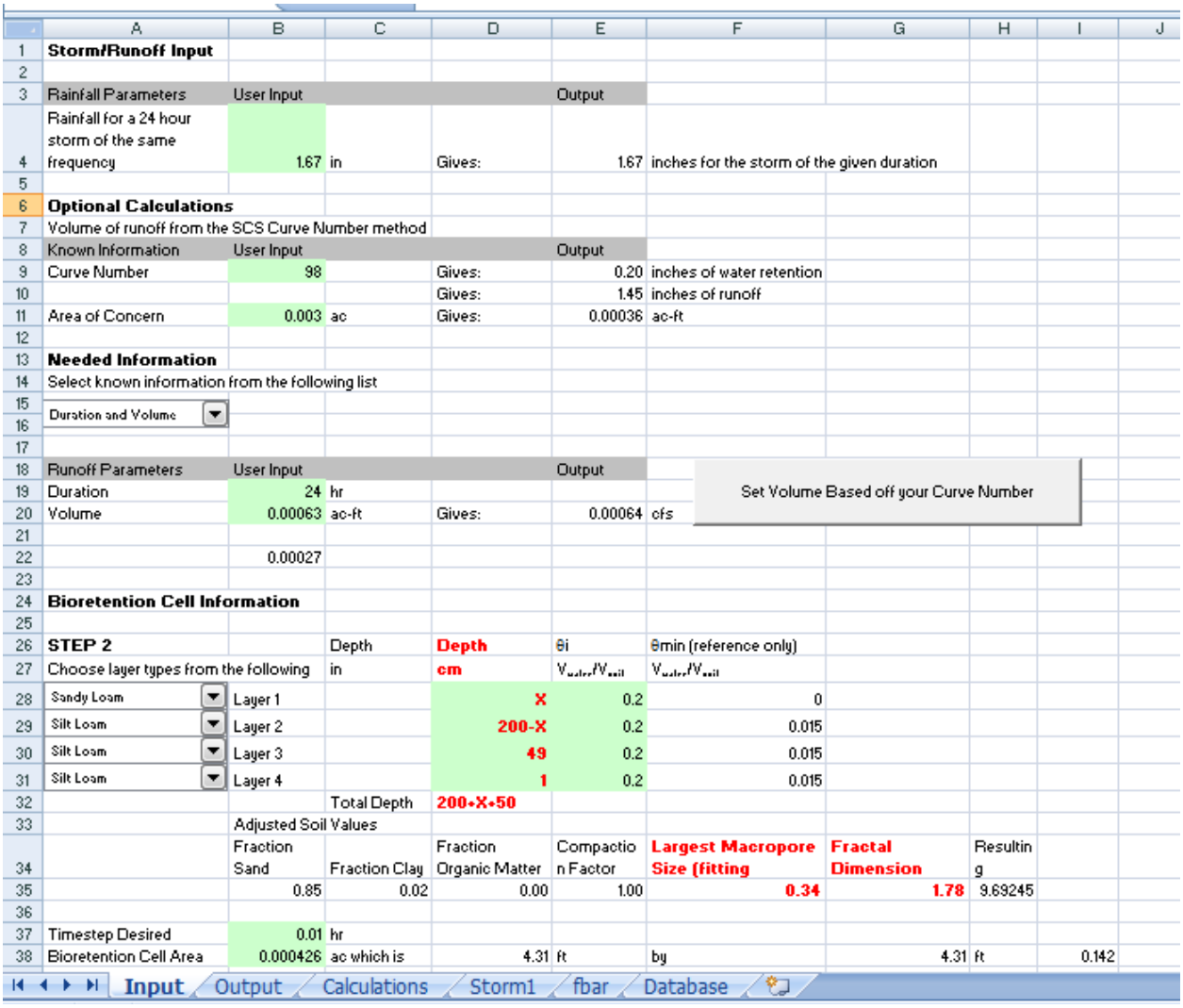


Comprehensive Bioretention Cell Model

The Comprehensive Bioretention Cell (BRC) Model was used to predict how a bioretention cell functions under a single storm event. The model allows cell designers to determine appropriate dimensions for bioretention layers based on desired pollutant trapping efficiency and effluent water quality (Christianson, 2005, Christianson et al. 2004). Three parameter inputs, fractal dimension (Dv), macropore size (MAC), and layer depth, were manipulated to represent earthworm and vegetation impacts on infiltration, all other parameters were held at default values (Figure 3.6). These input parameters were based on the rates of macropore formation by earthworms and vegetation and the resulting macropore densities. This information was taken from previous research on earthworm dynamics and soil physical properties (Bastardie et al. 2002, Binet and Curmi, 1992; Bouma et al. 1982, Urbanek and Dolezal, 1972, Edwards et al. 1992, Johnson-Maynard et al. 2007, and Willoughby and Kladivko, 2002).

To verify that the BRC model was an appropriate representation of the field study, the sensitivity of infiltration (the output from the model) to changes in three important input variables was analyzed. Fractal dimension, largest macropore size, and layer depth were important variables because they could be altered to represent changes in biological growth and diversity.

Figure 3.5 BRC model screen shot with Dv, MAC, and layer depth highlighted in red



	A	B	C	D	E	F	G	H	I	J
1	**Storm/Runoff Input**									
2										
3	Rainfall Parameters	User Input			Output					
4	Rainfall for a 24 hour storm of the same frequency	1.67	in	Gives:	1.67	inches for the storm of the given duration				
5										
6	**Optional Calculations**									
7	Volume of runoff from the SCS Curve Number method									
8	Known Information	User Input			Output					
9	Curve Number	98		Gives:	0.20	inches of water retention				
10				Gives:	1.45	inches of runoff				
11	Area of Concern	0.003	ac	Gives:	0.00036	ac-ft				
12										
13	**Needed Information**									
14	Select known information from the following list									
15										
16	Duration and Volume									
17										
18	Runoff Parameters	User Input			Output					
19	Duration	24	hr							
20	Volume	0.00063	ac-ft	Gives:	0.00064	cfs				
21										
22		0.00027								
23										
24	**Bioretention Cell Information**									
25										
26	**STEP 2**		Depth	**Depth**	θi	θmin (reference only)				
27	Choose layer types from the following		in	**cm**	V_{water}/V_{soil}	V_{water}/V_{soil}				
28	Sandy Loam	Layer 1		**X**	0.2	0				
29	Silt Loam	Layer 2		**200-X**	0.2	0.015				
30	Silt Loam	Layer 3		**49**	0.2	0.015				
31	Silt Loam	Layer 4		**1**	0.2	0.015				
32			Total Depth	**200+X+50**						
33		Adjusted Soil Values								
34		Fraction Sand	Fraction Clay	Fraction Organic Matter	Compactio n Factor	**Largest Macropore Size (fitting**	**Fractal Dimension**	Resultin g		
35		0.85	0.02	0.00	1.00	**0.34**	**1.78**	9.69245		
36										
37	Timestep Desired	0.01	hr							
38	Bioretention Cell Area	0.000426	ac which is	4.31	ft	by	4.31	ft	0.142	

Set Volume Based off your Curve Number

Input | Output | Calculations | Storm1 | fbar | Database

Fractal dimension is a parameter used to describe the distribution of pore sizes in soil and has a value ranging from 1-2 (Brakensiek et al. 1992, Rawls et al. 1996). Fractal dimension, or D_v, describes the relationship of the largest pore size to the next smallest pore size, so soils with a large range of evenly distributed pore sizes will have a moderate D_v. Soils dominated by large soil pores will have fractal dimensions close to 2, whereas soils with small macropores will have fractal dimensions closer to 1. For a loam/silt clay loam soil with a maximum pore size of 10 mm, D_v values typically range from 1.72-1.79 (Brakensiek and Rawls, 1992). If not otherwise known, D_v values can be estimated as the matrix fractal dimension (see Table 3.2).

Table 3.2 Estimation of Dv values from the matrix fractal dimension and soil texture

Soil Texture	Matrix Fractal Dimension (D)
Sand	1.41
Loamy Sand	1.53
Sandy Loam	1.68
Loam	1.78
Silt Loam	1.79
Sandy Clay Loam	1.75
Clay Loam	1.81
Silty Clay Loam	1.85
Sandy Clay	1.83
Silty Clay	1.87
Clay	1.87

Largest macropore size, or MAC, is used as a fitting parameter in the calculation of the hydraulic conductivity. Macropores formed by Canadian nightcrawlers range from 3-12 mm in diameter (Binet and Curmi, 1992, Edwards et al. 1990, Shipitalo and Butt, 1999).

Layer depth is the parameter used to describe the depth of each layer in the bioretention cell. To represent the changes in the depth of biological activity over time, all alterations in D_v and MAC were made to "layer 1". The physical properties of "layer 2" were not changed. Only the depth of "layer 2" was changed to maintain an overall depth of 200 cm. The screen shot of the user-model interface in Figure 3.3 designates the D_v, MAC, and layer depth variables.

To carry out the sensitivity analysis, a macro was created in Microsoft Excel to keep all variables constant at values from the lysimeter cells while one of the three important variables were changed. This was repeated for D_v, MAC, and layer depth. Table 3.2 summarizes the ranges of values used in the sensitivity analysis.

The results were used to create three dimensional graphs comparing the impact of fractal dimension and largest macropore size on the saturated conductivity of layer 1. It was these graphs that determined the ranges of D_v and MAC in which the saturated conductivity was most sensitive.

Table 3.3 Summary of the range of parameters used in the sensitivity analysis

Model Parameter	Units (SI Units)		Model Parameter	Units	
Rainfall	1.67	in (4.24 cm)	Porosity	0.2	
Bioretention Area	0.00043	ac	Fraction Sand	0.85	
Area of Concern	0.003	ac (12 m^2)	Fraction Clay	0.02	
Duration	24	hrs	Fraction Organic Matter	0	
Volume	0.0063	ac-ft (7.8 m^3)	Compaction Factor	1	
Depth Layer 1	X	cm	Largest Macropore	1.72-1.79	
Depth Layer 2	200-X	cm	Fractal Dimension	0.3-1.2	cm
Depth Layer 3	49	cm	Timestep Desired	0.01	hrs
Depth Layer 4	1	cm	Curve Number	98	

BRC Model and Field Comparison

It is very difficult to model the development of a living system over time as many different environmental factors control the progression of growth. The complex process was simplified for use in the BRC model by first compiling information on the burrow and root size, population density, depth, and season of activity from ecological literature. This information, which is summarized in Table 3.4 and described in the paragraph below, was then combined with data on the lifecycle of *L. terrestris* and on the annual increase of underground materials and root turnover in the prairie (Table 3.7).

A *L. terrestris* earthworm matures in one year and has average lifespan of six years. It is capable of producing an average of 38 cocoons per year (Thomas et al. 2008), and typically each cocoon generates a single hatchling (Butt and Nuutinen, 1998). *L. terrestris* are surface feeders and utilize 0.075-2.4 m depths of soil almost immediately upon introduction to an area (Binet and Curmi, 1992, Lee and Foster, 1991, Shipitalo and Butt, 1999) and continue to make use of the same burrows for extended periods of time (Edwards et al. 1992). Burrows can remain intact for five or six years (Bastardie et al. 2005) due to the 1-10 mm thick burrow wall (Edwards et al. 1990; Linden et al. 1991).

Table 3.4 Ecological data for BRC model parameters with sources

L. terrestris		Tallgrasses	
Macropore (mm)			
8	Binet and Curmi, 1992	Little bluestem, 0.5-1	Weaver and Rowland, 1952
3 to 10	Edwards *et al* . 1990	Sideoats grama, 1	Weaver and Rowland, 1952
≥ 12	Shipitalo and Butt, 1999		
Depth of Activity			
0.075	Binet and Curmi, 1992	Little bluestem, 1.2-1.5	Weaver 1958
> 1	Lee and Foster, 1991	Sideoats grama, 1.5-1.7	Weaver 1958
≥ 2	Edwards *et al.* 1990		
≥ 2.4	Shipitalo and Butt, 1999		
Density (burrow m^{-2} or g m^{-2})			
160	Edwards *et al.* 1988	859 to 1086	Rice et. al., 1998
100-300	Lee and Foster, 1991		
Season of Activity			
Late spring and early fall	Butt and Nuutenin, 1998	Max seasonal density of roots in early July in top 4 cm	Weaver, 1958
		Max root density after two growing seasons	Weaver, 1946

Earthworm activity peaks during late spring and early fall with moderate temperatures and high soil water content (Linden et al. 1991). In the tallgrass prairie ecosystem, earthworm density can exceed 300 individuals m^{-2} (Rice et al. 1998), whereas a new residential area may only support 26 individuals m^{-2} (Smetak et al. 2007). Thus, the introduction of earthworms to a bioretention cell in a residential area may expedite the formation of an ecological system similar to the native prairie. Springett et al. (1992) found that the introduction of earthworms to a sparsely populated horticulture land improved the infiltration and permeability of the bulk soil matrix, and that the population of earthworms nearly doubled (from 6.4 to 15 m^{-2} and 40.3-118 m^{-2} in non-tilled and 17-29 m^{-2} in tilled) over introduction numbers over the fall season of activity. This rate of population increase was used in the BRC model as to determine the seasonal rise in earthworm numbers (see Table 3.7).

Little bluestem composes 55-90% of the vegetation in prairie uplands, and thus is one of the most abundant native grasses. Little blue grows to heights of 17 to 30 cm in dry areas and 38 to 45 cm in more favorable sites (Weaver and Rowland, 1952; Weaver and Zinc, 1947). The grass is formed from a very dense root network that can branch up to the third order with root diameters ranging from 0.5 to 1 mm. Eastern grama grass is a clumping grass that forms dense root structure in the top 4 in. of soil (Weaver and Rowland, 1952). Indian grass usually grows in association with big bluestem and composes about 1-5% of the prairie grass population (Weaver

and Rowland, 1952). The grass grows in a sod-like manner and is composed of branched roots (Weaver and Rowland, 1952). Sideoats grama is common to western prairie ecosystems with 1 mm diameter roots that branch out 30 to 45 cm laterally and reach depths of 120 to 170 cm. The grass is very drought-resistant and grows to heights of 45 to 60 cm (Weaver and Rowland, 1952).

In comparing the root life between ten perennial range and pasture species, Weaver and Zink (1947) found that the number of little bluestem roots, initially seeded, increased by 72% over the first year of growth (88.9-165.6 g), from fall 1943 to fall 1944. Other grasses followed similar patterns of growth over the first year, and the loss of roots (by death) overall were negligible. This was supported by results from an earlier study by Weaver and Zink (1946) on annual increases of underground root mass in three range grasses. In the first year of growth after being transplanted as a seedling, the roots of big bluestem, little bluestem, and sideoats grama increased by 72, 86, and 56%, respectively. Little bluestem root yields continued to nearly double from the initial growing season during the second year, but did not substantially increase thereafter. It was from this study that Weaver and Zink (1946) concluded that the roots of little bluestem and most other prairie grasses reach maximum density after two years of growth. Table 4 is a reproduction of data from Weaver and Zink (1946) and presents the dry weight of roots for several depths at the end of the growing season. This information was used as a guideline for estimating the annual increase in root density for the BRC model (see Table 3.7).

Table 3.5 Ovendry weight of the roots (g) at incremental depths at the end of active season

Depth (inches)	1943	1944	1945	Percent
0-4	25.3	56.5	57.3	35.9
4-12	26.7	55.3	53.1	33.3
12-24	18.7	30.9	34.6	21.6
24+	18.2	22.9	14.8	9.2

Table 3.6 is a reproduction of data from Dahlman and Kucera (1967). This data was taken over one year in the 145 acre Missouri Prairie Research Station located in east-central Missouri. The primary grasses on this tract of land were little and big bluestem.

Table 3.6 Ovendry weight (g m^{-2}) of the total roots in Tallgrass prairie based on sampling increment and soil horizon

	Sampling Period			
Depth (inches)	**April**	**July**	**October**	**January**
0-2	766	1107	1025	839
2-4	188	255	238	291
4-6	115	130	151	170
6-10	119	125	161	170
10-14	74	65	79	97
14-18	52	52	70	60
18-22	49	45	65	49
22-26	38	37	45	38
26-30	36	31	44	32
30-34	12	13	23	9
Total	1449	1860	1901	1755
0-10 (A_1 horizon)	1188	1617	1575	1470
10-18 (A_2 horizon)	126	117	149	157
18-30 (B_2 horizon)	123	113	154	119

This data was useful in determining the evolution of the root system over a year of growth and dormancy. However, for entry into the BRC model, it was necessary to translate this data into actual root density, or number of roots per plant. Weaver and Darland (1947) measured the vigor of transplanted range grasses and found at the end of the growing season that each little bluestem produced 150 individual roots which weighed a total of 1.45 g. This information was used to convert all data in Tables 4 and 5 from a weight (g) to number of roots per square meter in a given soil depth. This information was used to estimate the changes in fractal dimension over time for each treatment. This resulted in the general increasing pattern of fractal dimension where the earthworm treatment was dominated by large pores (large D_v), the vegetation treatment was dominated by smaller pores (small D_v), and the dual treatment had an even distribution of pore sizes (moderate D_v). As stated in the initial paragraph of this section, Table 3.7 (below) shows the synthesis of all the preceding information which was used as inputs for the

D_v, MAC, and layer depth parameters in the BRC model to estimate the cell performance over the first three years of growth.

Table 3.7 BRC model inputs used to demonstrate the progression of growth in the bioretention cells for the endpoints of each season. All values are in cm except for Dv which is dimensionless

	Growing Season 1							
	D_v	**MAC**	**Layer 1**	**Layer 2**	**D_v**	**MAC**	**Layer 1**	**Layer 2**
	April				*September*			
EW	1.72	0.02	75	199	1.76	0.7	100	100
PL	1.72	0.02	1	199	1.74	0.05	30	170
EW + PL	1.72	0.02	1	199	1.75	0.9	100	100
Control	1.72	0.02	1	199	1.73	0.02	5	195
	Growing Season 2							
	D_v	**MAC**	**Layer 1**	**Layer 2**	**D_v**	**MAC**	**Layer 1**	**Layer 2**
	April				*September*			
EW	1.78	0.9	120	80	1.8	1	120	80
PL	1.74	0.05	50	150	1.75	0.1	70	130
EW + PL	1.76	1	120	80	1.76	1	120	80
Control	1.73	0.02	5	195	1.75	0.02	10	190
	Growing Season 3							
	D_v	**MAC**	**Layer 1**	**Layer 2**	**D_v**	**MAC**	**Layer 1**	**Layer 2**
	April				*September*			
EW	1.8	1	120	80	1.8	1	120	80
PL	1.75	0.1	80	120	1.75	0.1	90	110
EW + PL	1.76	1	120	80	1.76	1	120	80
Control	1.75	0.02	10	190	1.75	0.02	10	190

CHAPTER 4 - Results and Discussion

Summary of Results

Both the tallgrasses and earthworms became well established over the course of the study and had interesting impacts on bioretention cell function despite poor initial growing conditions. Perhaps the most notable impact was the high increase in infiltration rates in all treatments from April to October 2008. As predicted, the greatest increase in saturated hydraulic conductivity was in the vegetation and earthworm treatment. It was also apparent from similar improvements in all cell types that biological acvtivity occurs to a certain extent despite ecological additions made prior to establishment. Other findings illustrated the important balance between biology and function: cells with introductions of earthworms and vegetation components behaved more like a natural system. All treatments reduced P by 84-96%. A large amount of N was released during all events from all treatments probably because of a high initial N content and consequent leaching potential of the bioretention media. With continued establishment, mature grass will utilize excess N and reduce export over time. Table 4.1 provides a summary of the performance of six key functional parameters for each treatment type. It was evident that vegetation was the key biological input. The vegetation and earthworm combination treatment has the greatest impact on overall bioretention cell function, while the vegetation only treatment was second.

Table 4.1 Summary of bioretention cell performance by treatment type

	K_s[1]	Ponding 24 hrs	Ponding 48 hrs	Pollutant Retention	% Water Retained	Flow through time	30 cm Soil water Removal	Total
EW	+	-	+	0	-	0	+	1
VEG	0	+	+	0	+	+	+	5
VEGEW	++	+	+	0	-	+	++	7
CONT	0	-	-	0	+	0	-	-2

[1]The effective saturated hydraulic conductivity measured with double ring infiltrometer
+ indicates a positive performance in given category and counts as 1
- Indicates a poor performance in given category and counts as -1
0 indicates neither a positive nor poor performance and counts as 0
All +, -, and 0's were summed for the total in the right hand column

Establishment of Ecological System

Due to the late spring and low temperatures in March and April, the native grasses experienced delayed growth and establishment. Grasses were planted on April 15, 2008 (Figure 4.1) with the first sign of growth in late May when the indiangrass began to sprout (Figure 4.2). The most difficult maintenance procedure was keeping the weedy species at bay as the cells would become dominated by invasives if not maintained. Sideoats grama first appeared in June (Figure 4.2) and little bluestem did not appear until early August. The maximum vegetation density (visual) occurred in late August (Figure 4.3) and began to decline near the close of September and into October (Figure 4.4). All aboveground biomass was removed 5 cm above ground level on October 8, 2008. The dry-weight of aboveground biomass was determined (Table 4.1) and indicated that the system was very productive compared to the Konza Prairie.

Table 4.2 Dry weight (g/m^2) of aboveground biomass

Treatment*	Biomass Density (g/m^2)	Estimated Root Density** (g/m^2)
VEG1	942.19	753.76
VEG2	940.65	752.52
VEG3	839.53	671.62
AVE	*907.46*	*725.97*
VEGEW 1	473.81	379.05
VEGEW 2	1611.51	1289.21
VEGEW 3	1196.03	956.82
AVE	*1093.78*	*875.03*

* VEG is vegetation treatment and VEGEW is vegetation + earthworm treatment
** Assumed ratio of roots to tops was 0.8 (Weaver and Zink, 1946)

The root density was estimated based on the ratio of roots to tops presented by Weaver and Zink (1946) for little bluestem in the first growing season. The ratio of roots to tops for little bluestem was used as a benchmark since the vegetated cells were dominated by the grass when biomass was removed in October. A similar fraction of roots to tops was presented for Indian grass (Weaver and Zink, 1946). Although the differences between treatments were not significant ($P > 0.6384$), the amount of biomass indicates that on average cells treated with both vegetation and earthworms had higher densities of biomass and roots. This could be due to the symbiotic interaction between earthworms and plants (Baker *et al*. 2006 and Kirkham, 1982).

These rates of productivity are much higher than those measured on the Konza Prairie, which averages 412 g/m^2 annually (Knapp et al. 1998). The high productivity rates in the lysimeter cells were likely due to the high amount of nutrients available, particularly N, concentrated sunlight, and the lack of competition. The successful establishment of the grasses and earthworms may have been due in part to the management technique of routing the stormwater runoff away from the cell during the first few months of growth.

Figure 4.1 April 15, 2008 Cells immediately after planting and introduction of earthworms. Cells are covered with a thin layer of native grass hay

Figure 4.2 June 1, 2008 shortly after the appearance of vegetation

Figure 4.3 September 8, 2008 maximum vegetation growth

Figure 4.4 October 10, 2008 after a decrease in vegetation density

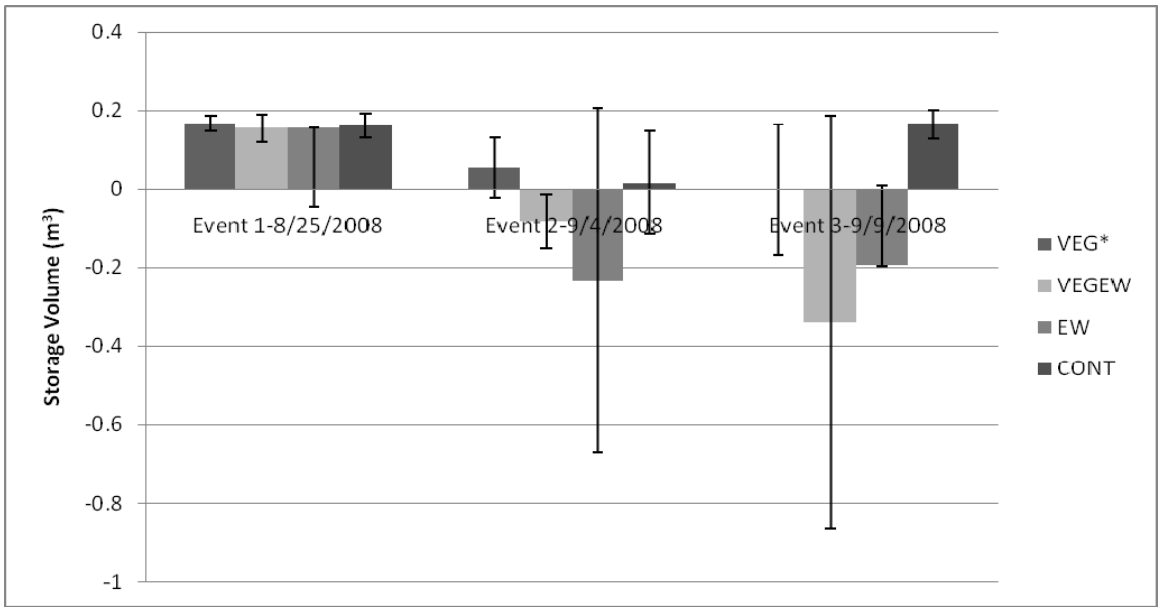
The earthworms remained active throughout the cool spring and into the mild summer weather. From July-September, there was no confirmation of earthworm activity (evident by lack of surfacing of the earthworm during rain events). During infiltrometer tests in October, several earthworms surfaced in Cells 3 and 4. It was difficult to quantify the earthworm population because most procedures are invasive to the soil profile. Because this was a long term study, the maintenance of the integrity of the tallgrass roots was important.

Water Balance

The storage capacity is an important factor in understanding how a bioretention cell functions. A cell with a large storage capacity will have a greater impact on water quality and quantity as it can ultimately process more runoff. However, there is a tradeoff between how much water a system can hold and how much it can filter and contribute to surface and groundwater recharge. An ideal bioretention facility would exhibit both behaviors by retaining runoff to reduce the peak discharge rate and also to filter pollutants from the first flush.

Investigation of the bioretention system water balance results in the knowledge of how much water was “removed” from downstream flow. This provides insight to both the storage capacity and clean contributions to other water sources. The balance was calculated on an event basis, so that inputs were natural precipitation and synthetic stormwater runoff and the output was the underdrain flow. Discrepancies in outflow volumes may be due to the complex nature of ecological systems and inefficient measuring practices in the first event. The results are presented below in Figures 4.5 and 4.6.

Figure 4.5 Average storage volumes in m^3 for each stormwater event by treatment type



Error bars indicate 1 standard deviation
*VEG is vegetation treatment, VEGEW is vegetation + earthworm treatment, EW is earthworm treatment, and CONT is control

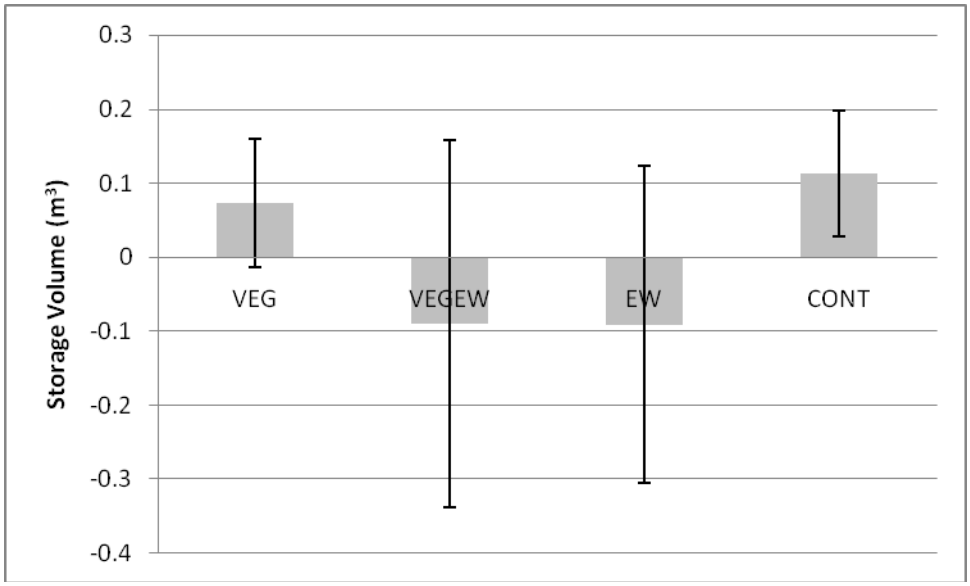
As shown in Figure 4.5, treatments with earthworms had less storage capacity. Although the differences between treatments was not significant ($P > 0.1698$) , treatments with earthworms did not have a high storage capacity while the vegetation only treatment and the control held more water. This can be explained by rapid water conduction through the soil profile by macropore flow. Similar results were found by Binet and Curmi (1992), Edwards et al. (1992), and Johnson-Maynard et al. (2007). Binet and Curmi (1992) attributed rapid infiltration rates to the creation of large burrows and the resulting pore size redistribution. These large macropores induce the flow of water under unsaturated conditions (Shipitalo and Butt, 1999, Pitakanen and Nuutinen, 1998). The negative storage volumes indicate that a higher volume of water exited the system than the volume applied in that event. This may be due to delayed water movement through the profile. Outflow valves were closed 48 hours after each storm event so that any water remaining in the cell would pool at the bottom until the valves were opened for the next event.

The vegetation and control treatments had greater storage capacities than treatments with earthworms. This could be attributed to delayed movement of water as it passed through the dense soil matrix of the control and the root systems of the vegetation treatment. Plant and root

growth preserves the fine structure of soil (Hino et al. 1987) and thus maintains a smaller pore size distribution. It is likely that, as the roots continue to develop over the next growing season, that the difference between the control and vegetation treatment will become more evident.

It may be more informative to consider the water balance on a percent-retained basis (Figure 4.6). This allows for a comparison normalized by the amount of incoming precipitation and synthetic stormwater.

Figure 4.6 Average percent water stored in cell by treatment type for all stormwater events



Error bars indicate 1 standard deviation
*VEG is vegetation treatment, VEGEW is vegetation + earthworm treatment, EW is earthworm treatment, and CONT is control

The trend that earthworm treatments had less storage capacity, while the vegetation and control treatment had greater water storage capacity was more evident in Figure 4.6. During the first growing season, storage in the VEG, VEGEW, and EW was 35%, 179%, and 180% less than the control. The differences between treatments were not significant ($P > 0.68$).

It is important to note that ponding occurred in all earthworm and control cells immediately after each large natural precipitation event and all synthetic stormwater events. Ponding durations greater than 24 hours were exhibited by cells 3 (EW), 6 (CONT), 7 (CONT), 11 (EW), and 12 (CONT) (Figure 4.7) after each synthetic stormwater event. This is likely due to the lack of surface roughness and because openings to macropores were blocked by surface sealing.

Figure 4.7 Stormwater ponding on control (cell 6) during the second stormwater event

Infiltration

Infiltration is the primary driver of bioretention cell function. The conductive capacity of soil determines the quantity and rate of runoff entry to the soil and the subsequent movement of contaminants. Being aware of the infiltration capabilities of the untreated soil matrix is important, but understanding how biological additions, such as plants and fauna, can improve those capabilities is imperative to having a comprehensive bioretention cell design.

On a seasonal-basis, the conductive ability of soil was enhanced by the introduction of vegetation and earthworms (Table 4.2, for calculations see Appendix A). The effective saturated hydraulic conductivity (K_{eff}) is indicative of the ability of the soil profile to infiltrate water. The saturated hydraulic conductivities measured in October 2008 were significantly different from each other ($P > 0.0429$) and showed a marked increase over rates measured in April 2008. The seasonal change in K_{eff} was significant in the earthworm only treatment and vegetation and earthworm combination treatment ($P > 0.0281$ and $P > 0.0046$, respectively). However, changes were not significant in the vegetation only and earthworm treatment ($P > 0.148$ and $P > 0.1254$, respectively).

Table 4.3 K_{eff} (cm/hr) by cell type

	Apr-08	Oct-08		Apr-08	Oct-08		Apr-08	Oct-08
VEG*	0.76	11.1	**EW**	0.7	18.3	***Overall Ave.***	*1.07*	*20.82*
VEG	0.9	1	**EW**	0	10.2	***Overall Std. Dev.***	*0.78*	*14.54*
VEG	0	21.5	**EW**	1.6	19.2			
Ave.	0.55	11.20	*Ave.*	1.15	15.90	***Treatment Ave.***	*1.32*	*20.94*
Std. Dev.	0.48	10.25	*Std. Dev.*	0.64	4.96	***Treatment Std. Dev.***	*0.73*	*13.63*
VEGEW	1.7	24.4	**CONT**	1.8	22.4			
VEGEW	0.9	38.5	**CONT**	0.6	4.9	***Control Ave.***	*1.20*	*11.47*
VEGEW	2.7	44.3	**CONT**	0	7.1	***Control Std. Dev.***	*0.92*	*9.53*
Ave.	1.77	35.73	*Ave.*	0.80	11.47			
Std. Dev.	0.90	10.23	*Std. Dev.*	0.92	9.53			

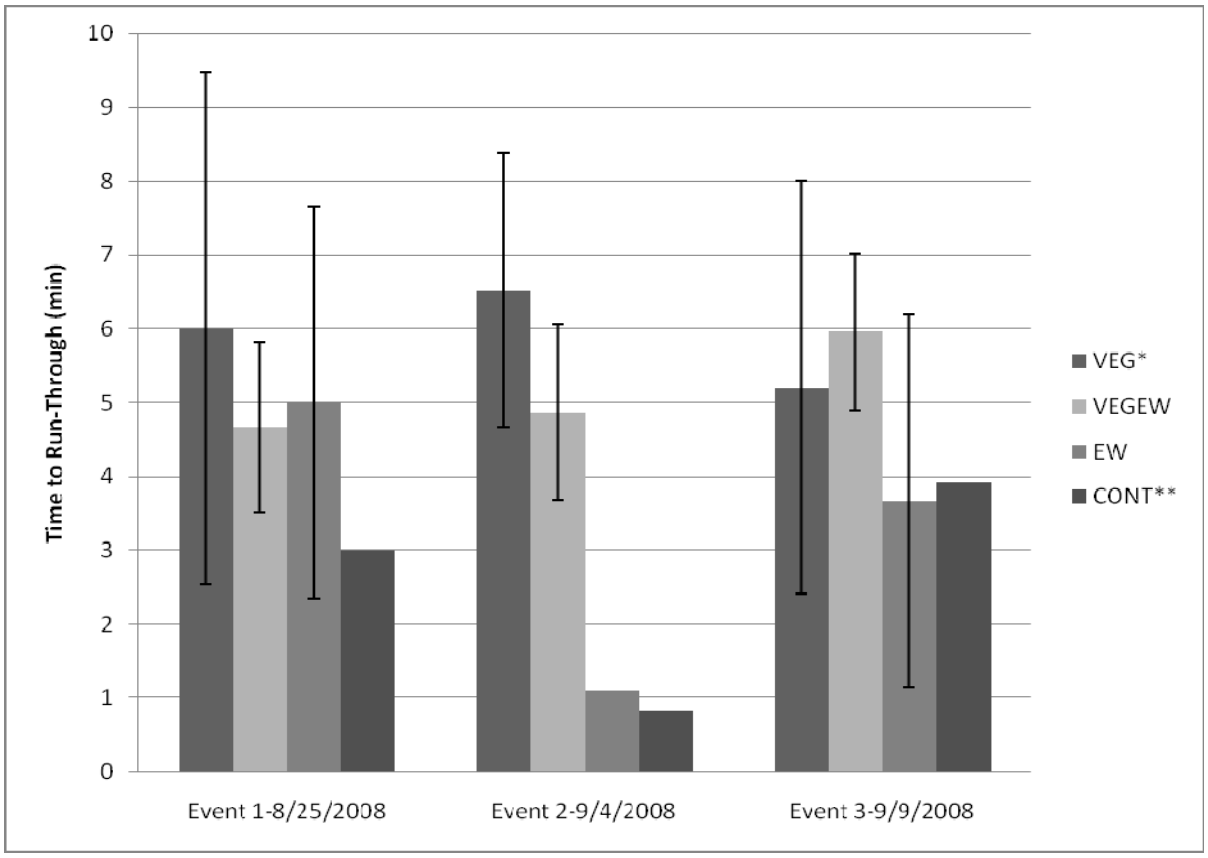
*VEG is vegetation treatment, VEGEW is vegetation + earthworm treatment, EW is earthworm treatment, and CONT is control

It is important to note that the typical K_{eff} for a silt loam is 0.65 cm/hr. In April 2008, the overall average saturated hydraulic conductivity for all cells was close to this K_{eff} value, at 1 cm/hr. The average infiltration rates of all treatment cells in October 2008 were around 20 cm/hr, almost double that of the control. The considerable increase in infiltration rates in all treatment types reflects the degree of establishment of the soil matrix, vegetation, and earthworms over the growing season. It is apparent that improvements in bioretention cell function occurred despite additions made prior to establishment. These improvements are likely due to soil physical processes and the natural introduction of biology. The greatest increase in K_{eff} was in the most biologically diverse treatment (vegetation/earthworm). The average K_{eff} of this treatment increased from 1.8 to 35.7 cm/hr. This implies earthworm and vegetation interactions in the combination treatment enhanced infiltration rates over vegetation or earthworm only treatments.

On an event-basis, the treatments had an interesting impact on infiltration. Note that the "time of run-through" is the time between stormwater application to cell and initial appearance of outflow (Figure 4.8). On an event basis, the difference between treatments was significant ($P > 0.0108$) and followed the trend that vegetation and vegetation/earthworm treatments had consistently greater run through times, while the earthworm and control treatments generally had shorter run through times. Although initially counterintuitive, this correlation can be explained by the presence of roots and the maintenance of the fine structure of the soil (Hino et al. 1987). This results in fewer macropores and an ability to remove water from the top soil via uptake and evapotranspiration. In the six vegetated cells, runoff was delayed by the fibrous roots and

micropores created by plant growth. Detainment of runoff in the soil profile dissipates runoff energy and allows time for filtration and pollutant removal. The control and earthworm treatment do not detain water; water is instead readily conducted through the soil matrix. This rapid infiltration rate could be beneficial if ponding water or mosquito attenuation is a concern.

Figure 4.8 Time to run-through averaged by treatment for each storm event



Error bars indicate a 1 standard deviation
*VEG is vegetation treatment, VEGEW is vegetation + earthworm treatment, EW is earthworm treatment, and CONT is control
**Indicates that there was not enough data to calculate the standard deviation

Figure 4.8 illustrates the important balance between biology and function: the introduction of earthworms and vegetation results in a system with more varied behavior. For example, in the vegetation treatment, the infiltration rate into the surface is relatively fast, but water is slowed in the soil profile through the presence of roots and due to the lack of macropores. Thus, the vegetation treatment results in a long time to run through.

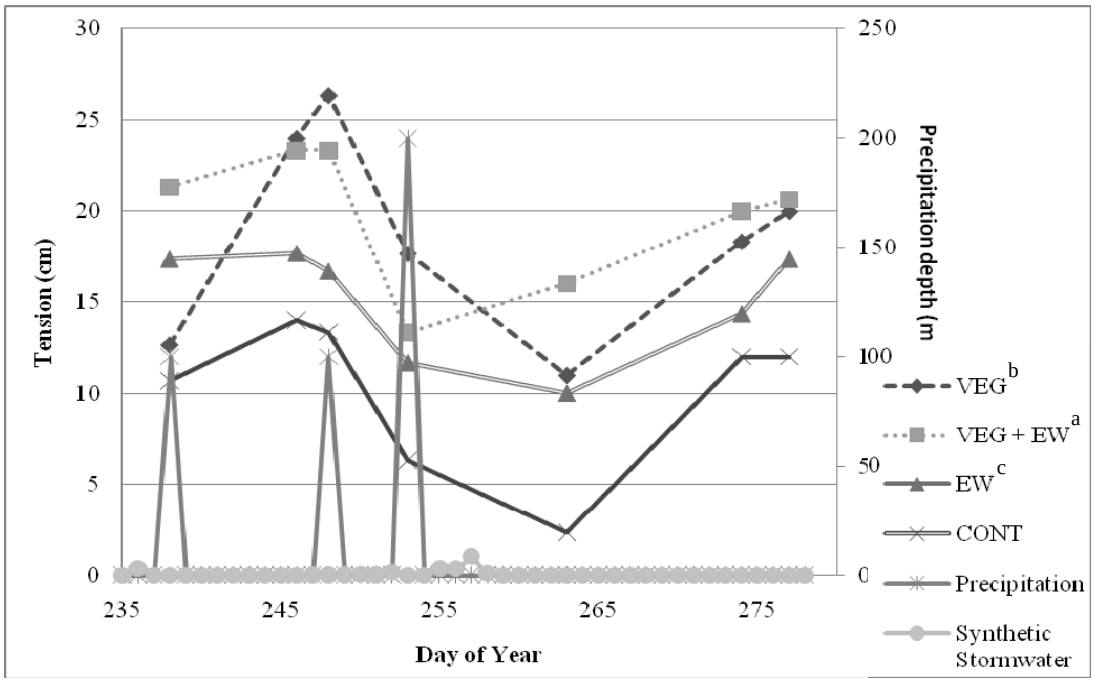
An infiltration trench with a sand media would also have a rapid conductive rate, but the water would also move rapidly through the soil and thus not exhibit the pollutant trapping and filtration ability of a system with components such as native grasses and earthworms. As mentioned in previous sections, the large error bars in Figures 4.8 are indicative of the natural variation inherent in complex systems such as a bioretention cell.

Soil Moisture Fluctuations

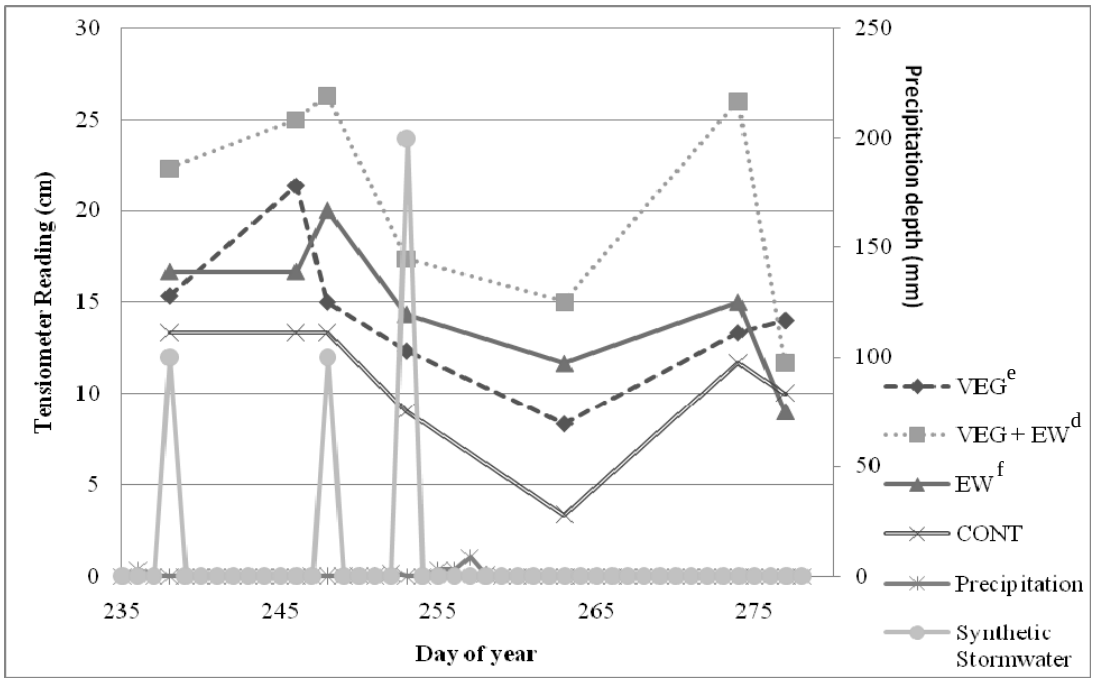
Soil moisture fluctuations are important in stormwater applications. A soil profile that dries out faster is more capable of accepting and treating water from subsequent stormwater events. Soil moisture fluctuations reflected how the presence of vegetation and earthworm impacts on long-term bioretention cell function. During the growing season, vegetation activity utilized water for growth and maintenance. Their influence continued in the off season through the macropores created during the active season that remained intact in the soil profile. The drying effect was evident in the tensiometer data at both 30 and 60 cm depths (Figures 4.9 a, b) because the tension of the control cell remained lower (wetter) than all other treatments. From this analysis, it was apparent that biological activity dried out the soil profile more efficiently than the cells lacking biological activity (Figure 4.9). The differences in tensiomater readings between treatments was significant at both 30 and 60 cm depths ($P > 0.001$ and $P > 0.0241$, respectively) and all treatments exhibited significantly different tensiometer readings from the control as indicated on Figure 4.9.

Figure 4.9 Tensiometer readings taken from August-October 2008 given in cm at a) 30 cm depth and b) 60 cm depth

a) 30 cm



b) 60 cm



Compared to control: [a]P > 0.0001, [b]P > 0.0025, [c]P > 0.0374, [d]P > 0.0207, [e]P > 0.2023, and [f]P > 0.0882)

Overall, the soil moisture fluctuated as expected with a decrease in tension after the second and third synthetic stormwater applications (Days 248 and 253). During the first stormwater event, the drainage valves were closed for 48 hours after the application of synthetic stormwater to assess the potential for enhanced denitrification by creating an anaerobic zone. Thus, any increase in tension after the first synthetic stormwater event may be explained by the cell top and bottom remaining more hydraulically connected as the water would have pooled near the cell drain and allowed water to flow more freely through the profile. The measurements of flow through for this storm event were inaccurate due to ineffective measuring practices, so there is no supporting evidence of this hypothesis from the volume of outflow.

In the top 30 cm of the soil profile, tension readings taken near the end of the growing season followed predicted trends of cells with more biological activity (VEG + EW > VEG > EW) drying out quicker. This was likely due to evapotranspiration and vegetation utilizing water for growth. However, the effect of the treatments on the soil moisture fluctuation was less pronounced at a 60 cm depth (Figure 4.4 b), although generally the tension readings increased with higher orders of biological activity (VEG + EW > VEG > EW). This may be due to the fact that the roots of the vegetation had not yet reached the 60 cm depth in the first growing season. The decrease in tension prior to day 275 in Figure 4.4 b was likely due to the movement of water from the upper 30 cm of soil, validated by the subsequent increase in tension Figure 4.4 a.

Soil Quality

An often overlooked driver of contaminant transport is the initial composition of the bioretention cell media. For example, soil pH has been shown to influence the sorption of heavy metals, such as copper (Hsieh and Davis, 2005), and soils with a high nutrient levels have limited nutrient retention capabilities. The media composition analysis (Table 4.2) of the cells in November 2007 prior to plant and earthworm inoculation showed high levels of N and P, a relatively neutral pH, and varying levels of chloride (from 0.5-12.5 ppm). The elevated levels of nutrients and chloride is likely a residual from the last experiment conducted in the lysimeter cells (Roberts, 2007).

Table 4.4 Initial and final soil quality expressed in mg/kg

Positive values of percent change indicate an accumulation of that parameter in the soil, while negative values indicate removal by plant, earthworm, or physical processes

	Mehlich-3 P			NH4-N			NO3-N			Total N			Total P			Chloride			pH		
	I	F	% Δ	I	F	% Δ	I	F	% Δ	I	F	% Δ	I	F	% Δ	I	F	% Δ	I	F	% Δ
VEG1	13	456	3487	4.4	3.6	-19	5.3	12.2	130	292	752	157	407	896	120	1.0	12.7	1200	8.0	8.1	2
VEG2	12	520	4128	3.0	2.9	-4	4.1	11.6	181	172	840	388	396	925	134	1.1	10.5	856	8.1	8.1	0
VEG3	11	440	3900	3.1	2.6	-17	2.8	11.5	311	179	725	304	397	791	99	0.7	11.1	1486	8.2	8.1	-2
AVE	12	472	3838	3	3	-13	4	12	207	215	772	283	400	871	118	1	11	1181	8	8	0
STDEV	0.89	42.43	324.97	0.79	0.50	8.49	1.25	0.38	93.31	67.19	60.56	116.57	6.27	70.71	17.48	0.21	1.15	315.12	0.10	0.05	1.75
VEGEW1	12	535	4552	3.9	3.5	-11	3.7	11.9	224	229	948	313	399	1007	152	0.7	11.4	1529	8.0	8.1	1
VEGEW2	12	555	4726	3.9	3.4	-13	6.0	11.0	85	219	839	283	417	942	126	2.1	13.6	550	8.0	8.2	2
VEGEW3	13	580	4540	3.8	3.5	-8	8.3	17.7	113	227	1128	396	404	1093	170	4.5	11.4	153	8.2	8.1	-1
AVE	12	557	4606	4	3	-10	6	14	140	225	971	331	407	1014	150	2	12	744	8	8	1
STDEV	0.58	22.55	104.10	0.06	0.04	2.33	2.32	3.62	73.55	5.64	146.22	58.54	8.90	76.04	22.25	1.93	1.29	708.19	0.12	0.05	1.79
EW1	11	600	5560	4.4	3.5	-22	3.1	16.7	449	194	1017	424	409	1152	182	0.5	9.3	1842	8.1	8.0	-2
EW2	13	520	3900	4.8	3.1	-36	23.1	12.0	-48	242	762	215	434	857	98	12.5	6.2	-50	8.0	8.0	0
EW3	16	595	3596	4.0	2.4	-41	14.7	19.8	34	227	974	328	408	996	144	4.1	8.5	106	8.1	8.0	-1
AVE	13	572	4352	4	3	-33	14	16	145	221	918	323	417	1001	141	6	8	633	8	8	-1
STDEV	2.76	44.81	1057.48	0.42	0.57	9.85	10.08	3.91	266.36	24.33	136.63	104.45	14.36	147.88	42.07	6.19	1.59	1050.01	0.06	0.03	1.00
CONT1	11	338	2918	3.5	2.7	-21	7.1	15.8	122	208	686	229	402	824	105	3.1	10.8	249	8.1	8.0	-1
CONT2	10	665	6294	3.9	2.7	-31	3.7	32.2	761	186	1246	570	382	1268	232	0.9	11.0	1148	8.2	7.8	-5
CONT3	12	560	4416	4.4	1.8	-59	4.7	21.2	353	220	973	342	401	945	136	0.6	6.7	941	8.0	8.0	0
AVE	11	521	4543	4	2	-37	5	23	412	205	968	380	395	1012	157	2	9	779	8	8	-2
STDEV	1.01	166.95	1691.74	0.49	0.52	19.74	1.74	8.34	323.40	17.22	279.92	173.39	11.08	229.74	66.15	1.34	2.43	470.43	0.10	0.14	2.68

Table 4.5 Summary of average percent change in soil quality by treatment type

	Mehlich-3 P	NH4-N	NO3-N	Total N	Total P	Chloride	pH
	VEG						
Ave.	3838	-13	207	283	118	1181	0
Std. Dev.	324.97	8.49	93.31	116.57	17.48	315.12	1.75
	VEGEW						
Ave.	4606	-10	140	331	150	744	1
Std. Dev.	104.10	2.33	73.55	58.54	22.25	708.19	1.79
	EW						
Ave.	4352	-33	145	323	141	633	-1
Std. Dev.	1057.48	9.85	266.36	104.45	42.07	1050.01	1.00
	CONT						
Ave.	4543	-37	412	380	157	779	-2
Std. Dev.	1691.74	19.74	323.40	173.39	66.15	470.43	2.68

These large increases in P, N, and chloride indicate that plant uptake of water and nutrients did not sufficiently decrease the concentrations of pollutants in the topsoil. However, trapping pollutants in the top 30 cm of soil prevents pollutants from exiting the cells as effluent.

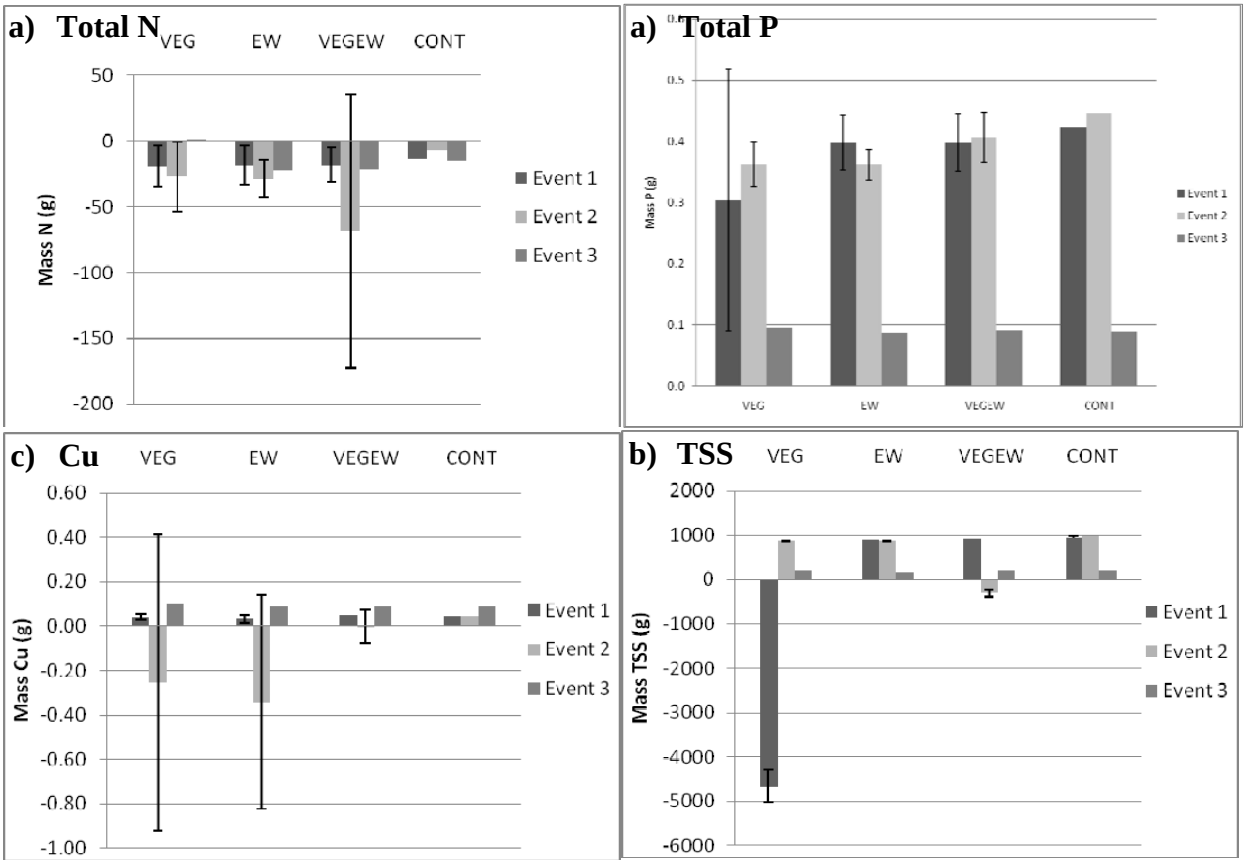
The pH was similar among all treatments and remained constant throughout the growing season. The amount of chloride increased substantially in the vegetation treatment, but to a lesser extent in all other treatments. The vegetation treatment also resulted in the greatest increase in total nitrogen and total phosphorus concentrations, while the treatments with earthworms consistently had about a 40% increase in total nitrogen and a 30% increase in total phosphorus. The amount of ammonia (NH_4-N) decreased slightly in vegetated treatments and by greater than 50% in the earthworm treatment and control, while nitrate (NO_3-N) levels doubled in the control and all treatments except the earthworm only treatment. In vegetated treatments, the total phosphorus levels increased substantially. The Melich 3-P test indicated a two-fold increase in plant-available forms of phosphorus. This is an unexpected result due to the fact that only 1.8 grams of P was added to each cell over the course of the season. This translates to a maximum of 2.4 mg of pollutant/kg of soil assuming all P is retained in the top 30 cm of soil (depth of soil samples).

These results show that plant processes minimally affected the uptake of nutrients and salts in the top 30 cm of soil. However, retention of the pollutants in the top soil reduced the concentration of pollutants in outflow.

Water Quality

One of the principle roles of stormwater best management practices is to improve the quality of water entering surface- and ground-water sources. Thus, contaminant transport is an important aspect of bioretention cell function and should be assessed on a mass basis. A mass basis is more informative than a concentration balance in environmental applications because concentrations change depending on the volume of water leaving the system. For example, an amount of pollutant may be "washed" out of the cell by a relatively small volume of water. This would result in a relatively high concentration of pollutant in the effluent. Conversely, if a large volume of water washes off the same mass of pollutant, the resulting concentration is more dilute. The mass balance was calculated for each synthetic stormwater event (See Appendix B) and the results are presented below.

Figure 4.10 Average mass of each pollutant retained for each event a) Total N, b) Total P, c) Cu, and d) TSS



Bars indicate error bars with 1 standard deviation

There was high inter- and intra-event variability in the mass of each pollutant in the effluent (Figure 4.10). It was apparent that the system was not efficient in trapping nitrogen (N) as the pollutant mass increased in the effluent from all events. The negative value of suspended solids (TSS) in Figure 4.1 d in the vegetation treatment for the first event was likely due a leak from Cell 9 that contaminated the collection apparatus. The inconsistent data was reflective of the complex system and its various effects on pollutant dynamics, and it was difficult to form many conclusions.

Table 4.11 shows the percent reduction for N, P, and TSS. As discussed above, N increased in the through flow resulting in a negative percent reduction. This was also seen in the results for Cu in vegetation and earthworm treatments and TSS in the vegetation treatment. Interestingly, the control improved through flow water quality as compared to the other treatments. While the differences were not significant, these results were unexpected.

Table 4.6 Percent trapping efficiency for each pollutant averaged over all storm events

	Total N		**Total P**		**Cu**		**TSS**	
	Ave	Std Dev	Ave	Std Dev	Ave	Std Dev	Ave	Std Dev
VEG	-1205	1143	85	17	-171	452	-94	322
EW	-1541	710	84	4	-124	341	77	20
VEGEW	-2590	2512	85	4	62	53	28	62
CONT	-736	323	96	3	93	9	95	5

All treatments were effective in reducing the concentration of P. Although not significant ($P > 0.6908$), the control treatment had the greatest P trapping efficiency of 96% while all other treatments exhibited lesser, but similar reductions in P (84-85%). It was difficult to analyze the results of Cu and TSS; the percent trapping efficiency was highly variable in the VEG, EW, and VEGEW treatments, as indicated by the large standard deviations. A large amount of N was released from all treatments for all storm events. This was likely due to the high N content and consequent leaching potential of the bioretention media. With continued establishment, the mature grass will use more N and reduce the export of the nutrient with outflow over time.

It is important to note that there was no significant difference among the treatments in transporting pollutants. Past studies have suggested that macropore flow increases the movement of pollutants, particularly with the transport of herbicides and in tile-drained agricultural fields (Nuutinen and Butt, 2002, Shipitalo and Gibbs, 2000). However, results from

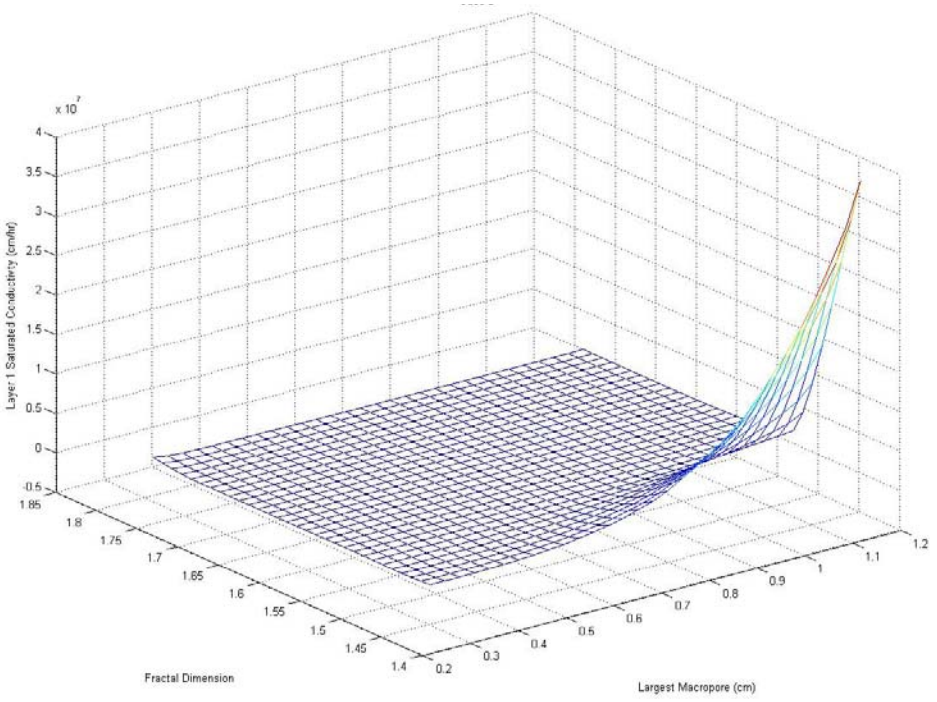
this study did not support these findings. Instead all treatments behaved similarly, suggesting that treatments with earthworms may have induced pollutant degradation and sorption through interaction with the organic-rich drilosphere of earthworm burrows. Edwards *et al*. (1992) and Binet et al. (2006) reported decreased alachlor and atrazine concentration in runoff after interaction with earthworm burrows and sorption into the burrow wall. Additionally, a mature plant system enhances organic matter development; thus providing more sorption sites for heavy metals such as Cu.

Model Results

Sensitivity Analysis

The Comprehensive Bioretention Cell (BRC) model was used to predict how a bioretention cell will function under certain volume and pollutant loadings. Three input parameters, fractal dimension (D_v), macropore size (MAC), and layer depth were manipulated to reflect earthworm and vegetation impacts on infiltration. These parameters were evaluated for their sensitivity by checking their influence on saturated hydraulic conductivity.

Figure 4.11 Impact of Dv* (1.45-1.8) and MAC (0.3-1.2 cm) on the saturated hydraulic conductivity in the first layer of the bioretention cell**

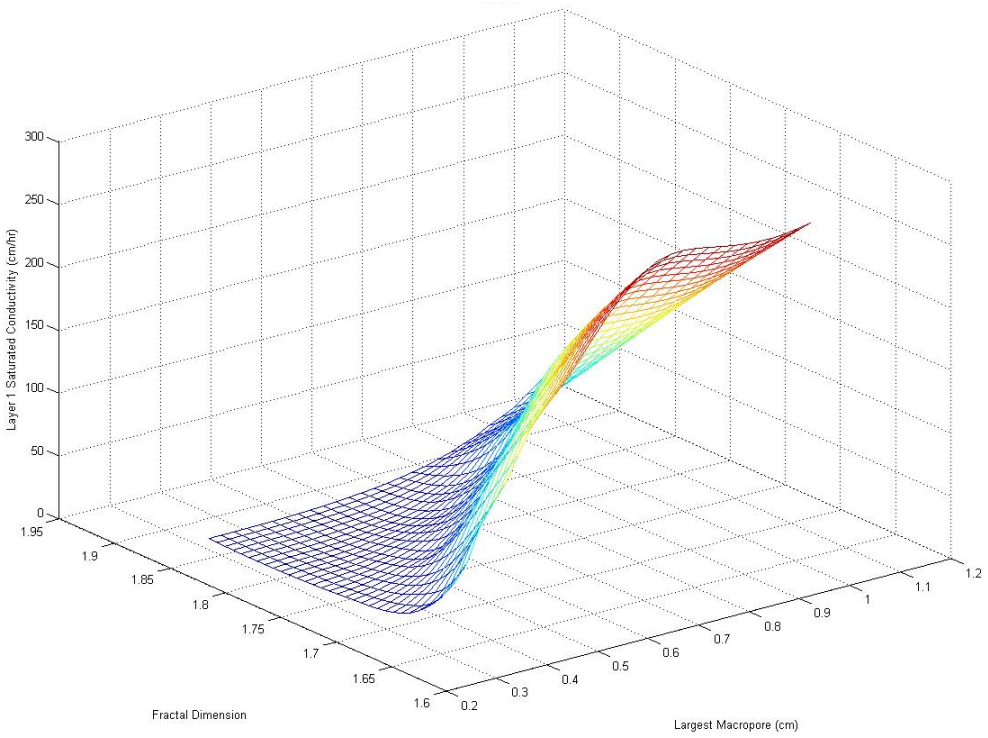


***Fractal dimension**
**Largest macropore size

As depicted in Figure 4.12, hydraulic conductivities did not appear to be sensitive to changes in MAC and D_v except for the large conductivities (up to 3.5×10^7 cm/hr) that resulted from high MAC and low D_v values at the right-hand side of figure. D_v values for a silt loam soil

typically range from 1.72-1.79 with a maximum pore size of 10 mm. With the augmentation of a typical silt loam soil with earthworms and vegetation, we would expect a higher range of D_v values to represent a soil dominated by large pores (earthworms) and with a larger range of pores (combination treatment). Thus, another analysis was performed to look at D_v values ranging from 1.65-1.85 with a minimum pore size of 10 mm (Figure 4.13).

Figure 4.12 A graph showing the impact of Dv* (1.65-1.85) and MAC (0.3-1.0 cm) on the saturated hydraulic conductivity in the first layer of the bioretention cell**



***Fractal dimension**
**Largest macropore size

This graph illustrates that having a smaller range of fractal dimension and macropore size resulted in more realistic saturated hydraulic conductivities. Thus, estimates for MAC and D_v based on rates of macropore formation by earthworms and vegetation are valid within this range of values. This is indicated by similar conductivities found through earthworm burrows (Bouma et al. 1982, Urbankek and Dolezal, 1972, Wang et al. 1994, and Ehlers et al. 1975). The BRC model was employed for three seasons of growth and approximations for MAC and D_v were made based on the rate of macropore formation and population density. There is not a direct

translation from these parameters to D_v, but estimates were formulated based on the fact that the earthworm treatment would be dominated by large pores effective immediately upon introduction, the vegetation treatment would be dominated by small, uniform pores effective during the first season, and the combination treatment would have the largest range of pore sizes. Both the vegetation and combination treatment would reach the maximum root density, and therefore ideal MAC and range of D_v after the second growing season.

Validation of Model

Functional parameters investigated in this study included hydraulic conductivity, ponding depth, drawdown time, infiltration depth, storage, and volume outflow. The model results validated the hypothesis that the introduction of an ecologically diverse system improves bioretention function during the first two years of establishment by improving infiltration, increasing infiltration depth, storage capacity, and reducing drawdown time. The model results for Season 1 reflected data collected from the first season of the field study.

Table 4.7 Results from BRC model analysis from April to September of the first three growing seasons

	EW	VEG	VEGEW	CONT	EW	VEG	VEGEW	CONT
	Season 1							
	April				September			
Hyd. Cond. (cm/hr)	8.5	8.5	8.5	8.5	101.9	8.5	470	8.5
Max. Pond (m)	10.1	26.5	26.5	26.5	3.5	19.1	3.4	25.2
Drawdown (hrs)	30.1	Ponded	Ponded	Ponded	24	42.4	24	Ponded
Infil. Depth (cm)	195.1	163.1	163.1	163.1	201.6	183.2	202.1	169.3
Storage (m^3)	0.9	0.8	0.8	0.8	0.9	0.9	0.9	0.8
Volume out (m^3)	0.9	0.8	0.8	0.8	0.9	0.9	0.9	0.8
% Storage Inc. from Control	7.7	No inc	No inc		4.4	4.4	4.4	
	Season 2							
	April				September			
Hyd. Cond. (cm/hr)	225.9	8.5	636.2	8.5	248	8.5	636.2	8.5
Max. Pond (m)	0.2	14.8	0.2	25.2	0.2	10.9	0.2	23.9
Drawdown (hrs)	24.0	36.2	24	Ponded	24	31.2	24	Ponded
Infil. Depth (cm)	207.1	188.5	219.1	169.3	211.3	193.8	219.1	176.7
Storage (m^3)	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9
Volume out (m^3)	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9
% Storage Inc. from Control	4.4	4.2	4.2		0.5	0.5	0.5	
	Season 3							
	April				September			
Hyd. Cond. (cm/hr)	248	8.5	636.2	8.5	248	8.5	636.2	8.5
Max. Pond (m)	0.2	9.0	0.2	23.9	0.2	7.2	0.2	23.9
Drawdown (hrs)	24.0	29.1	24.0	Ponded	24.0	27.2	24.0	Ponded
Infil. Depth (cm)	211.3	196.4	219.1	176.7	211.3	199	219.1	176.7
Storage (m^3)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Volume out (m^3)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
% Storage Inc. from Control	0.5	0.5	0.5		0.5	0.5	0.5	

As depicted in Table 4.6, the earthworm treatment had an immediate impact on the ponding and storage in April of the first growing season. All three biological treatments showed a marked improvement in function over the control in the first year of establishment. However, the vegetation treatment alone did not have much influence on the hydraulic conductivity. This was reflected in results from the field study in that infiltration rate increased with increasing orders of biological diversity (EW < VEG < VEGEW). Without earthworm burrows, soils would likely be dominated by smaller, more uniform pores that would restrict infiltration to saturated flow only.

Treatments with earthworms permitted unsaturated water flow via macropores and reduced the ponding drawdown to 24 hours within the first growing season. In the field, treatments with only earthworms actually restricted water movement due to surface sealing effects. Both control and earthworm treatments induced ponding times of greater than 24 hours. Although the model results indicate that the control treatment drawdown time was always greater than 48 hours, the effects of surface sealing in the earthworm treatments are were accurately characterized.

Model results indicated that treatments with earthworms consistently had higher volumes of outflow. This was supported by results from the field study where vegetation treatments had greater storage capacity than treatments with earthworms due to the preservation of fine structure of soil. Model outcomes also show that biological treatments had greater infiltration depths than the control. This was reflected in soil moisture patterns from the field study. Soil moisture was retained in the control cell to a greater extent than other treatments because of the shallow depth of infiltration.

By the end of the first growing season, the vegetation and earthworm combination treatment exhibited the greatest impact on bioretention cell function. The maximum impact of vegetation on bioretention cell function occurred at the end of the second growing season, reflecting the fact that Tallgrass prairie root systems reach their greatest density after the second year of growth.

CHAPTER 5 - Conclusions

Despite poor initial growing conditions, the tallgrass plants and earthworms became well established over the course of the study and had interesting impacts on bioretention cell function. Perhaps the most notable impact was the considerable increase in infiltration rates in all treatments. As predicted, the greatest increase in saturated hydraulic conductivity was in the treatment with both vegetation and earthworms. It is also apparent from similar improvements in all cell types that ecological succession occurs to a certain extent despite ecological additions made prior to establishment.

Other findings illustrate the important balance between biology and function: cells with biological components, such as earthworms and native vegetation, behave more like a natural system. Soil moisture fluctuations determined from tensiometer readings indicate a drying effect in treatments with biological activity. The control treatment (little to no macro-biology) consistently had a lower tension reading over time, indicating that the soil profile remained wetter longer than other treatments. Tensiometer readings taken at the end of the growing season (after day 265) followed the trend that higher levels of biology had a greater impact on soil moisture regimes. The trend was not as pronounced in the 60 cm deep tensiometers. This demonstrated that soil moisture fluctuations reflect the level of ecological establishment not only in the time it takes to dry the soil profile, but also in the depth of activity. With continued development, it is expected that the plant roots will have a greater impact deeper in the soil profile.

Treatments with earthworms had a lesser ability to store water because earthworm burrows permitted high conductivities, but these high conductivities reduced the likelihood of ponding and mosquito attenuation. However, a large application of stormwater on cells with earthworms only and no vegetation would pond due to the sealing of the surface. Treatments of only vegetation had a greater storage capacity due to the preservation of the fine structure of soil and fibrous root structure.

All treatments were effective in reducing the concentration of P in runoff water. Although not significant ($P > 0.6908$), the control treatment had the greatest P trapping efficiency of 96% while all other treatments exhibited lesser but similar reductions in P (84-

85%). A large amount of N was released as effluent during all events from all treatments probably because of a high initial N content of the bioretention media. With continued establishment, mature grass will utilize excess N and reduce export over time. No treatment performed significantly better in improving the quality of runoff water. This indicates that macropore flow did not induce a higher rate of pollutant transport. Interaction with the organic-rich drilosphere may even have contributed to pollutant degradation.

Results from the model supported field data in that all biological treatments showed a marked improvement in function over the control in the first year of establishment, and that the vegetation and earthworm treatment exhibited the greatest impact. When operated within the valid bounds of fractal dimension and macropore size, the BRC model can be an informative tool for bioretention cell design providing estimates for desired outcomes. However, the fractal dimension parameter is difficult to understand and even difficult to measure. The model is very sensitive to changes in fractal dimension, so care should be taken in estimating field parameters since there is no direct translation from macropore diameter and density (field parameters) to fractal dimension (model parameter only).

The results of this study show that ecological development is improved with diverse inputs. More biologically diverse bioretention cells experienced enhanced grass/root development, a decrease in drawdown time, reduced ponding, and an increase in infiltration rates. Cells with vegetation and earthworms also were more effective in drying out the soil profile, improving the ability of the cell to function in subsequent stormwater events. Tensiometer measurements indicate the presence and depth of the influence that biological activity has on soil moisture fluctuations. For the successful establishment of nascent grasses and earthworms, it is recommended that stormwater runoff be routed away from the cell during the establishment period to prevent nascent grasses from being stressed by flooding.

By conducting research in the Midwest utilizing native plants, fauna, and soil, the results of this study contribute to a growing pool of information which developers can use to guide effective BMP design. It is critical to continue developing our understanding of NPS pollution generation, transport, and mitigation in the urban environment. This will enhance our ability to develop and implement BMPs that have initial and long term viability and sustainability.

This study will continue for the next few seasons to monitor the further establishment of the ecological system. In future bioretention cell studies, I recommend a few method changes.

First of all, the pump and flow-meter system installed for this experiment was somewhat unreliable in measuring outflow. Wires would often corrode during synthetic stormwater tests and consequently stop measuring flow. Additionally, water balances should still be completed on an event-basis, but with a greater understanding of the outflow hydrograph. Outflow should be measured on a time basis to understand when the peak flow passes through the system. As the system continues to evolve, the depth of roots and earthworm burrows will continue to increase. Thus tensiometers that reach depths beyond 60 cm would allow the examination of the depth of biological influence on soil moisture regimes.

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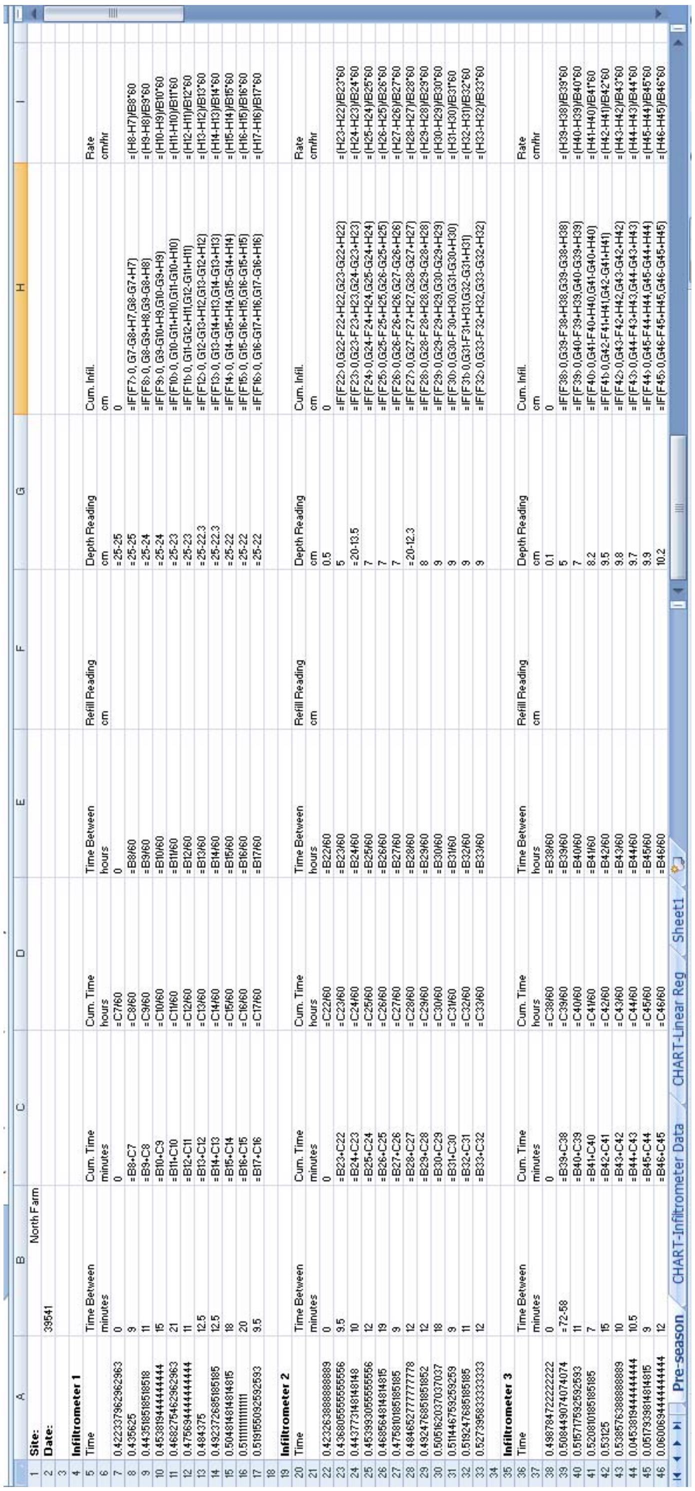
Appendix A - Infiltrometer Calculations

This appendix provides the procedure used to determine the saturated hydraulic conductivity of each cell from infiltrometer measurements. The data is presented in order of analysis with first the measurements, the linear regression analysis, and then SAS codes and statistical analysis output.

Field Measurements and Calculations

The infiltration rate was determined by taking the difference between cumulative infiltration depths and dividing that quantity by the time between measurements. All calculations were conducted in Microsoft excel and included in this appendix.

Figure A.1 Excel spreadsheet showing calculations for hydraulic conductivity. The infiltration rate (far right column) was determined by taking the difference between cumulative infiltration depths and dividing that quantity by the time between measurements.



April 2008 Infiltrometer Calculations

Table 5.1 Infiltration calculations from April 3, 2008 infiltrometer test

Site: North Farm
Date: 4/3/2008

Infiltrometer 1

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:08:10	0.0	0.0	0.00	0.00		0.0	0.00	
10:27:18	9.0	9.0	0.15	0.15		0.0	0.00	0.00
10:38:40	11.0	20.0	0.33	0.18		1.0	1.00	5.45
10:53:30	15.0	35.0	0.58	0.25		1.0	1.00	0.00
11:14:19	21.0	56.0	0.93	0.35		2.0	2.00	2.86
11:25:00	11.0	67.0	1.12	0.18		2.0	2.00	0.00
11:37:30	12.5	79.5	1.33	0.21		2.7	2.70	3.36
11:49:01	12.5	92.0	1.53	0.21		2.7	2.70	0.00
12:06:56	18.0	110.0	1.83	0.30		3.0	3.00	1.00
12:16:00	20.0	130.0	2.17	0.33		3.0	3.00	0.00
12:27:35	9.5	139.5	2.33	0.16		3.0	3.00	0.00

Infiltrometer 2

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:09:30	0.0	0.00	0.00	0.00		0.5	0.00	
10:29:00	9.5	9.50	0.16	0.16		5.0	4.50	28.42
10:39:02	10.0	19.50	0.33	0.17		6.5	6.00	9.00
10:53:45	12.0	31.50	0.53	0.20		7.0	6.50	2.50
11:14:44	19.0	50.50	0.84	0.32		7.0	6.50	0.00
11:25:10	9.0	59.50	0.99	0.15		7.0	6.50	0.00
11:37:54	12.0	71.50	1.19	0.20		7.7	7.20	3.50
11:49:10	12.0	83.50	1.39	0.20		8.0	7.50	1.50
12:07:26	18.0	101.50	1.69	0.30		9.0	8.50	3.33
12:16:29	9.0	110.50	1.84	0.15		9.0	8.50	0.00
12:27:43	11.0	121.50	2.03	0.18		9.0	8.50	0.00
12:39:27	12.0	133.50	2.23	0.20		9.0	8.50	0.00

Infiltrometer 3

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
11:58:15	0.0	0	0.00	0.00		0.1	0.00	
12:12:10	14.0	14	0.23	0.23		5.0	4.90	21.00
12:22:38	11.0	25	0.42	0.18		7.0	6.90	10.91
12:29:58	7.0	32	0.53	0.12		8.2	8.10	10.29
12:45:00	15.0	47	0.78	0.25		9.5	9.40	5.20
12:55:33	10.0	57	0.95	0.17		9.8	9.70	1.80
1:05:21	10.5	67.5	1.13	0.18		9.7	9.60	-0.57
1:14:35	9.0	76.5	1.28	0.15		9.9	9.80	1.33
1:26:30	12.0	88.5	1.48	0.20		10.2	10.10	1.50
1:37:42	12.0	100.5	1.68	0.20		10.0	9.90	-1.00
1:46:01	8.0	108.5	1.81	0.13		10.3	10.20	2.25
1:56:39	11.0	119.5	1.99	0.18		10.3	10.20	0.00
2:04:43	8.0	127.5	2.13	0.13		10.2	10.10	-0.75
2:16:19	9.0	136.5	2.28	0.15		10.5	10.40	2.00
2:25;56	10.0	146.5	2.44	0.17		10.5	10.40	0.00
2:36:36	10.0	156.5	2.61	0.17		11.0	10.90	3.00
2:46:07	10.0	166.5	2.78	0.17		11.0	10.90	0.00
2:54:49	8.0	174.5	2.91	0.13		11.0	10.90	0.00

Infiltrometer 4

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:11:06	0.0	0	0.00	0.00		0.2	0.00	
10:29:30	18.0	18	0.30	0.30		2.0	1.80	6.00
11:39:40	10.0	28	0.47	0.17		2.0	1.80	0.00
10:54:15	14.5	42.5	0.71	0.24		2.0	1.80	0.00
11:15:21	21.0	63.5	1.06	0.35		3.0	2.80	2.86
11:26:30	11.5	75	1.25	0.19		3.3	3.10	1.57
11:38:28	12.0	87	1.45	0.20		3.7	3.50	2.00
11:49:52	11.5	98.5	1.64	0.19		3.9	3.70	1.04
12:08:00	18.0	116.5	1.94	0.30		3.9	3.70	0.00
12:16:45	9.0	125.5	2.09	0.15		3.9	3.70	0.00
12:28:06	11.0	136.5	2.28	0.18		3.9	3.70	0.00
12:39:48	12.0	148.5	2.48	0.20		3.9	3.70	0.00

Infiltrometer 6

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
12:01:10	0.0	0	0.00	0.00		0.1	0.00	
12:12:56	11.0	11	0.18	0.18		3.5	3.40	18.55
12:23:06	10.0	21	0.35	0.17		4.2	4.10	4.20
12:30:19	7.0	28	0.47	0.12		4.5	4.40	2.57
12:46:34	16.5	44.5	0.74	0.28		5.5	5.40	3.64
12:55:54	9.5	54	0.90	0.16		6.3	6.20	5.05
1:05:30	9.5	63.5	1.06	0.16		6.5	6.40	1.26
1:15:01	9.5	73	1.22	0.16		7.0	6.90	3.16
1:27:00	12.0	85	1.42	0.20		7.0	6.90	0.00
1:38:02	11.0	96	1.60	0.18		7.5	7.40	2.73
1:46:20	8.0	104	1.73	0.13		8.0	7.90	3.75
1:56:55	11.0	115	1.92	0.18		8.2	8.10	1.09
2:04:59	8.0	123	2.05	0.13		8.7	8.60	3.75
2:16:42	12.0	135	2.25	0.20		8.8	8.70	0.50
2:26:16	9.0	144	2.40	0.15		9.4	9.30	4.00
2:36:51	11.0	155	2.58	0.18		9.5	9.40	0.55
2:46:30	8.5	163.5	2.73	0.14		9.9	9.80	2.82
2:54:50	8.5	172	2.87	0.14		9.9	9.80	0.00

Infiltrometer 7

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:17:30	0.0	0	0.00	0.00		0.3	0.00	
10:31:00	13.5	13.5	0.23	0.23		1.0	0.70	3.11
10:40:38	10.0	23.5	0.39	0.17		3.0	2.70	12.00
10:54:45	14.0	37.5	0.63	0.23		3.0	2.70	0.00
11:16:03	26.0	63.5	1.06	0.43		3.0	2.70	0.00
11:28:42	13.0	76.5	1.28	0.22		3.5	3.20	2.31
11:39:15	10.0	86.5	1.44	0.17		4.0	3.70	3.00
11:50:39	11.0	97.5	1.63	0.18		4.0	3.70	0.00
12:08:21	17.0	114.5	1.91	0.28		4.0	3.70	0.00
12:17:23	9.0	123.5	2.06	0.15		4.0	3.70	0.00
12:29:30	12.0	135.5	2.26	0.20		4.0	3.70	0.00
12:40:18	11.0	146.5	2.44	0.18		4.0	3.70	0.00

Infiltrometer 8

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
12:03:41	0.0	0	0.00	0.00		0.2	0.00	
12:13:50	10.0	10	0.17	0.17		2.2	2.00	12.00
12:23:29	10.0	20	0.33	0.17		2.2	2.00	0.00
12:30:43	7.0	27	0.45	0.12		2.5	2.30	2.57
12:46:59	16.0	43	0.72	0.27		3.3	3.10	3.00
12:56:58	10.0	53	0.88	0.17		3.5	3.30	1.20
1:06:12	9.0	62	1.03	0.15		3.8	3.60	2.00
1:15:12	9.0	71	1.18	0.15		4.0	3.80	1.33
1:27:38	12.5	83.5	1.39	0.21		4.3	4.10	1.44
1:38:23	10.0	93.5	1.56	0.17		5.0	4.80	4.20
1:46:50	9.0	102.5	1.71	0.15		5.0	4.80	0.00
1:57:15	11.0	113.5	1.89	0.18		5.8	5.60	4.36
2:05:17	8.0	121.5	2.03	0.13		6.3	6.10	3.75
2:17:02	12.0	133.5	2.23	0.20		6.8	6.60	2.50
2:26:35	9.5	143	2.38	0.16		7.2	7.00	2.53
2:37:09	10.5	153.5	2.56	0.18		7.8	7.60	3.43
2:46:48	10.0	163.5	2.73	0.17		8.0	7.80	1.20
2:55:20	9.0	172.5	2.88	0.15		8.2	8.00	1.33

Infiltrometer 9

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:17:30	0.0	0	0.00	0.00		0.1	0.00	
10:31:00	13.5	13.5	0.23	0.23		1.0	0.90	4.00
10:40:38	10.0	23.5	0.39	0.17		3.0	2.90	12.00
10:54:45	14.0	37.5	0.63	0.23		3.0	2.90	0.00
11:16:03	26.0	63.5	1.06	0.43		3.0	2.90	0.00
11:28:42	13.0	76.5	1.28	0.22		3.5	3.40	2.31
11:39:15	10.0	86.5	1.44	0.17		4.0	3.90	3.00
11:50:39	11.0	97.5	1.63	0.18		4.0	3.90	0.00
12:08:21	17.0	114.5	1.91	0.28		4.0	3.90	0.00
12:17:23	9.0	123.5	2.06	0.15		4.0	3.90	0.00
12:29:30	12.0	135.5	2.26	0.20		4.0	3.90	0.00
12:40:18	11.0	146.5	2.44	0.18		4.0	3.90	0.00

Infiltrometer 10

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:19:30	0.0	0	0.00	0.00		0.0	0.00	
10:31:30	12.0	12	0.20	0.20		1.0	1.00	5.00
10:41:56	11.5	23.5	0.39	0.19		1.0	1.00	0.00
10:55:20	13.0	36.5	0.61	0.22		1.0	1.00	0.00
11:16:30	11.0	47.5	0.79	0.18		1.0	1.00	0.00
11:30:30	14.0	61.5	1.03	0.23		1.0	1.00	0.00
11:40:10	9.5	71	1.18	0.16		1.0	1.00	0.00
12:09:09	29.0	100	1.67	0.48		1.0	1.00	0.00
12:17:39	9.0	109	1.82	0.15		1.0	1.00	0.00
12:28:49	11.0	120	2.00	0.18		1.0	1.00	0.00
12:40:29	11.5	131.5	2.19	0.19		1.0	1.00	0.00

Infiltrometer 11

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
10:20:00	0.0	0	0.00	0.00		0.0	0.00	
11:31:30	11.5	11.5	0.19	0.19		1.0	1.00	5.22
11:43:00	11.5	23	0.38	0.19		1.0	1.00	0.00
10:55:45	13.0	36	0.60	0.22		1.0	1.00	0.00
11:17:11	11.0	47	0.78	0.18		1.0	1.00	0.00
11:30:46	14.0	61	1.02	0.23		1.0	1.00	0.00
11:40:19	9.0	70	1.17	0.15		1.0	1.00	0.00
11:51:36	11.5	81.5	1.36	0.19		1.0	1.00	0.00
12:09:19	18.0	99.5	1.66	0.30		1.0	1.00	0.00
12:19:59	11.0	110.5	1.84	0.18		2.0	2.00	5.45
12:29:05	9.0	119.5	1.99	0.15		2.0	2.00	0.00
12:40:40	11.0	130.5	2.18	0.18		3.0	3.00	5.45

Infiltrometer 12

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
12:01:10	12.5	0	0.00	0.21		0.2	0.00	
12:13:33	11.0	11	0.18	0.18		1.0	0.80	4.36
12:23:54	10.5	21.5	0.36	0.18		1.0	0.80	0.00
12:35:05	11.0	32.5	0.54	0.18		1.0	0.80	0.00
12:47:27	12.5	45	0.75	0.21		1.0	0.80	0.00
12:56:58	9.5	54.5	0.91	0.16		1.0	0.80	0.00
1:06:31	9.5	64	1.07	0.16		1.0	0.80	0.00
1:14:35	8.0	72	1.20	0.13		1.0	0.80	0.00
1:26:30	12.0	84	1.40	0.20		1.0	0.80	0.00
1:47:00	10.5	94.5	1.58	0.18		1.0	0.80	0.00
1:57:25	10.5	105	1.75	0.18		1.0	0.80	0.00
2:05:19	8.0	113	1.88	0.13		1.0	0.80	0.00
2:26:39	22.0	135	2.25	0.37		1.0	0.80	0.00
2:55:20	31.0	166	2.77	0.52		1.0	0.80	0.00

Figure A.1 Plot of cumulative infiltration depth versus cumulative time for each cell

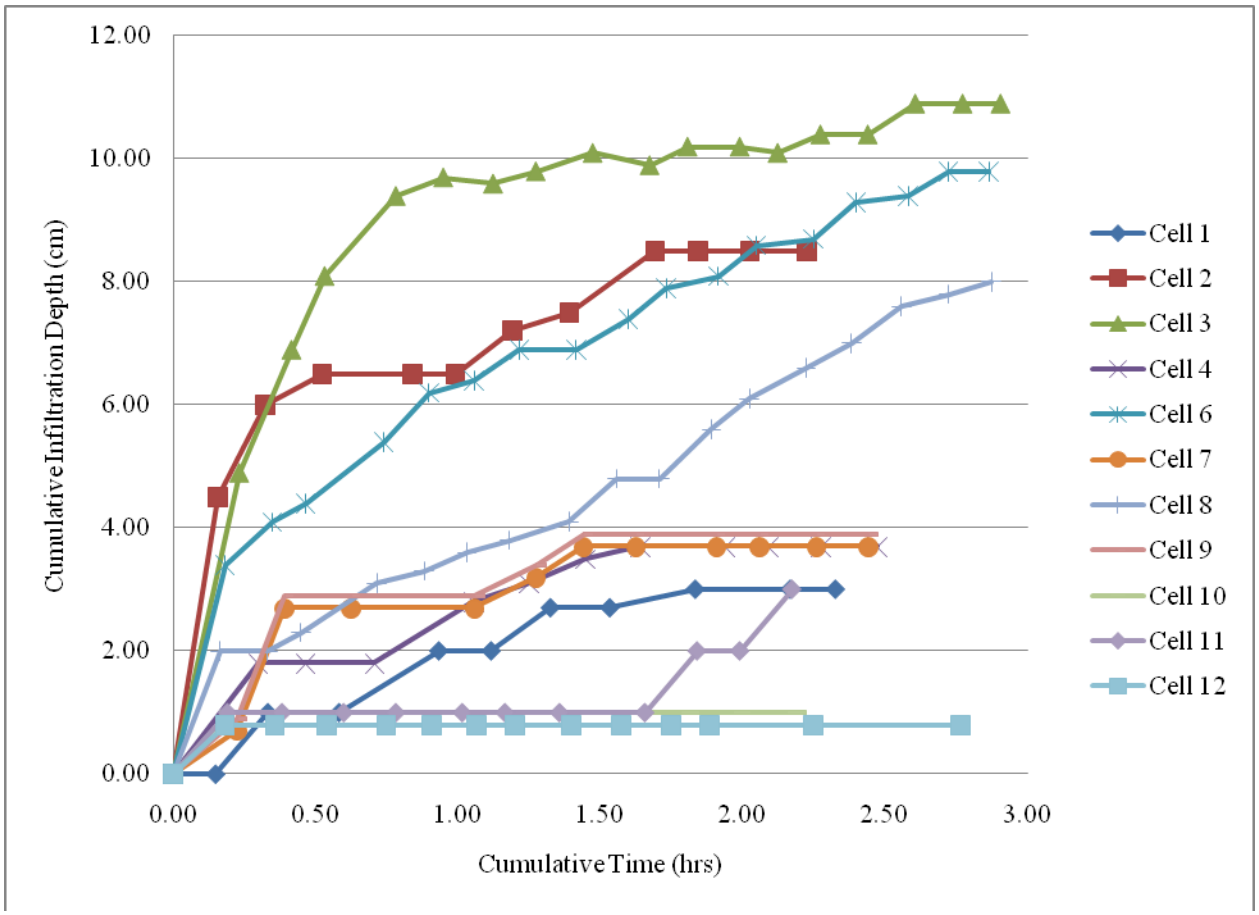


Figure A.2 Linear regression analysis on linear portion of each curve

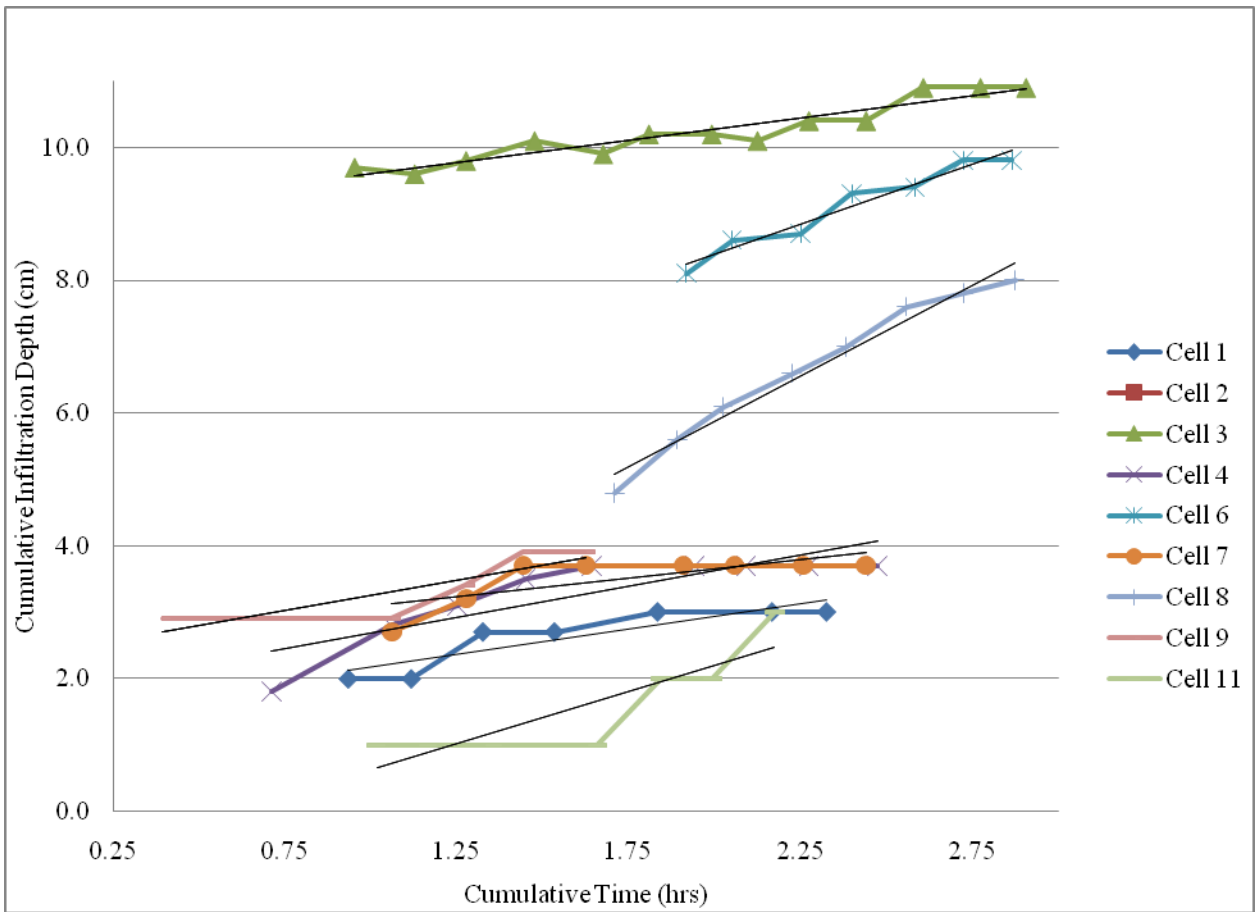


Table A.2 The saturated conductivities determined from linear regression analysis

Cell	Reg. Eqn.	K_{sat} (cm/hr)
3	Y = 0.7X + 8.9	0.7
4	Y = 0.9X +1.7	0.9
6	Y = 1.8 + 4.8X	1.8
7	Y = 0.6X + 2.5	0.6
8	Y = 2.7X + 0.4	2.7
9	Y = 0.9X + 2.36	0.9
11	Y = 1.6X + 0.9	1.6

October 2008 Infiltrometer Calculations

Table A.3 Data from field measurements on October 10, 2008

Site: North Farm
Date: 10/10/2008

Infiltrometer 1

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:22:12	0.0	0.0	0.00	0.00		0.0	0.00	
3:32:46	10.0	10.0	0.17	0.17		10.2	10.16	60.96
3:43:16	11.0	21.0	0.35	0.18		15.9	15.88	31.17
3:52:58	10.0	31.0	0.52	0.17		19.4	19.37	20.96
4:03:40	11.0	42.0	0.70	0.18		22.9	22.86	19.05
4:12:18	9.0	51.0	0.85	0.15		23.5	23.50	4.23
4:23:01	11.0	62.0	1.03	0.18		25.4	25.40	10.39
4:38:05	15.0	77.0	1.28	0.25		27.0	26.99	6.35
4:47:17	9.0	86.0	1.43	0.15		27.6	27.62	4.23
4:56:31	9.0	95.0	1.58	0.15		29.2	29.21	10.58
4:57:36	1.00	104.0	1.73	0.15		33.0	32.00	18.60
5:06:46	9.0	114.0	1.90	0.17		40.3	33.00	6.00
5:16:17	10.0	123.0	2.05	0.15		44.8	37.45	29.63
5:24:57	9.0	132.0	2.20	0.15		48.3	40.94	23.28

Infiltrometer 2

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:23:14	0.0	0.14	0.00	0.00		0.0	0.00	
3:33:16	11.0	0.15	0.00	0.18		11.4	11.43	62.35
3:43:43	10.0	10.15	0.17	0.17		19.4	19.37	47.63
3:53:20	10.0	20.15	0.34	0.17		21.0	20.96	9.53
4:03:52	11.0	31.15	0.52	0.18		30.5	30.48	51.95
4:04:24	10.5	41.65	0.69	0.18		31.1	31.12	3.63
4:12:34	8.0	49.65	0.83	0.13		37.8	37.78	50.01
4:23:14	11.0	60.65	1.01	0.18		43.2	43.18	29.44
4:38:27	15.0	75.65	1.26	0.25		48.9	48.90	22.86
4:47:26	9.0	84.65	1.41	0.15		52.4	52.39	23.28
4:59:19	2.0	86.65	1.44	0.03		57.5	57.47	152.40
5:07:16	8.0	94.65	1.58	0.13		57.5	57.47	0.00
5:16:30	9.0	103.65	1.73	0.15		58.4	58.42	6.35
5:25:15	10.0	113.65	1.89	0.17		60.3	60.30	11.28

Infiltrometer 3

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:23:54	0.0	0	0.00	0.00		**0.0**	0.00	
3:33:41	14.0	14	0.23	0.23		14.0	13.97	59.87
3:43:43	11.0	25	0.42	0.18		21.3	21.27	39.83
3:53:20	7.0	32	0.53	0.12		25.4	25.40	35.38
4:06:10	15.0	47	0.78	0.25		33.0	33.02	30.48
4:12	10.0	57	0.95	0.17		41.6	41.59	51.44
4:23:34	10.5	67.5	1.13	0.18		49.5	49.53	45.36
4:38:48	9.0	76.5	1.28	0.15		55.9	55.88	42.33
4:47:33	12.0	88.5	1.48	0.20		58.4	58.42	12.70
4:59:40	12.0	100.5	1.68	0.20		61.6	61.60	15.88
5:07:47	8.0	108.5	1.81	0.13		61.9	61.91	2.38
5:16:47	11.0	119.5	1.99	0.18		64.1	64.14	12.12
5:25:28	8.0	127.5	2.13	0.13		65.4	65.41	9.52

Infiltrometer 4

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:24:48	0.0	0	0.00	0.00		0.0	0.00	
3:25:41	18.0	18	0.30	0.30		20.3	20.32	67.73
3:34:13	10.0	28	0.47	0.17		53.3	53.34	198.12
3:35:26	14.5	42.5	0.71	0.24		86.4	86.36	136.63
3:43:54	21.0	63.5	1.06	0.35		111.8	111.76	72.57
3:53:35	11.5	75	1.25	0.19		114.3	114.30	13.25
4:06:26	12.0	87	1.45	0.20		137.2	137.16	114.30
4:12:53	11.5	98.5	1.64	0.19		138.4	138.43	6.63
4:23:43	18.0	116.5	1.94	0.30		139.7	139.70	4.23
4:26:16	9.0	125.5	2.09	0.15		144.8	144.78	33.87
4:39:15	11.0	136.5	2.28	0.18		168.6	168.59	129.89
4:47:40	12.0	148.5	2.48	0.20		170.2	170.18	7.94
4:59:48	13.0	161.5	2.69	0.22		170.2	170.18	0.00
5:08:13	14.0	175.5	2.93	0.23		170.5	170.50	1.36
5:17:18	15.0	190.5	3.18	0.25		171.8	171.77	5.08
5:25:45	16.0	206.5	3.44	0.27		173.0	173.04	4.76

Infiltrometer 5

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:25:25	12.5	0	0.00	0.21		0.0	0.00	
3:36:02	11.0	11	0.18	0.18		7.0	6.99	38.10
3:44:17	10.5	21.5	0.36	0.18		10.2	10.16	18.14
3:53:53	11.0	32.5	0.54	0.18		14.0	13.97	20.78
4:06:38	12.5	45	0.75	0.21		18.1	18.10	19.81
4:13:16	9.5	54.5	0.91	0.16		19.1	19.05	6.02
4:24:14	9.5	64	1.07	0.16		21.0	20.96	12.03
4:39:39	8.0	72	1.20	0.13		23.8	23.81	21.43
4:47:36	12.0	84	1.40	0.20		25.4	25.40	7.94
5:00:08	10.5	94.5	1.58	0.18		27.0	26.99	9.07
5:08:26	10.5	105	1.75	0.18		28.9	28.89	10.89
5:17:29	8.0	113	1.88	0.13		30.5	30.48	11.91
5:26:57	22.0	135	2.25	0.37		31.1	31.12	1.73

Infiltrometer 6

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:28:44	0.0	0	0.00	0.00		0.0	0.00	
3:36:14	11.0	11	0.18	0.18		12.1	12.07	65.81
3:44:27	10.0	21	0.35	0.17		17.8	17.78	34.29
3:54:03	7.0	28	0.47	0.12		20.3	20.32	21.77
4:06:40	16.5	44.5	0.74	0.28		25.4	25.40	18.47
4:13:22	9.5	54	0.90	0.16		25.4	25.40	0.00
4:26:42	9.5	63.5	1.06	0.16		28.8	28.83	21.66
4:27:37	9.5	73	1.22	0.16		31.8	31.75	18.45
4:39:55	12.0	85	1.42	0.20		40.6	40.64	44.45
4:48:14	11.0	96	1.60	0.18		43.5	43.50	15.59
5:00:29	8.0	104	1.73	0.13		47.3	47.31	28.58
5:08:40	11.0	115	1.92	0.18		47.3	47.31	0.00
5:17:55	8.0	123	2.05	0.13		51.4	51.44	30.96
5:27:07	9.0	132	2.20	0.15		53.3	53.34	12.70

Infiltrometer 7

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:29:20	0.0	0	0.00	0.00		0.0	0.00	
3:36:39	13.5	13.5	0.23	0.23		1.9	1.91	8.47
3:44:41	10.0	23.5	0.39	0.17		2.5	2.54	3.81
3:54	14.0	37.5	0.63	0.23		5.1	5.08	10.89
4:07:03	26.0	63.5	1.06	0.43		5.1	5.08	0.00
4:13:47	13.0	76.5	1.28	0.22		5.1	5.08	0.00
4:28:20	10.0	86.5	1.44	0.17		6.0	6.03	5.72
4:40:16	11.0	97.5	1.63	0.18		7.6	7.62	8.66
4:48:41	17.0	114.5	1.91	0.28		7.6	7.62	0.00
5:00:49	9.0	123.5	2.06	0.15		8.9	8.89	8.47
5:09:01	12.0	135.5	2.26	0.20		9.8	9.84	4.76
5:18:31	11.0	146.5	2.44	0.18		10.2	10.16	1.73
5:27:21	12.0	158.5	2.64	0.20		11.2	11.16	5.00

Infiltrometer 8

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:30:01	0.0	0	0.00	0.00		0.0	0.00	
3:36:49	10.0	10	0.17	0.17		19.7	19.69	118.11
3:38:00	10.0	20	0.33	0.17		27.9	27.94	49.53
3:44:57	7.0	27	0.45	0.12		44.5	44.45	141.51
3:54:34	16.0	43	0.72	0.27		54.0	53.98	35.72
3:55:40	10.0	53	0.88	0.17		55.9	55.88	11.43
4:07:12	9.0	62	1.03	0.15		76.2	76.20	135.47
4:14:10	9.0	71	1.18	0.15		80.0	80.01	25.40
4:28:44	12.5	83.5	1.39	0.21		85.1	85.09	24.38
4:29:29	10.0	93.5	1.56	0.17		83.8	83.82	-7.62
4:40:31	9.0	102.5	1.71	0.15		98.4	98.43	97.37
4:49:04	11.0	113.5	1.89	0.18		104.5	104.46	32.90
5:00:59	8.0	121.5	2.03	0.13		110.2	110.17	42.86
5:10:04	12.0	133.5	2.23	0.20		111.8	111.76	7.94
5:10:11	9.5	143	2.38	0.16		119.4	119.38	48.13
5:18:42	10.5	153.5	2.56	0.18		122.9	122.87	19.96
5:27:29	10.0	163.5	2.73	0.17		130.5	130.49	45.72

Infiltrometer 9

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:30:13	0.0	0	0.00	0.00		0.0	0.00	
3:38:29	13.5	13.5	0.23	0.23		2.5	2.54	11.29
3:39:37	10.0	23.5	0.39	0.17		2.9	2.86	1.91
3:45:09	14.0	37.5	0.63	0.23		4.4	4.45	6.80
3:55:56	26.0	63.5	1.06	0.43		5.1	5.08	1.47
4:07:36	13.0	76.5	1.28	0.22		5.1	5.08	0.00
4:14:24	10.0	86.5	1.44	0.17		5.1	5.08	0.00
4:29:55	11.0	97.5	1.63	0.18		5.1	5.08	0.00
4:40:00	17.0	114.5	1.91	0.28		5.1	5.08	0.00
4:49:13	9.0	123.5	2.06	0.15		5.7	5.72	4.23
5:01:36	12.0	135.5	2.26	0.20		5.7	5.72	0.00
5:10:17	11.0	146.5	2.44	0.18		6.0	6.03	1.73
5:18:59	12.0	158.5	2.64	0.20		6.0	6.03	0.00
5:27:39	13.0	171.5	2.86	0.22		6.0	6.03	0.00

Infiltrometer 11

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:31:09	0.0	0	0.00	0.00		0.0	0.00	
3:38:52	11.5	11.5	0.19	0.19		20.3	20.32	106.02
3:45:32	11.5	23	0.38	0.19		43.8	43.82	122.58
3:56:21	13.0	36	0.60	0.22		69.2	69.22	117.23
4:07:46	11.0	47	0.78	0.18		96.5	96.52	148.94
4:14:33	14.0	61	1.02	0.23		109.2	109.22	54.43
4:31:25	9.0	70	1.17	0.15		113.0	113.03	25.40
4:42:14	11.5	81.5	1.36	0.19		120.0	120.02	36.44
4:49:40	18.0	99.5	1.66	0.30		123.2	123.19	10.58
4:50:57	11.0	110.5	1.84	0.18		123.8	123.83	3.46
5:02:00	9.0	119.5	1.99	0.15		128.3	128.27	29.63
5:10:34	11.0	130.5	2.18	0.18		128.9	128.91	3.46
5:19:25	12.0	142.5	2.38	0.20		129.8575	129.86	4.76
5:27:57	13.0	155.5	2.59	0.22		131.4	131.45	7.33

Infiltrometer 12

Time	Time Between minutes	Cum. Time minutes	Cum. Time hours	Time Between hours	Refill Reading cm	Depth Reading cm	Cum. Infil. cm	Rate cm/hr
3:31:52	12.5	0	0.00	0.21		0.2	0.00	
3:40:02	11.0	11	0.18	0.18		1.0	4.45	24.25
3:45:43	10.5	21.5	0.36	0.18		1.0	5.72	7.26
3:57:38	11.0	32.5	0.54	0.18		1.0	9.53	20.78
4:07:56	12.5	45	0.75	0.21		1.0	12.70	15.24
4:14:47	9.5	54.5	0.91	0.16		1.0	13.02	2.01
4:31:44	9.5	64	1.07	0.16		1.0	15.24	14.04
4:42:27	8.0	72	1.20	0.13		1.0	17.46	16.67
4:51:00	12.0	84	1.40	0.20		1.0	18.42	4.76
5:02:09	10.5	94.5	1.58	0.18		1.0	19.05	3.63
5:10:45	10.5	105	1.75	0.18		1.0	20.32	7.26
5:19:32	8.0	113	1.88	0.13		1.0	21.27	7.14
5:28:10	22.0	135	2.25	0.37		1.0	21.59	0.87

Figure A.4 Plot of cumulative infiltration depth versus cumulative time for each cell

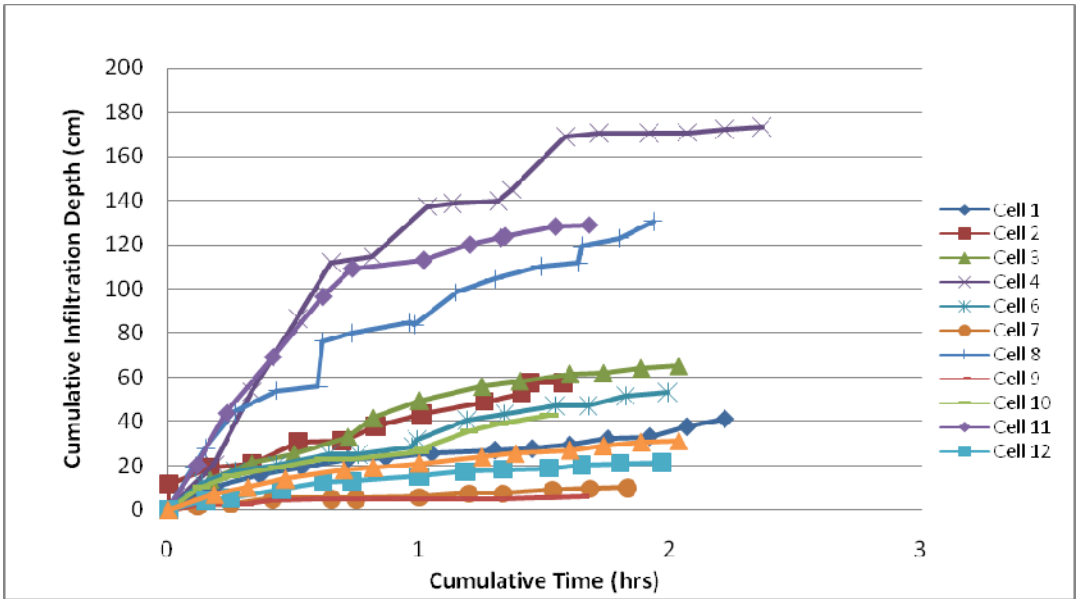


Figure A.5 Linear regression analysis on linear portion of each curve

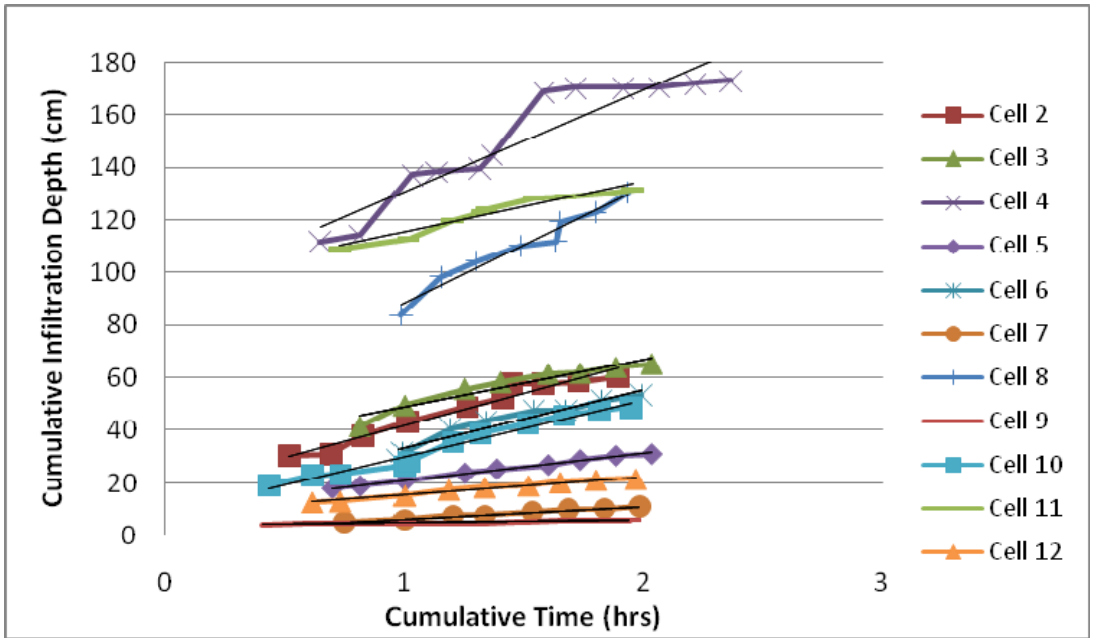


Table A.4 Hydraulic saturated conductivities determined from linear regression analysis

Cell	Reg. Eqn.	K_{sat} (cm/hr)
1	Y = 11.1X + 13.3	11.1
2	Y = 24.4X + 17.5	24.4
3	Y = 18.3X + 30.5	18.3
4	Y = 38.5X + 92.5	38.5
5	Y = 10.2X + 11.0	10.2
6	Y = 22.4X + 10.7	22.4
7	Y = 4.9X + 1.32	4.9
8	Y = 44.3X + 44.1	44.3
9	Y =1X + 4.215	1
10	Y = 21.5X + 8.4	21.5
11	Y = 19.2X 96.2	19.2
12	Y = 7.1X + 8.4	7.1

Appendix B - SAS Code and Output Biomass

This appendix includes the SAS input and output used to perform statistical analysis on biomass measurements. In the input table, E is event number, T is treatment type, R is replication number, and the fourth variable is biomass.

Inputs

T	R	B
1	1	942.19
1	2	940.65
1	3	839.53
2	1	473.81
2	2	1611.51
2	3	1196.03

```
proc glm data = sasuser.biomass;
class T R;
model B=T R;
lsmeans T R;
run;
```

Output

Class Level Information

Class	Levels	Values
T	2	1 2
R	3	1 2 3

Number of Observations Read	6
Number of Observations Used	6

Dependent Variable: B B

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	375671.3546	125223.7849	0.72	0.6246
Error	2	346188.7408	173094.3704		
Corrected Total	5	721860.0953			

R-Square	Coeff Var	Root MSE	B Mean
0.520421	41.57884	416.0461	1000.620

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	52076.7522	52076.7522	0.30	0.6384
R	2	323594.6024	161797.3012	0.93	0.5169

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	1	52076.7522	52076.7522	0.30	0.6384
R	2	323594.6024	161797.3012	0.93	0.5169

Least Squares Means

T	B LSMEAN
1	907.45631
2	1093.78353

R	B LSMEAN
1	708.00233
2	1276.07925
3	1017.77817

Appendix C - SAS Code and Output: Water Balance

This appendix includes the SAS input and output used to perform statistical analysis on water balance calculations and measurements. In the input table, E is event number, T is treatment type, R is replication number, and the fourth variable is volume of outflow.

Inputs

E	T	R	Q
1	1	1	0.130
2	1	1	0.138
3	1	1	0.294
1	2	1	0.130
2	2	1	-0.060
3	2	1	0.112
1	3	1	0.130
2	3	1	0.006
3	3	1	0.161
1	2	2	0.130
2	2	2	0.046
3	2	2	0.067
1	3	2	0.130
2	3	2	-0.685
3	3	2	-0.221
1	4	1	0.130
2	4	1	0.118
3	4	1	0.283
1	4	2	0.107
2	4	2	-0.083
3	4	2	0.256
1	2	3	0.164
2	2	3	0.159
3	2	3	-0.823
1	1	2	0.130
2	1	2	0.159
3	1	2	-0.035
1	1	3	0.164
2	1	3	0.019

3	1	3	0.112
1	3	3	0.130
2	3	3	0.133
3	3	3	-0.149
1	4	3	0.167
2	4	3	0.163
3	4	3	0.328

```
proc sort data = sasuser.perc;
by E;
proc glm data = sasuser.perc;
by E;
class T R;
model Q = T R;
lsmeans T R;
run;
```

Output

```
------------------------------------------------- E=1 -----------------------------------------------
                                  Class Level Information

                                Class         Levels    Values

                                T                  4    1 2 3 4

                                R                  3    1 2 3


                             Number of Observations Read          12
                             Number of Observations Used          12

       Dependent Variable: Q   Q

                                                              Sum of
                          Source                     DF         Squares     Mean Square    F Value
Pr > F

                          Model                       5      0.00263182      0.00052636       2.98
0.1082

                          Error                       6      0.00106037      0.00017673

                          Corrected Total            11      0.00369219


                                        R-Square     Coeff Var      Root MSE        Q Mean

                                        0.712807      9.742297      0.013294      0.136456


                          Source                     DF       Type I SS     Mean Square    F Value
Pr > F

                          T                           3      0.00027226      0.00009075       0.51
0.6878

                          R                           2      0.00235957      0.00117978       6.68
0.0298
```

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	0.00027226	0.00009075	0.51	0.6878
R	2	0.00235957	0.00117978	6.68	0.0298

Least Squares Means

T	Q LSMEAN
1	0.14087212
2	0.14087212
3	0.12951588
4	0.13456310

R	Q LSMEAN
1	0.12951588
2	0.12383776
3	0.15601376

---------- E=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: Q Q

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.29665064	0.05933013	1.14	0.4316
Error	6	0.31247016	0.05207836		
Corrected Total	11	0.60912079			

R-Square	Coeff Var	Root MSE	Q Mean
0.487014	2451.498	0.228207	0.009309

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	0.15197931	0.05065977	0.97	0.4651
R	2	0.14467133	0.07233567	1.39	0.3194

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	0.15197931	0.05065977	0.97	0.4651
R	2	0.14467133	0.07233567	1.39	0.3194

Least Squares Means

T	Q LSMEAN
1	0.10548692
2	0.04821284
3	-0.18227337
4	0.06580910

R	Q LSMEAN
1	0.05031750
2	-0.14089755
3	0.11850666

---------- E=3 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: Q Q

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.67648109	0.13529622	1.78	0.2506
Error	6	0.45544621	0.07590770		
Corrected Total	11	1.13192729			

R-Square	Coeff Var	Root MSE	Q Mean
0.597637	856.6702	0.275514	0.032161

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	0.43641923	0.14547308	1.92	0.2281
R	2	0.24006186	0.12003093	1.58	0.2808

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	0.43641923	0.14547308	1.92	0.2281
R	2	0.24006186	0.12003093	1.58	0.2808

Least Squares Means

T	Q LSMEAN
1	0.12364176
2	-0.21452169
3	-0.06941424
4	0.28893808

R	Q LSMEAN
1	0.21259894
2	0.01670388
3	-0.13281988

Inputs

E	T	Q
1	1	0.130
2	1	0.138
3	1	0.294
1	2	0.130
2	2	-0.060
3	2	0.112
1	3	0.130
2	3	0.006
3	3	0.161
1	2	0.130
2	2	0.046
3	2	0.067
1	3	0.130
2	3	-0.685
3	3	-0.221
1	4	0.130
2	4	0.118
3	4	0.283
1	4	0.107
2	4	-0.083
3	4	0.256
1	2	0.164
2	2	0.159
3	2	-0.823
1	1	0.130
2	1	0.159
3	1	-0.035
1	1	0.164
2	1	0.019
3	1	0.112
1	3	0.130
2	3	0.133
3	3	-0.149
1	4	0.167
2	4	0.163
3	4	0.328

```
proc glm data = sasuser.perc;
      class E T;
      model Q = E T;
      lsmeans E T;
      run;
```

Output

Class Level Information

Class	Levels	Values
E	3	1 2 3
T	4	1 2 3 4

Number of Observations Read	36
Number of Observations Used	36

Dependent Variable: Q

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.37553183	0.07510637	1.52	0.2124
Error	30	1.47947234	0.04931574		
Corrected Total	35	1.85500417			

R-Square	Coeff Var	Root MSE	Q Mean
0.202443	374.4342	0.222071	0.059309

Source	DF	Type I SS	Mean Square	F Value	Pr > F
E	2	0.11026389	0.05513194	1.12	0.3402
T	3	0.26526794	0.08842265	1.79	0.1698

Source	DF	Type III SS	Mean Square	F Value	Pr > F
E	2	0.11026389	0.05513194	1.12	0.3402
T	3	0.26526794	0.08842265	1.79	0.1698

The GLM Procedure
Least Squares Means

E	Q LSMEAN
1	0.13645580
2	0.00930887
3	0.03216098

T	Q LSMEAN
1	0.12333360
2	-0.00847891
3	-0.04072391
4	0.16310342

Inputs

E	T	R	Percent
1	1	1	77.38297
2	1	1	84.88904
3	1	1	10.38509
1	2	1	77.38297
2	2	1	-36.9869
3	2	1	34.22776
1	3	1	77.38297
2	3	1	3.522331
3	3	1	50.77156
1	2	2	77.38297
2	2	2	28.02384
3	2	2	20.38097
1	3	2	77.38297
2	3	2	-420.747
3	3	2	167.3154
1	4	1	77.38297
2	4	1	72.13826
3	4	1	86.15321
1	4	2	63.81276
2	4	2	-51.1096
3	4	2	21.92408
1	2	3	97.7383
2	2	3	97.67819
3	2	3	-250.785
1	1	2	77.38297
2	1	2	97.67524
3	1	2	110.7743
1	1	3	97.7383
2	1	3	11.77116
3	1	3	34.22776
1	3	3	77.38297
2	3	3	81.4019
3	3	3	145.3913
1	4	3	100
2	4	3	100
3	4	3	100

```
proc sort data = sasuser.perc;
      by E;
      proc glm data = sasuser.perc;
      by E;
      class T R;
      model Percent = T R;
      lsmeans T R;
      run;
```

Output

---------- E=1 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: Percent Percent

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	939.509921	187.901984	2.98	0.1082
Error	6	378.532128	63.088688		
Corrected Total	11	1318.042049			

R-Square	Coeff Var	Root MSE	Percent Mean
0.712807	9.742297	7.942839	81.52943

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	97.1906815	32.3968938	0.51	0.6878
R	2	842.3192394	421.1596197	6.68	0.0298

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	97.1906815	32.3968938	0.51	0.6878
R	2	842.3192394	421.1596197	6.68	0.0298

Least Squares Means

T	Percent LSMEAN

1	84.1680812
2	84.1680812
3	77.3829732
4	80.3985768

R	Percent LSMEAN
1	77.3829732
2	73.9904191
3	93.2148920

---------- E=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: Percent Percent

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	111832.4622	22366.4924	1.14	0.4318
Error	6	117841.6275	19640.2713		
Corrected Total	11	229674.0897			

R-Square	Coeff Var	Root MSE	Percent Mean
0.486918	2463.830	140.1438	5.688045

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	57298.91121	19099.63707	0.97	0.4652
R	2	54533.55099	27266.77549	1.39	0.3195

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	57298.91121	19099.63707	0.97	0.4652
R	2	54533.55099	27266.77549	1.39	0.3195

Least Squares Means

Percent

T	LSMEAN
1	64.778480
2	29.571718
3	-111.940904
4	40.342887

R	Percent LSMEAN
1	30.8906889
2	-86.5393648
3	72.7128119

---------- E=3 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: Percent Percent

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	66505.5656	13301.1131	1.38	0.3482
Error	6	57662.7465	9610.4578		
Corrected Total	11	124168.3121			

R-Square	Coeff Var	Root MSE	Percent Mean
0.535608	221.6410	98.03294	44.23051

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	55871.60196	18623.86732	1.94	0.2248
R	2	10633.96366	5316.98183	0.55	0.6018

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	55871.60196	18623.86732	1.94	0.2248
R	2	10633.96366	5316.98183	0.55	0.6018

Least Squares Means

T	Percent LSMEAN
1	51.795717
2	-65.392188
3	121.159394
4	69.359098

R	Percent LSMEAN
1	45.3844041
2	80.0986766

Inputs

E	T	Percent
1	1	77.38297
2	1	84.88904
3	1	10.38509
1	2	77.38297
2	2	-36.9869
3	2	34.22776
1	3	77.38297
2	3	3.522331
3	3	50.77156
1	2	77.38297
2	2	28.02384
3	2	20.38097
1	3	77.38297
2	3	-420.747
3	3	167.3154
1	4	77.38297
2	4	72.13826
3	4	86.15321
1	4	63.81276
2	4	-51.1096
3	4	21.92408
1	2	97.7383
2	2	97.67819
3	2	-250.785
1	1	77.38297
2	1	97.67524
3	1	110.7743
1	1	97.7383
2	1	11.77116
3	1	34.22776
1	3	77.38297
2	3	81.4019
3	3	145.3913
1	4	100
2	4	100
3	4	100

```
proc glm data = sasuser.perc;
class E T;
model Percent = E T;
lsmeans E T;
run;
```

Output

Class Level Information

Class	Levels	Values
E	3	1 2 3
T	4	1 2 3 4

Number of Observations Read	36
Number of Observations Used	36

Dependent Variable: Percent Percent

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	51673.2912	10334.6582	0.92	0.4833
Error	30	338001.7375	11266.7246		
Corrected Total	35	389675.0287			

R-Square	Coeff Var	Root MSE	Percent Mean
0.132606	242.2513	106.1448	43.81599

Source	DF	Type I SS	Mean Square	F Value	Pr > F
E	2	34514.58481	17257.29241	1.53	0.2326
T	3	17158.70638	5719.56879	0.51	0.6800

Source	DF	Type III SS	Mean Square	F Value	Pr > F
E	2	34514.58481	17257.29241	1.53	0.2326
T	3	17158.70638	5719.56879	0.51	0.6800

Least Squares Means

E	Percent LSMEAN
1	81.5294281
2	5.6880453
3	44.2305051

T	Percent LSMEAN
1	66.9140928
2	16.1158706
3	28.8671542
4	63.3668537

Appendix D - SAS Code and Output: Infiltrometer Measurements

This appendix includes the SAS input and output used to perform statistical analysis on infiltrometer measurements. In the input table, S indicates the first and second season, T is treatment type, R is replication number, and the fourth variable is saturated hydraulic conductivity.

Inputs

S	T	R	K
1	1	1	0.8
1	2	1	1.7
1	3	1	0.7
1	2	2	0.9
1	4	1	1.8
1	4	2	0.6
1	2	3	2.7
1	1	2	0.9
1	1	3	0
1	3	2	1.6
1	4	3	0
2	1	1	11
2	2	1	24
2	3	1	18
2	2	2	39
2	3	2	10
2	4	1	22
2	4	2	4.9
2	2	3	44
2	1	2	1
2	1	3	22
2	3	3	19
2	4	3	7.1

```
proc sort data = sasuser.infiltrometer;
by S;
proc glm data = sasuser.infiltrometer;
by S;
class T R;
model K=T R;
lsmeans T R;
run;
```

Output

```
---------------------------------------- S=1 ----------------------------------------
                                  Class Level Information

                                Class         Levels    Values

                                T                  4    1 2 3 4

                                R                  3    1 2 3


                             Number of Observations Read          11
                             Number of Observations Used          11

Dependent Variable: K   K

                                                 Sum of
                    Source                DF       Squares     Mean Square    F Value
Pr > F

                    Model                  5    2.69066667      0.53813333       0.68
0.6608

                    Error                  5    3.97733333      0.79546667

                    Corrected Total       10    6.66800000

                                R-Square     Coeff Var      Root MSE        K Mean

                                0.403519      84.14051      0.891889      1.060000

                    Source                DF     Type I SS     Mean Square    F Value
Pr > F

                    T                      3    2.48726667      0.82908889       1.04
0.4499
                    R                      2    0.20340000      0.10170000       0.13
0.8828

                    Source                DF   Type III SS     Mean Square    F Value
Pr > F

                    T                      3    2.46986667      0.82328889       1.03
0.4524
                    R                      2    0.20340000      0.10170000       0.13
0.8828

                                   Least Squares Means

                                    T        K LSMEAN

                                    1      0.55333333
```

2	1.76666667
3	1.08000000
4	0.80000000

R	K LSMEAN
1	1.24000000
2	1.00000000
3	0.91000000

---------- S=2 ----------

The GLM Procedure

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: K K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	1395.689987	279.137997	3.53	0.0784
Error	6	475.003524	79.167254		
Corrected Total	11	1870.693511			

R-Square	Coeff Var	Root MSE	K Mean
0.746082	47.90115	8.897598	18.57492

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	1218.545137	406.181712	5.13	0.0429
R	2	177.144850	88.572425	1.12	0.3864

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	1218.545137	406.181712	5.13	0.0429
R	2	177.144850	88.572425	1.12	0.386

Least Squares Means

T	K LSMEAN
1	11.2230000
2	35.7333333
3	15.8666667
4	11.4766667

R	K LSMEAN
1	19.0500000
2	13.6497500
3	23.0250000

Inputs

T	R	K
1	1	0.8
2	1	1.7
3	1	0.7
2	2	0.9
4	1	1.8
4	2	0.6
2	3	2.7
1	2	0.9
1	3	0
3	2	1.6
4	3	0
1	1	11
2	1	24
3	1	18
2	2	39
3	2	10
4	1	22
4	2	4.9
2	3	44
1	2	1
1	3	22
3	3	19
4	3	7.1

```
proc glm data = sasuser.infiltrometers;
class T R;
model K=T R;
lsmeans T R;
run;
```

```
                    Class Level Information

    Class         Levels    Values

    T                  4    1 2 3 4

    R                  3    1 2 3

Number of Observations Read          23
Number of Observations Used          23
```

Dependent Variable: K K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	793.985539	158.797108	0.95	0.4751
Error	17	2843.982249	167.293073		
Corrected Total	22	3637.967788			

R-Square	Coeff Var	Root MSE	K Mean
0.218250	126.8279	12.93418	10.19822

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	649.3911837	216.4637279	1.29	0.3087
R	2	144.5943553	72.2971776	0.43	0.6560

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	649.6078048	216.5359349	1.29	0.3085
R	2	144.5943553	72.2971776	0.43	0.6560

The GLM Procedure
Least Squares Means

T	K LSMEAN
1	5.8881667
2	18.7500000
3	10.6263056
4	6.1383333

R	K LSMEAN
1	10.1450000
2	7.3248750
3	13.5822292

Inputs-Vegetation Only

S	K
1	0.76
1	0.9
1	0
2	11.1
2	0.969
2	21.6

```
proc glm data = sasuser.VEG;
class S;
model K=S;
lsmeans S;
run;
```

Ouput

Class Level Information

Class	Levels	Values
S	2	1 2

Number of Observations Read	6
Number of Observations Used	6

Dependent Variable: K K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	170.7626802	170.7626802	3.20	0.1480
Error	4	213.3108407	53.3277102		
Corrected Total	5	384.0735208			

R-Square	Coeff Var	Root MSE	K Mean
0.444609	124.0213	7.302582	5.8881

Source	DF	Type I SS	Mean Square	F Value	Pr > F
S	1	170.7626802	170.7626802	3.20	0.1480

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S	1	170.7626802	170.7626802	3.20	0.1480

Least Squares Means

S	K LSMEAN
1	0.5533333
2	11.2230000

Inputs-Vegetation and Earthworm

S	K
1	1.7
1	0.9
1	2.7
2	24.4
2	38.5
2	44.3

```
proc glm data = sasuser.vegew;
class S;
model K=S;
lsmeans S;
run;
```

Output

Class Level Information

Class	Levels	Values
S	2	1 2

Number of Observations Read	6
Number of Observations Used	6

Dependent Variable: K K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1730.601667	1730.601667	32.79	0.0046
Error	4	211.113333	52.778333		
Corrected Total	5	1941.715000			

R-Square	Coeff Var	Root MSE	K Mean
0.891275	38.74597	7.264870	18.75000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
S	1	1730.601667	1730.601667	32.79	0.0046

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S	1	1730.601667	1730.601667	32.79	0.0046

Least Squares Means

S	K LSMEAN
1	1.7666667
2	35.7333333

Inputs- Earthworm Only

S	K
1	0.7
1	1.6
2	18.3
2	10.2
2	19.1

```
proc glm data = sasuser.EW;
class S;
model K=S;
lsmeans S;
run;
```

Ouput

Class Level Information

Class	Levels	Values
S	2	1 2

Number of Observations Read 5
Number of Observations Used 5

Dependent Variable: K K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	259.8963333	259.8963333	15.95	0.0281
Error	3	48.8916667	16.2972222		
Corrected Total	4	308.7880000			

R-Square	Coeff Var	Root MSE	K Mean
0.841666	40.45072	4.036982	9.980000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
S	1	259.8963333	259.8963333	15.95	0.0281

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S	1	259.8963333	259.8963333	15.95	0.0281

The GLM Procedure
Least Squares Means

S	K LSMEAN
1	1.1500000
2	15.8666667

Inputs- Control

S	K
1	1.8
1	0.6
1	0
2	22.4
2	4.93
2	7.1

```
proc glm data = sasuser.EW;
class S;
model K=S;
lsmeans S;
run;
```

Ouput

Class Level Information

Class	Levels	Values
S	2	1 2

Number of Observations Read	6
Number of Observations Used	6

Dependent Variable: K K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	170.9868167	170.9868167	3.74	0.1254
Error	4	183.0132667	45.7533167		
Corrected Total	5	354.0000833			

R-Square	Coeff Var	Root MSE	K Mean
0.483013	110.1947	6.764120	6.138333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
S	1	170.9868167	170.9868167	3.74	0.1254

Source	DF	Type III SS	Mean Square	F Value	Pr > F
S	1	170.9868167	170.9868167	3.74	0.1254

Least Squares Means

S	K LSMEAN
1	0.8000000
2	11.4766667

Appendix E - Time to Run-through

This appendix includes the SAS input and output used to perform statistical analysis on the time to run-through. In the input table, E is event number, T is treatment type, R is replication number, and the time to run-through.

Inputs

E	T	R	I
1	1	1	10
1	1	2	4
1	1	3	4
1	2	1	4
1	2	2	4
1	2	3	6
1	3	1	4
1	3	2	8
1	3	3	3
1	4	1	2
1	4	2	4
2	1	1	8
2	1	2	2.4
2	1	3	5.22
2	2	1	4.8
2	2	2	6.87
2	2	3	6.22
2	3	1	6
2	3	2	4
2	3	3	1
2	4	1	3.83
2	4	2	4
3	1	1	8.65
3	1	2	5.23
3	1	3	5.68
3	2	1	4.17
3	2	2	6.26
3	2	3	4.2
3	3	1	0.93
3	3	2	1.35
3	3	3	1
3	4	1	1.17
3	4	2	0.5

```
proc sort data = sasuser.time;
      by E;
      proc glm data = sasuser.time;
      by E;
      class T R;
      model I=T R;
      lsmeans T R;
      run
```

Output

```
------------------------------------------------- E=1 -----------------------------------------------

                                  Class Level Information

                                Class         Levels    Values

                                T                  4    1 2 3 4

                                R                  3    1 2 3


                             Number of Observations Read          11
                             Number of Observations Used          11


        Dependent Variable: I   I

                                                              Sum of
                            Source                     DF        Squares     Mean Square    F Value
Pr > F

                            Model                       5     14.52525253      2.90505051       0.37
0.8495

                            Error                       5     39.11111111      7.82222222

                            Corrected Total            10     53.63636364

                                          R-Square     Coeff Var      Root MSE        I Mean

                                          0.270810      58.04728      2.796824      4.818182
```

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	10.96969697	3.65656566	0.47	0.7178
R	2	3.55555556	1.77777778	0.23	0.8045

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	13.55555556	4.51851852	0.58	0.6545
R	2	3.55555556	1.77777778	0.23	0.8045

Least Squares Means

T	I LSMEAN
1	6.00000000
2	4.66666667
3	5.00000000
4	2.55555556

R	I LSMEAN
1	5.00000000
2	5.00000000
3	3.66666667

---------- E=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	11
Number of Observations Used	11

Dependent Variable: I I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	16.41420072	3.28284014	0.68	0.6585
Error	5	24.12069413	4.82413883		
Corrected Total	10	40.53489485			

R-Square	Coeff Var	Root MSE	I Mean
0.404940	46.16853	2.196392	4.757336

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	9.93929959	3.31309986	0.69	0.5977
R	2	6.47490113	3.23745057	0.67	0.5519

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	11.27009695	3.75669898	0.78	0.5543
R	2	6.47490113	3.23745057	0.67	0.5519

Least Squares Means

T	I LSMEAN
1	5.20556667
2	5.96133333
3	3.66666667
4	3.51502222

R	I LSMEAN
1	5.65750000
2	4.31675000
3	3.78719167

---------- E=3 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	11
Number of Observations Used	11

Dependent Variable: I I

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	66.21635352	13.24327070	7.81	0.0208
Error	5	8.47850060	1.69570012		
Corrected Total	10	74.69485412			

R-Square	Coeff Var	Root MSE	I Mean
0.886492	36.59664	1.302191	3.558224

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	64.61261285	21.53753762	12.70	0.0089
R	2	1.60374067	0.80187033	0.47	0.6485

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	65.88568203	21.96189401	12.95	0.0086
R	2	1.60374067	0.80187033	0.47	0.6485

The GLM Procedure
Least Squares Means

T	I LSMEAN
1	6.52210000
2	4.87466667
3	1.09450000
4	0.56531667

R	I LSMEAN
1	3.72925000
2	3.33507500
3	2.72811250

Input

T	R	I
1	1	10
1	2	4
1	3	4
2	1	4
2	2	4
2	3	6
3	1	4
3	2	8
3	3	3
4	1	2
4	2	4
1	1	8
1	2	2.4
1	3	5.2167
2	1	4.8
2	2	6.867
2	3	6.217
3	1	6
3	2	4
3	3	1
4	1	3.83
4	2	4

1	1	8.65
1	2	5.2333
1	3	5.683
2	1	4.167
2	2	6.257
2	3	4.2
3	1	0.933333
3	2	1.35
3	3	1.000167
4	1	1.166667
4	2	0.5

```
proc glm data = sasuser.totime;
class T R;
model I=T R;
lsmeans T R;
run;
```

Output

```
                    Class Level Information

          Class         Levels    Values

          T                  4    1 2 3 4

          R                  3    1 2 3


                Number of Observations Read          33
                Number of Observations Used          33


          Dependent Variable: I   I

                                                 Sum of
                          Source                     DF         Squares     Mean Square    F Value
Pr > F

                          Model                       5      66.8570615      13.3714123       3.19
0.0216

                          Error                      27     113.1156233       4.1894675

                          Corrected Total            32     179.9726848


                                  R-Square     Coeff Var      Root MSE        I Mean

                                  0.371484      46.75329      2.046819      4.377914


                          Source                     DF       Type I SS     Mean Square    F Value
Pr > F

                          T                           3     57.42529664     19.14176555       4.57
0.0103
```

Source	DF	Type III SS	Mean Square	F Value	Pr > F
R	2	9.43176486	4.71588243	1.13	0.3392

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	63.39700049	21.13233350	5.04	0.0066
R	2	9.43176486	4.71588243	1.13	0.3392

Least Squares Means

T	I LSMEAN
1	5.90922222
2	5.16755556
3	3.25372222
4	2.21196481

R	I LSMEAN
1	4.79558333
2	4.21727500
3	3.39399028

Appendix F - Soil Moisture Fluctuations

This appendix includes the SAS input and output used to perform statistical analysis on tensiometer measurements. In the input table T is treatment type, R is replication number, and the C in the tensiometer measurement.

Inputs

T	R	C
1	1	4
1	2	15
1	3	19
2	1	20
2	2	20
2	3	24
3	1	10
3	2	17
3	3	25
4	1	17
4	2	15
4	3	0
1	1	20
1	2	32
1	3	20
2	1	23
2	2	20
2	3	27
3	1	18
3	2	20
3	3	15
4	1	25
4	2	17
4	3	0
1	1	24
1	2	35
1	3	20
2	1	23
2	2	20
2	3	27
3	1	15
3	2	20
3	3	15
4	1	20
4	2	20
4	3	0

1	1	14
1	2	29
1	3	10
2	1	10
2	2	10
2	3	20
3	1	10
3	2	15
3	3	10
4	1	12
4	2	7
4	3	0
1	1	15
1	2	15
1	3	3
2	1	13
2	2	15
2	3	20
3	1	0
3	2	15
3	3	15
4	1	7
4	2	0
4	3	0
1	1	22
1	2	21
1	3	12
2	1	20
2	2	15
2	3	25
3	1	10
3	2	18
3	3	15
4	1	20
4	2	16
4	3	0
1	1	20
1	2	22
1	3	18
2	1	20
2	2	17
2	3	25
3	1	15
3	2	22
3	3	15
4	1	18
4	2	18
4	3	0

```
proc glm data = sasuser.tensio30;
class T R;
model C=T R;
lsmeans T R;
run;
```

Output

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	84
Number of Observations Used	84

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	1463.345238	292.669048	6.27	<.0001
Error	78	3641.642857	46.687729		
Corrected Total	83	5104.988095			

R-Square	Coeff Var	Root MSE	C Mean
0.286650	43.12237	6.832842	15.84524

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	1179.750000	393.250000	8.42	<.0001
R	2	283.595238	141.797619	3.04	0.0537

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	1179.750000	393.250000	8.42	<.0001
R	2	283.595238	141.797619	3.04	0.0537

Least Squares Means

T	C LSMEAN
1	18.5714286
2	19.7142857
3	15.0000000
4	10.0952381

R	C LSMEAN
1	15.8928571
2	18.0714286
3	13.5714286

Inputs

T	R	C
1	1	0
1	2	25
1	3	21
2	1	12
2	2	5
2	3	50
3	1	10
3	2	20
3	3	20
4	1	20
4	2	20
4	3	0
1	1	24
1	2	20
1	3	20
2	1	5
2	2	20
2	3	50
3	1	10
3	2	20
3	3	20
4	1	20
4	2	20
4	3	0
1	1	5
1	2	20
1	3	20
2	1	9
2	2	20
2	3	50
3	1	20
3	2	20
3	3	20
4	1	20
4	2	20
4	3	0
1	1	3
1	2	19
1	3	15

2	1	12
2	2	10
2	3	30
3	1	12
3	2	19
3	3	12
4	1	15
4	2	12
4	3	0
1	1	0
1	2	20
1	3	5
2	1	0
2	2	15
2	3	30
3	1	0
3	2	17
3	3	18
4	1	10
4	2	0
4	3	0
1	1	0
1	2	20
1	3	20
2	1	13
2	2	15
2	3	50
3	1	12
3	2	20
3	3	13
4	1	15
4	2	20
4	3	0
1	1	0
1	2	20
1	3	22
2	1	0
2	2	15
2	3	20
3	1	0
3	2	15
3	3	12
4	1	20
4	2	10
4	3	0

Output

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read 84
Number of Observations Used 84

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	2360.97619	472.19524	4.41	0.0014
Error	78	8350.97619	107.06380		
Corrected Total	83	10711.95238			

R-Square	Coeff Var	Root MSE	C Mean
0.220406	68.87177	10.34716	15.02381

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	1065.952381	355.317460	3.32	0.0241
R	2	1295.023810	647.511905	6.05	0.0036

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	1065.952381	355.317460	3.32	0.0241
R	2	1295.023810	647.511905	6.05	

Least Squares Means

T	C LSMEAN
1	14.2380952
2	20.5238095
3	14.7619048
4	10.5714286

R	C LSMEAN
1	9.5357143
2	17.0357143
3	18.5000000

Inputs-VEG vs. CONT 30 cm

T	C
1	4
1	15
1	19
1	20
1	32
1	20
1	24
1	35
1	20
1	14
1	29
1	10
1	15
1	15
1	3
1	22
1	21
1	12
1	20
1	22
1	18
4	17
4	15
4	0
4	25
4	17
4	0
4	20
4	20
4	0
4	12
4	7
4	0
4	7
4	0
4	0
4	20
4	16
4	0
4	18
4	18
4	0

```
Proc glm data = sasuser.v130;
class T;
model C=T;
lsmeans T;
run;
```

Output

Class Level Information

Class	Levels	Values
T	2	1 4

Number of Observations Read	42
Number of Observations Used	42

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	754.380952	754.380952	10.44	0.0025
Error	40	2890.952381	72.273810		
Corrected Total	41	3645.333333			

R-Square	Coeff Var	Root MSE	C Mean
0.206944	59.31210	8.501400	14.33333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	754.3809524	754.3809524	10.44	0.0025

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	1	754.3809524	754.3809524	10.44	0.0025

The GLM Procedure
Least Squares Means

T	C LSMEAN
1	18.5714286
4	10.0952381

Inputs-VEGEW vs. CONT 30 cm

T	C
2	20
2	20
2	24
2	23
2	20
2	27
2	23
2	20
2	27
2	10
2	10
2	20
2	13
2	15
2	20
2	20
2	15
2	25
2	20
2	17
2	25
4	17
4	15
4	0
4	25
4	17
4	0
4	20
4	20
4	0
4	12
4	7
4	0
4	7
4	0
4	0
4	20
4	16
4	0
4	18
4	18
4	0

```
proc glm data = sasuser.v230;
class T;
model C=T;
lsmeans T;
run;
```

Output

Class Level Information

Class	Levels	Values
T	2	2 4

Number of Observations Read	42
Number of Observations Used	42

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	971.523810	971.523810	18.31	0.0001
Error	40	2122.095238	53.052381		
Corrected Total	41	3093.619048			

R-Square	Coeff Var	Root MSE	C Mean
0.314041	48.86832	7.283707	14.90476

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	971.5238095	971.5238095	18.31	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	1	971.5238095	971.5238095	18.31	0.0001

Least Squares Means

T	C LSMEAN
2	19.7142857
4	10.0952381

Inputs-EW vs. CONT 30 cm

T	C
3	10
3	17
3	25
3	18
3	20
3	15
3	15
3	20
3	15
3	10
3	15
3	10
3	0
3	15
3	15
3	10
3	18
3	15
3	15
3	22
3	15
4	17
4	15
4	0
4	25
4	17
4	0
4	20
4	20
4	0
4	12
4	7
4	0
4	7
4	0
4	0
4	20
4	16
4	0
4	18
4	18
4	0

```
proc glm data = sasuser.v330;
class T;
model C=T;
lsmeans T;
run;
```

Output

Class Level Information

Class	Levels	Values
T	2	3 4

Number of Observations Read	42
Number of Observations Used	42

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	252.595238	252.595238	4.64	0.0374
Error	40	2179.809524	54.495238		
Corrected Total	41	2432.404762			

R-Square	Coeff Var	Root MSE	C Mean
0.103846	58.83259	7.382089	12.54762

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	252.5952381	252.5952381	4.64	0.0374

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	1	252.5952381	252.5952381	4.64	0.0374

Least Squares Means

T	C LSMEAN
3	15.0000000
4	10.0952381

Inputs-VEG vs. CONT 60 cm

T	C
1	0
1	25
1	21
1	24
1	20
1	20
1	5
1	20
1	20
1	3
1	19
1	15
1	0
1	20
1	5
1	0
1	20
1	20
1	0
1	20
1	22
4	20
4	20
4	0
4	20
4	20
4	0
4	20
4	20
4	0
4	15
4	12
4	0
4	10
4	0
4	0
4	15
4	20
4	0
4	20
4	10
4	0

```
proc glm data = sasuser.v160;
class T;
model C=T;
lsmeans T;
run;
```

Output

Class Level Information

Class	Levels	Values
T	2	1 4

Number of Observations Read	42
Number of Observations Used	42

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	141.166667	141.166667	1.68	0.2023
Error	40	3360.952381	84.023810		
Corrected Total	41	3502.119048			

R-Square	Coeff Var	Root MSE	C Mean
0.040309	73.89461	9.166450	12.40476

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	141.1666667	141.1666667	1.68	0.2023

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	1	141.1666667	141.1666667	1.68	0.2023

Least Squares Means

T	C LSMEAN
1	14.2380952
4	10.5714286

Inputs-VEGEW vs. CONT 60 cm

T	C
2	12
2	5
2	50
2	5
2	20
2	50
2	9
2	20
2	50
2	12
2	10
2	30
2	0
2	15
2	30
2	13
2	15
2	50
2	0
2	15
2	20
4	20
4	20
4	0
4	20
4	20
4	0
4	20
4	20
4	0
4	15
4	12
4	0
4	10
4	0
4	0
4	15
4	20
4	0
4	20
4	10
4	0

```
proc glm data = sasuser.v260;
class T;
model C=T;
lsmeans T;
run;
```

Output

Class Level Information

Class	Levels	Values
T	2	2 4

Number of Observations Read	42
Number of Observations Used	42

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1040.023810	1040.023810	5.81	0.0207
Error	40	7164.380952	179.109524		
Corrected Total	41	8204.404762			

R-Square	Coeff Var	Root MSE	C Mean
0.126764	86.07865	13.38318	15.54762

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	1	1040.023810	1040.023810	5.81	0.0207

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	1	1040.023810	1040.023810	5.81	0.0207

Least Squares Means

T	C LSMEAN
2	20.5238095
4	10.5714286

Inputs-EW vs. CONT 60 cm

T	C
3	10
3	20
3	20
3	10
3	20
3	20
3	20
3	20
3	20
3	12
3	19
3	12
3	0
3	17
3	18
3	12
3	20
3	13
3	0
3	15
3	12
4	20
4	20
4	0
4	20
4	20
4	0
4	20
4	20
4	0
4	15
4	12
4	0
4	10
4	0
4	0
4	15
4	20
4	0
4	20
4	10
4	0

```
proc glm data = sasuser.v360;
class T;
model C=T;
lsmeans T;
run;
```

Output

```
                    Class Level Information

                Class         Levels    Values

                T                  2    3 4


                Number of Observations Read          42
                Number of Observations Used          42

Dependent Variable: C   C

                                            Sum of
Source                       DF           Squares      Mean Square    F Value    Pr > F

Model                         1       184.380952       184.380952       3.05    0.0882

Error                        40      2414.952381        60.373810

Corrected Total              41      2599.333333


                  R-Square     Coeff Var      Root MSE        C Mean

                  0.070934      61.34257      7.770059      12.66667


Source                       DF        Type I SS     Mean Square    F Value    Pr > F

T                             1      184.3809524     184.3809524       3.05    0.0882


Source                       DF      Type III SS     Mean Square    F Value    Pr > F

T                             1      184.3809524     184.3809524       3.05    0.0882

                    Least Squares Means

                     T        C LSMEAN

                     3      14.7619048
                     4      10.5714286
```

Appendix G - Soil Quality

This appendix includes the SAS input and output used to perform statistical analysis on soil quality parameters. In the input table, S indicates the date the sample was taken-wither the beginning (1) or end (2) of the experiment, T is the treatment type, R is replication number, P is total phosphorus, C is chloride, N is total nitrogen, H is ammonia, O is nitrate, and M is Melich-3P.

Input

S	T	R	P	C	N	H	O	M
1	1	1	382	0.9	186	3.9	3.7	13
1	2	1	404	4.5	227	3.8	8.3	12
1	3	1	396	1.1	172	3.0	4.1	11
1	2	2	397	0.7	179	3.1	2.8	12
1	3	2	408	4.1	227	4.0	14.7	13
1	4	1	401	0.6	220	4.4	4.7	11
1	4	2	407	1.0	292	4.4	5.3	10
1	2	3	399	0.7	229	3.9	3.7	13
1	1	2	409	0.5	194	4.4	3.1	12
1	1	3	417	2.1	219	3.9	6.0	11
1	3	3	434	12.5	242	4.8	23.1	16
1	4	3	402	3.1	208	3.5	7.1	12
2	1	1	896	12.7	752	3.6	12.2	456
2	2	1	1007	11.4	948	3.5	11.9	535
2	3	1	1152	9.3	1017	3.5	16.7	600
2	2	2	942	13.6	839	3.4	11.0	555
2	3	2	857	6.2	762	3.1	12.0	520
2	4	1	824	10.8	686	2.7	15.8	338
2	4	2	1268	11.0	1246	2.7	32.2	665
2	2	3	1093	11.4	1128	3.5	17.7	580
2	1	2	925	10.5	840	2.9	11.6	520
2	1	3	791	11.1	725	2.6	11.5	440
2	3	3	996	8.5	974	2.4	19.8	595
2	4	3	945	6.7	973	1.8	21.2	560

```
proc sort data = sasuser.infiltrometer;
      by S;
      proc glm data = sasuser.infiltrometer;
      by S;
      class T R;
      model P = T R;
      lsmeans T R;
      run;
```

Output

NH_3-N

```
------------------------------------------------------ S=1 ------------------------------------------------
                                                  Class Level Information

                                                Class         Levels    Values

                                                T                  4    1 2 3 4

                                                R                  3    1 2 3


                                             Number of Observations Read          12
                                             Number of Observations Used          12

       Dependent Variable: H   H

                                                                  Sum of
                           Source                     DF         Squares     Mean Square    F Value
Pr > F

                           Model                       5      0.64183333      0.12836667       0.29
0.9031

                           Error                       6      2.66893333      0.44482222

                           Corrected Total            11      3.31076667


                                          R-Square     Coeff Var      Root MSE        H Mean

                                          0.193862      17.02127      0.666950      3.918333


                           Source                     DF       Type I SS     Mean Square    F Value
Pr > F

                           T                           3      0.51776667      0.17258889       0.39
0.7661
                           R                           2      0.12406667      0.06203333       0.14
0.8726


                           Source                     DF     Type III SS     Mean Square    F Value
Pr > F

                           T                           3      0.51776667      0.17258889       0.39
0.7661
                           R                           2      0.12406667      0.06203333       0.14
0.8726
```

---------- S=1 ----------

The GLM Procedure
Least Squares Means

T	H LSMEAN
1	4.08333333
2	3.58333333
3	3.90666667
4	4.10000000

R	H LSMEAN
1	3.77500000
2	3.98000000
3	4.00000000

---------- S=2 ----------

The GLM Procedure

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read 12
Number of Observations Used 12

Dependent Variable: H H

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	2.75650833	0.55130167	5.96	0.0252
Error	6	0.55478333	0.09246389		
Corrected Total	11	3.31129167			

R-Square	Coeff Var	Root MSE	H Mean
0.832457	10.31067	0.304079	2.949167

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	1.62349167	0.54116389	5.85	0.0325
R	2	1.13301667	0.56650833	6.13	0.0355

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	1.62349167	0.54116389	5.85	0.0325
R	2	1.13301667	0.56650833	6.13	0.0355

Least Squares Means

T	H LSMEAN
1	2.99666667
2	3.44000000
3	2.95666667
4	2.40333333

R	H LSMEAN
1	3.29750000
2	3.00000000
3	2.55000000

Chloride

---------- S=1 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	66.5523667	13.3104733	1.29	0.3786
Error	6	62.0248000	10.3374667		
Corrected Total	11	128.5771667			

R-Square	Coeff Var	Root MSE	C Mean
0.517606	121.2518	3.215193	2.651667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	43.56250000	14.52083333	1.40	0.3300
R	2	22.98986667	11.49493333	1.11	0.3883

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	43.56250000	14.52083333	1.40	0.3300
R	2	22.98986667	11.49493333	1.11	0.3883

Least Squares Means

T	C LSMEAN
1	1.15333333
2	1.97333333
3	5.91333333
4	1.56666667

R	C LSMEAN
1	1.78500000
2	1.56500000
3	4.60500000

---------- S=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: C C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	37.59153333	7.51830667	2.59	0.1390
Error	6	17.41286667	2.90214444		
Corrected Total	11	55.00440000			

R-Square	Coeff Var	Root MSE	C Mean
0.683428	16.58781	1.703568	10.27000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	32.14573333	10.71524444	3.69	0.0813
R	2	5.44580000	2.72290000	0.94	0.4420

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	32.14573333	10.71524444	3.69	0.0813
R	2	5.44580000	2.72290000	0.94	0.4420

Least Squares Means

T	C LSMEAN
1	11.4533333
2	12.1533333
3	8.0066667
4	9.4666667

R	C LSMEAN
1	11.0550000
2	10.3450000
3	9.4100000

Melich-3P

---------- S=1 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: M M

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	12.50000000	2.50000000	1.14	0.4316
Error	6	13.16666667	2.19444444		
Corrected Total	11	25.66666667			

R-Square	Coeff Var	Root MSE	M Mean
0.487013	12.17561	1.481366	12.16667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	8.33333333	2.77777778	1.27	0.3673
R	2	4.16666667	2.08333333	0.95	0.4383

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	8.33333333	2.77777778	1.27	0.3673
R	2	4.16666667	2.08333333	0.95	0.4383

Least Squares Means

T	M LSMEAN
1	12.0000000
2	12.3333333
3	13.3333333
4	11.0000000

R	M LSMEAN
1	11.7500000
2	11.7500000
3	13.0000000

---------- S=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: M M

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	32557.02083	6511.40417	0.79	0.5939
Error	6	49556.20833	8259.36806		
Corrected Total	11	82113.22917			

R-Square	Coeff Var	Root MSE	M Mean
0.396489	17.13794	90.88107	530.2917

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	17733.72917	5911.24306	0.72	0.5777
R	2	14823.29167	7411.64583	0.90	0.4561

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	17733.72917	5911.24306	0.72	0.5777
R	2	14823.29167	7411.64583	0.90	0.4561

Least Squares Means

T	M LSMEAN
1	471.833333
2	556.666667
3	571.666667
4	521.000000

R	M LSMEAN
1	482.125000
2	565.000000
3	543.750000

Total Nitrogen

---------- S=1 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read 12
Number of Observations Used 12

Dependent Variable: N N

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	3948.78435	789.75687	0.62	0.6913
Error	6	7633.50142	1272.25024		
Corrected Total	11	11582.28577			

R-Square	Coeff Var	Root MSE	N Mean
0.340933	16.48766	35.66862	216.3352

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	2602.052013	867.350671	0.68	0.5948
R	2	1346.732341	673.366170	0.53	0.6142

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	2602.052013	867.350671	0.68	0.5948
R	2	1346.732341	673.366170	0.53	0.6142

Least Squares Means

T	N	LSMEAN
1		199.615347
2		211.958575
3		213.728244
4		240.038493

R	N	LSMEAN
1		201.373126
2		223.149406
3		224.482962

---------- S=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: N N

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	99328.1184	19865.6237	0.53	0.7461
Error	6	223217.4021	37202.9004		
Corrected Total	11	322545.5205			

R-Square	Coeff Var	Root MSE	N Mean
0.307951	21.25716	192.8805	907.3673

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	78409.70016	26136.56672	0.70	0.5842
R	2	20918.41826	10459.20913	0.28	0.7643

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	78409.70016	26136.56672	0.70	0.5842
R	2	20918.41826	10459.20913	0.28	0.7643

Least Squares Means

T	N	LSMEAN
1		772.298787
2		971.483591
3		917.693076
4		967.993557

R	N	LSMEAN
1		850.598647
2		921.687546
3		949.815565

NO_3-N

---------- S=1 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: O O

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	235.0747833	47.0149567	1.79	0.2497
Error	6	157.9018833	26.3169806		
Corrected Total	11	392.9766667			

R-Square	Coeff Var	Root MSE	O Mean
0.598190	71.08556	5.130008	7.216667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	186.6996667	62.2332222	2.36	0.1701
R	2	48.3751167	24.1875583	0.92	0.4485

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	186.6996667	62.2332222	2.36	0.1701
R	2	48.3751167	24.1875583	0.92	0.4485

Least Squares Means

T	O LSMEAN
1	4.2466667
2	4.9266667
3	13.9900000
4	5.7033333

R	O LSMEAN
1	5.21750000
2	6.47000000
3	9.96250000

---------- S=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: O O

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	247.1868750	49.4373750	1.73	0.2615
Error	6	171.5882167	28.5980361		
Corrected Total	11	418.7750917			

R-Square	Coeff Var	Root MSE	O Mean
0.590262	33.15212	5.347713	16.13083

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	222.3945583	74.1315194	2.59	0.1480
R	2	24.7923167	12.3961583	0.43	0.6671

Source	DF	Type III SS	Mean Square	F Value	Pr > F

T	3	222.3945583	74.1315194	2.59	0.1480
R	2	24.7923167	12.3961583	0.43	0.6671

Least Squares Means

T	O LSMEAN
1	11.7700000
2	13.5100000
3	16.1666667
4	23.0766667

R	O LSMEAN
1	14.1575000
2	16.6950000
3	17.5400000

Total P

---------- S=1 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: P P

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	852.778452	170.555690	1.20	0.4095
Error	6	853.853468	142.308911		
Corrected Total	11	1706.631920			

R-Square	Coeff Var	Root MSE	P Mean
0.499685	2.947629	11.92933	404.7093

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	262.3036622	87.4345541	0.61	0.6303
R	2	590.4747898	295.2373949	2.07	0.2066

Source	DF	Type III SS	Mean Square	F Value	Pr > F
T	3	262.3036622	87.4345541	0.61	0.6303
R	2	590.4747898	295.2373949	2.07	0.2066

Least Squares Means

T	P LSMEAN
1	402.706419
2	400.193952
3	412.539576
4	403.397266

R	P LSMEAN
1	395.769820
2	405.454320
3	412.903770

---------- S=2 ----------

Class Level Information

Class	Levels	Values
T	4	1 2 3 4
R	3	1 2 3

Number of Observations Read	12
Number of Observations Used	12

Dependent Variable: P P

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	47162.0918	9432.4184	0.34	0.8726
Error	6	167213.0720	27868.8453		
Corrected Total	11	214375.1639			

R-Square	Coeff Var	Root MSE	P Mean
0.219998	17.13041	166.9396	974.5224

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	3	43511.72605	14503.90868	0.52	0.6837
R	2	3650.36578	1825.18289	0.07	0.9373

Source	DF	Type III SS	Mean Square	F Value	Pr > F

T	3	43511.72605	14503.90868	0.52	0.6837
R	2	3650.36578	1825.18289	0.07	0.9373

Least Squares Means

T	P LSMEAN
1	870.55357
2	1013.99602
3	1001.45972
4	1012.08043

R	P LSMEAN
1	969.433006
2	997.968561
3	956.165737

Appendix H - Water Quality by Sample

Phosphorus (P)

Inputs

Sample	P
VEG	0.46
EW	0.19
VEGEW	0.28
CONT	0.17
VEGEW	0.31
EW	0.45
VEG	0.22
EW	0.22
EW	0.17
CONT	0.35
VEG	0.22
EW	0.23
VEGEW	0.29
VEGEW	0.29
CONT	0.15
VEGEW	0.12
VEG	0.25
VEG	0.27
EW	0.24
CONT	0.38
EW	0.28
VEG	0.61
VEGEW	0.41
EW	0.10
VEGEW	0.25
EW	0.20
CONT	1.16
CONT	0.21
VEGEW	0.13
VEG	0.14
VEG	0.15
EW	0.09
VEG	0.26
EW	0.25
EW	0.27
CONT	0.34
VEG	1.09
EW	0.28
VEGEW	0.12

VEGEW	0.26
CONT	0.14
VEGEW	0.32
VEG	0.19
CONT	0.23

```
proca anova data=sasuser.p;
        class sample;
        model P = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read	44
Number of Observations Used	44

Dependent Variable: P P

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.13535703	0.04511901	1.01	0.3985
Error	40	1.78743388	0.04468585		
Corrected Total	43	1.92279091			

R-Square	Coeff Var	Root MSE	P Mean
0.070396	73.00763	0.211390	0.289545

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	0.13535703	0.04511901	1.01	0.3985

Level of Sample	N	P Mean	P Std Dev
CONT	9	0.34777778	0.31771755
EW	13	0.22846154	0.09044760
VEG	11	0.35090909	0.28200903
VEGEW	11	0.25272727	0.09296138

Copper (Cu)

Inputs

Sample	Cu
VEG	0.02
EW	0.01
VEGEW	0.02
CONT	0.06
VEGEW	0.06
EW	5.17
VEG	0.20
EW	0.04
EW	0.06
CONT	0.03
VEG	0.01
EW	0.01
VEGEW	0.02
VEGEW	0.02
CONT	0.02
VEGEW	0.12
VEG	5.38
VEG	0.16
EW	0.05
CONT	0.07
EW	0.02
VEG	ND
VEGEW	0.02
EW	0.84
VEGEW	0.10
EW	0.38
CONT	0.11
CONT	0.04
VEGEW	0.54
VEG	0.06
VEG	0.32
EW	0.21
VEG	0.03
EW	0.24
EW	0.10
CONT	0.03
VEG	0.06
EW	0.03
VEGEW	ND
VEGEW	ND
CONT	ND
VEGEW	ND
VEG	ND

CONT	ND

```
proca anova data=sasuser.cu;
        class sample;
        model cu = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read 44
Number of Observations Used 37

Dependent Variable: Cu Cu

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	2.58294546	0.86098182	0.58	0.6304
Error	33	48.74437166	1.47710217		
Corrected Total	36	51.32731713			

R-Square	Coeff Var	Root MSE	Cu Mean
0.050323	307.2305	1.215361	0.395586

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	2.58294546	0.86098182	0.58	0.6304

The ANOVA Procedure

Level of Sample	N	Cu Mean	Cu Std Dev
CONT	7	0.05104612	0.03275004
EW	13	0.54984666	1.40605507
VEG	9	0.69321403	1.76055355
VEGEW	8	0.11155325	0.17633395

Nitrate-N (NO_3-N)

Inputs

Sample	NO3N
VEG	140.08
EW	86.66
VEGEW	46.14
CONT	109.62
VEGEW	138.15
EW	92.60
VEG	47.69
EW	75.87
EW	52.39
CONT	129.17
VEG	129.12
EW	48.87
VEGEW	48.46
VEGEW	23.07
CONT	108.71
VEGEW	137.67
VEG	103.87
VEG	39.04
EW	58.90
CONT	89.26
EW	38.29
VEG	32.87
VEGEW	102.91
EW	53.80
VEGEW	17.24
EW	91.29
CONT	48.72
CONT	89.41
VEGEW	84.00
VEG	32.98
VEG	87.11
EW	96.43
VEG	76.91
EW	71.46
EW	74.16
CONT	162.11
VEG	79.69
EW	91.86
VEGEW	97.55
VEGEW	61.30
CONT	59.88
VEGEW	100.76
VEG	98.68

CONT	79.71

```
proca anova data=sasuser.no3n;
        class sample;
        model no3n = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read	44
Number of Observations Used	44

Dependent Variable: NO3N NO3N

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	3667.41457	1222.47152	1.06	0.3758
Error	40	46027.83155	1150.69579		
Corrected Total	43	49695.24612			

R-Square	Coeff Var	Root MSE	NO3N Mean
0.073798	42.22891	33.92191	80.32864

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	3667.414571	1222.471524	1.06	0.3758

Level of Sample	N	NO3N Mean	NO3N Std Dev
CONT	9	97.3988889	34.8110796
EW	13	71.7369231	19.5371903
VEG	11	78.9127273	37.6059405
VEGEW	11	77.9318182	41.9652858

Ammonia (NH_4-N)

Inputs

Sample	NH4N
VEG	0.56
EW	0.25
VEGEW	0.23
CONT	0.21
VEGEW	0.36
EW	1.57
VEG	0.18
EW	0.19
EW	0.28
CONT	0.26
VEG	0.22
EW	0.39
VEGEW	0.42
VEGEW	0.09
CONT	0.11
VEGEW	0.95
VEG	2.07
VEG	0.19
EW	0.02
CONT	0.02
EW	0.83
VEG	0.27
VEGEW	0.91
EW	0.15
VEGEW	0.11
EW	0.19
CONT	1.04
CONT	0.41
VEGEW	0.36
VEG	0.22
VEG	0.15
EW	0.19
VEG	0.29
EW	0.23
EW	0.24
CONT	0.48
VEG	0.20
EW	0.25
VEGEW	0.13
VEGEW	0.16
CONT	0.19
VEGEW	0.25
VEG	0.16
CONT	0.23

```
proca anova data=sasuser.nh4n;
        class sample;
        model nh4n = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read	44
Number of Observations Used	44

Dependent Variable: NH4N NH4N

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	0.03451140	0.01150380	0.07	0.9767
Error	40	6.79107723	0.16977693		
Corrected Total	43	6.82558864			

R-Square	Coeff Var	Root MSE	NH4N Mean
0.005056	111.8430	0.412040	0.368409

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	0.03451140	0.01150380	0.07	0.9767

The ANOVA Procedure

Level of Sample	N	NH4N Mean	NH4N Std Dev
CONT	9	0.32777778	0.30132116
EW	13	0.36769231	0.40757727
VEG	11	0.41000000	0.56212098
VEGEW	11	0.36090909	0.30190908

OrthoP

Inputs

Sample	OrthoP
VEG	325
EW	182
VEGEW	253
CONT	158
VEGEW	236
EW	410
VEG	303
EW	220
EW	184
CONT	324
VEG	237
EW	238
VEGEW	293
VEGEW	317
CONT	168
VEGEW	33
VEG	29
VEG	224
EW	226
CONT	46
EW	212
VEG	192
VEGEW	8
EW	7
VEGEW	215
EW	127
CONT	17
CONT	53
VEGEW	9
VEG	36
VEG	20
EW	24
VEG	202
EW	129
EW	216
CONT	303
VEG	249
EW	242
VEGEW	37
VEGEW	237
CONT	133
VEGEW	313
VEG	182

CONT	218

```
proca anova data=sasuser.orthop;
        class sample;
        model orthop = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read	44
Number of Observations Used	44

Dependent Variable: OrthoP OrthoP

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	4606.9905	1535.6635	0.12	0.9462
Error	40	500587.7949	12514.6949		
Corrected Total	43	505194.7854			

R-Square	Coeff Var	Root MSE	OrthoP Mean
0.009119	63.21343	111.8691	176.9705

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	4606.990452	1535.663484	0.12	0.9462

Level of Sample	N	OrthoP Mean	OrthoP Std Dev
CONT	9	157.762222	109.486328
EW	13	185.929231	102.196106
VEG	11	181.649091	107.660026
VEGEW	11	177.420000	127.849288

TSS

Inputs

Sample	TSS
VEG	203
EW	14
VEGEW	66
CONT	11
VEGEW	38
EW	55
VEG	9
EW	3
EW	9
CONT	13
VEG	21
EW	28
VEGEW	32
VEGEW	17
CONT	15
VEGEW	119
VEG	33
VEG	16
EW	12
CONT	100
EW	39
VEG	120
VEGEW	217
EW	29
VEGEW	6
EW	14
CONT	754
CONT	12
VEGEW	42
VEG	41
VEG	411
EW	17
VEG	4
EW	39
EW	19
CONT	14
VEG	1757
EW	10
VEGEW	48
VEGEW	12
CONT	9
VEGEW	13
VEG	16
CONT	29

```
proca anova data=sasuser.TSS;
        class sample;
        model TSS = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read	44
Number of Observations Used	44

Dependent Variable: TSS TSS

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	313953.059	104651.020	1.30	0.2862
Error	40	3208167.853	80204.196		
Corrected Total	43	3522120.912			

R-Square	Coeff Var	Root MSE	TSS Mean
0.089138	277.6754	283.2035	101.9908

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	313953.0586	104651.0195	1.30	0.2862

Level of Sample	N	TSS Mean	TSS Std Dev
CONT	9	106.376387	244.745263
EW	13	22.127944	14.909116
VEG	11	239.219366	518.379054
VEGEW	11	55.557562	62.554046

Nitrogen (N)

Inputs

Sample	N
VEG	183.93
EW	97.69
VEGEW	50.73
CONT	122.90
VEGEW	167.33
EW	104.56
VEG	51.30
EW	82.21
EW	56.83
CONT	143.22
VEG	152.02
EW	46.27
VEGEW	57.15
VEGEW	25.76
CONT	119.49
VEGEW	164.87
VEG	126.73
VEG	42.03
EW	63.66
CONT	102.22
EW	46.01
VEG	31.46
VEGEW	110.92
EW	54.07
VEGEW	14.29
EW	99.42
CONT	56.09
CONT	95.05
VEGEW	99.74
VEG	31.87
VEG	81.39
EW	115.87
VEG	92.99
EW	85.83
EW	86.15
CONT	190.69
VEG	90.60

EW	110.62
VEGEW	113.38
VEGEW	72.11
CONT	65.00
VEGEW	127.23
VEG	116.16
CONT	92.30

```
proca anova data=sasuser.N;
        class sample;
        model N = sample;
        means sample;
run;
```

Output

Class Level Information

Class	Levels	Values
Sample	4	CONT EW VEG VEGEW

Number of Observations Read	44
Number of Observations Used	44

Dependent Variable: N N

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	4482.54431	1494.18144	0.82	0.4910
Error	40	72973.00215	1824.32505		
Corrected Total	43	77455.54646			

R-Square	Coeff Var	Root MSE	N Mean
0.057872	46.51653	42.71212	91.82139

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Sample	3	4482.544310	1494.181437	0.82	0.4910

Level of Sample	N	N Mean	N Std Dev
CONT	9	109.661778	40.9240582
EW	13	80.707077	24.7609765
VEG	11	90.953000	50.3805907
VEGEW	11	91.228182	51.8029566