INFILTRATION AND POTENTIAL GROUNDWATER RECHARGE PERFORMANCE OF STORMWATER BIORETENTION DESIGNED FOR SEMIARID CLIMATES

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Bioretention is a structure which captures runoff from small catchments and stores it in porous vegetated areas with the intent of infiltrating all or a large fraction of the annual runoff volume. The effects of bioretention on potential groundwater recharge are oftentimes unknown because of variable infiltration rates. This study examined the performance of a field site on the University of Utah campus in Salt Lake City, Utah. Data were collected between March, 2012 and November, 2012.

The site demonstrated improvement in volume retention and infiltration over the preexisting conditions. The average storm event produced 5.6 mm (0.22 in) of precipitation. For all storm events examined, nearly all inflow volume was retained and either infiltrated, lost through evapotranspiration, or utilized by plants. Average vertical and horizontal infiltration rates ranged between 0.5 cm/hr and 20 cm/hr for the sandy loam subsoils. The wetting front took 1 to 2 days (24 to 48 hrs) to reach the 1.8 m (6 ft) depth and 7 to 14 days to reach the 3.7 m (12 ft) depth depending on the spatial location. At depths of 1.8 m (6 ft), 3.7 m (12 ft) and 4.6 m (15 ft) outside the basin, the wetting front progressed at least 3 m (10 ft) laterally in three days (72 hrs), but without additional sensors located at larger lateral distances, it remains unclear exactly where the lateral extent of the wetting front ceases. Without additional engineering to protect infrastructure such as building foundations and retaining walls, it is recommended that bioretention cells constructed in semiarid climates and with similar subsoils be located at least 6.1 m (20 ft) from infrastructure.

Overall, this research indicates that bioretention is a viable stormwater best management practice in Utah. It was shown that with proper design and sizing, nearly all annual runoff volume can be controlled on site and either infiltrated or utilized by native plant species. As measured infiltration data were limited to the vadose zone, the infiltrated volume was considered potential recharge; future work may include modeling and installation of deeper sensors as a means of approximating recharge.

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INTRODUCTION

The United States Environmental Protection Agency (EPA) has initiated regulations to reduce stormwater discharges from new development and redevelopment (U.S. Environmental Protection Agency, 2010). These regulatory actions are leading to modifications to urban stormwater runoff control that seeks to address stormwater quality and volume reduction in addition to the traditional peak discharge control. Nutrient loading in urban stormwater runoff is also a significant concern for the health and sustainability of receiving waters and the ecosystems they support in Utah and internationally. Nutrient criteria are being developed nationally and in Utah that will set limits to the amount that can be discharged. One approach being applied to address these issues is low impact development (LID). LID seeks to implement stormwater controls upland in the urban watershed, near to where the surface runoff is generated. LID green infrastructure practices seek to infiltrate or capture and reuse stormwater such that the natural hydrologic cycle is better recreated compared to the use of traditional grey infrastructure such as underground pipes and detention basins. Due to the ability to target multiple environmental management objectives, the use of LID green infrastructure practices is being promoted nationally. For example, a recent EPA Needs Survey of urban wastewater management infrastructure needs listed green infrastructure needs at $42 billion, which is comparable in magnitude to advanced wastewater treatment ($46 billion), secondary wastewater treatment ($60 billion), and sewer rehabilitation ($33 billion).

As LID implementation expands, its use is becoming more widespread, including in Utah. One LID component that is gaining wide application is bioretention. Bioretention is a structure that captures runoff from small catchments and stores it in porous vegetated areas with the intent of infiltrating all or a large fraction of the annual runoff volume. Typically, bioretention cells are designed such that the stormwater input to the systems is retained in soil storage layers for treatment and consumption by deep rooting natural vegetation. Pollution loading to receiving waters can be reduced with bioretention components, including vegetation (i.e., nutrient removal) and the soil properties (i.e., adsorption).

Oftentimes, legal and political barriers prevent the widespread implementation of bioretention. Specifically, the effects of bioretention and decentralized stormwater management on groundwater recharge are often viewed as potential risks to a project because of unknown storage capacities and infiltration rates. Infiltration and potential groundwater recharge can be studied through design and monitoring of topsoil, reservoir layers, and in-situ soils. As such, results of this research study will help educate policy makers and water resources professionals on the effects of bioretention on infiltration and groundwater recharge in semiarid climates.

Bioretention cells have been found to be effective for controlling the hydrologic cycle in limited laboratory studies, but few studies have investigated the effectiveness in field sites. Furthermore, the newness of the approach has led to uncertainty in planning and design and no studies have been performed to quantify the field performance of bioretention systems in Utah and to help specify design criteria. Currently, a small number of bioretention design guidelines are available as references for planners and designers; however, these consist of bioretention design focusing on mesic systems, which receive 30 to 80 inches of precipitation each year, and address traditional stormwater engineering approaches, such as facility sizing and hydraulics design (U.S. Environmental Protection Agency, 2008; Prince George's County Maryland, 2009). Quantifying the hydrologic impacts of bioretention facilities on urban environments in semiarid climates, such as in Utah, is a field of study to which little progress has been made (Houdeshel *et al*., 2012). Consequently, the objectives and research questions outlined below led to the inception of this study.

Objectives

1. Design and construct two new bioretention facilities, the first field based bioretention research cells in Utah.
2. Assess the ability of bioretention to reduce stormwater runoff volume in Utah.
3. Determine the infiltration rates through the bioretention and into the natural subsoils over the course of nine months, and characterize the impact of infiltration from bioretention on potential groundwater recharge.
4. Provide demonstration, education, and outreach engagement opportunities for planners, engineers, policy makers, and others.

Research Questions

1. To what extent do bioretention cells reduce stormwater runoff volume in semiarid climates? (Primary Question)

1a. Can volume reduction credit be granted for these facilities located in semiarid climates? Should credit be granted for storage underground, and storage in the porous soil, and storage in surface depressions? Or should credit be granted for only the surface depression storage, assuming the water subsequently infiltrates into the porous soil? (Secondary Question – Policy Recommendation)

2. What are the vertical and horizontal infiltration rates through the bioretention and into the natural subsoils? (Primary Question)

2a. How far away from infrastructure (i.e. building foundations, etc.) should these facilities be placed considering Utah's semiarid hydrologic conditions? (Secondary Question – Design Recommendation)

3. Are engineered soils really required in the top layers in these types of semiarid bioretention with native species? Or, can suitable infiltration be achieved with native backfill and a forebay? (Primary Question)

4. How does the cost of these facilities compare to traditional stormwater retention infrastructure? (Secondary Question – Appendix/Supporting Material)

Hypotheses correlating to each numbered research question were developed.

Hypotheses

1. Bioretention facilities can be designed specifically for semiarid climates with less than 500 mm (20 in) of rain annually, such that onsite retention of stormwater allows native species to thrive and a substantial (nearly 100%) reduction in stormwater runoff to downstream infrastructure is realized locally.

1a. The volume reduction achieved by these facilities in semiarid climates is substantial enough to garner credit under new stormwater regulations expected to be released in early 2013. Furthermore, it is hypothesized that credit can be earned for both underground storage and surface depression storage depending on the site-specific design.

2. Vertical infiltration rates in the range of 1 to 20 cm/hr can be expected in semiarid bioretention cells constructed with subsoils consisting of mixtures of sand, loam, and clay. Horizontal infiltration rates in the range of 1 to 20 cm/hr can be expected in semiarid bioretention cells constructed with similar subsoils. The horizontal extent of the wetting front in semiarid bioretention cells extends 3 to 4.6 m (10 to 15 ft) laterally from the edge of the cell in most applications.

2a. Consequently, a design recommendation for placement of semiarid bioretention cells at least 6.1 m (20 ft) away from susceptible infrastructure (without additional engineering to protect the infrastructure) should be adopted by local designers.

3. Substantial infiltration and reduction in stormwater runoff volume (nearly 100%) can be achieved by semiarid bioretention cells without designing the cells with engineered topsoil layers. Instead, using native backfill, native vegetation, and a properly sized forebay consisting of a suitable media such as highly porous (53%) Utelite 3/8” aggregate can suffice in meeting volume reduction, infiltration, and potential groundwater recharge design goals or specifications.

4. Bioretention cells designed and constructed specifically for semiarid climates can be competitive on a cost basis with traditional retention infrastructure. The whole

life costs of the two newly constructed field sites examined in this study will be within 15% of the whole life costs calculated for a comparable traditional retention facility.

Overall, observations of stormwater inflow, soil moisture, and outflow (infiltration) were monitored to quantify the fluxes and stores of the bioretention water budget across the 2012 spring to fall seasons when stormwater runoff was most active. The observed data was used to quantify stormwater runoff volume control in the unit.

REVIEW OF LITERATURE

Many of the bioretention sites examined in available literature were designed according to guidelines (North Carolina Division of Water Quality, 2007; Prince George's County Maryland, 2009) developed for mesic climates receiving 750 to 2000 mm (30 to 80 in) of annual precipitation (Houdeshel *et al.*, 2012). Generally, with the goals of reducing runoff volumes and promoting infiltration onsite, the design guidelines target three soils: loam, sandy loam, and loamy sand with infiltration rates of 1.3 cm/hr (0.5 in/hr), 2.5 cm/hr (1.0 in/hr), and 5.1 cm/hr (2.0 in/hr) respectively (Davis *et al.*, 2009). A media composition of 20% organic fines, 30% topsoil, and 50% sand is specified by Prince George's County (Davis *et al.*, 2009; Prince George's County Maryland, 2009), whereas North Carolina (North Carolina Division of Water Quality, 2007; Davis *et al.*, 2009) recommends 3-5% organics, 8-12% fines (silt and clay), and 85-88% sand. Infiltrating BMPs designed according to these guidelines have been shown to be effective in substantially reducing peak flows and runoff volume. Davis *et al.* (2009) reported bioretention peak flow reductions as high as 85% in New Hampshire and 99% [from storms up to 3.8 cm (1.5 in)] in North Carolina. The Villanova bioinfiltration site, designed to capture the initial 2.5 cm (1 in) of runoff, has been shown to reduce runoff to surface waters by 80% (Ermilio, 2005; Davis *et al.*, 2009).

Groundwater in the Salt Lake Valley can range from nearly 46 m (150 ft) below land surface in regions referred to as the “benches”, to as shallow as 6 m (20 ft) below land surface in regions close to the Jordan River. The "benches" generally are those areas along the Wasatch Front closest to the mountains; the University of Utah campus and thus the SCIF 4 bioretention site are located in this region and have expansive vadose zones and deep groundwater tables. The Mountview Park bioretention site is located within 8 km (5 mi) of the Jordan River in the central valley area, and is characterized by a shallower groundwater table in the 6 to 15 m (20 to 50 ft) depth range.

Several methods, each with their own challenges, are employed in practice to study vadose zone percolation, often referred to as deep drainage. Methods to provide groundwater recharge estimates over small spatial scales include numerical modeling, Darcy's Law, surface water balance equations coupled with infiltration equations such as Green-Ampt, zero-flux plane, soil moisture measurements, and lysimeters (Scanlon *et al.*, 2002; Dussaillant *et al.*, 2005; Bradford and Denich, 2008; Barkle *et al.*, 2011) . Scanlon *et al.* (2002) examined these methods in detail and concluded that space and time scales are important factors to consider in choosing a method. In arid and semiarid climates, where recharge occurs in focused regions with deep vadose zones, continuous monitoring and spatially focused methods are attractive (Scanlon *et al.*, 2002). The zero-flux plane method requires measurement of soil moisture content to estimate changes in water storage and matric potential to estimate the spatial location of the zero-flux plane; this method is difficult to use when the wetting front is progressing downward because the front often masks the true location of the zero-flux plane, and the method can be applied only at certain times of the year (Scanlon *et al.*, 2002). The Darcy's Law approach can be applied to deep vadose zones and throughout the entire year, and is thus often used. However, due to dependency on the hydraulic conductivity, which can vary spatially by several orders of magnitude, Darcy's Law and numerical models which solve forms of Darcy's Law may produce results with high uncertainty without validation by field data (Scanlon *et al*., 2002). Water budget approaches, deemed by Scanlon *et al*. (2002) to be questionable for arid and semiarid climates, are applicable over a large range of space and time scales, but suffer from limited accuracy if the recharge term is comparatively small or if evapotranspiration (ET) terms are substantial or unknown.

Work conducted by Bradford and Denich (2008), Barkle *et al*. (2011), Arauzo *et al*. (2010), and Jabro *et al*. (2008) has examined in detail the effectiveness of a variety of lysimeters: weighing lysimeters, zero-tension (i.e., pan lysimeters), fixed-tension (i.e., Gee passive capillary lysimeters), and equilibrium-tension lysimeters. Weighing lysimeters require a substantial investment in infrastructure, and their accuracy below 5.0 m is questionable (Barkle *et al*., 2011). Likewise, as shown by Barkle *et al*. (2011), equilibrium tension lysimeters also require substantial investment and construction, although they may provide the most accurate results. Dr. Glendon W. Gee (Gee *et al*., 2003; Gee *et al*., 2005; Gee *et al*., 2007; Gee *et al*., 2009; Meissner *et al*., 2010) developed the passive capillary lysimeter as an affordable alternative which can be deployed fairly easily while still capturing an undisturbed soil monolith core. The effectiveness of the Gee lysimeter has been validated (Arauzo *et al*., 2010; Meissner *et al*., 2010) in multiple field studies across a range of soil types and climates.

Soil moisture monitoring within the vadose zone can be accomplished with time domain reflectometry probes which measure the volumetric soil moisture content by sensing the dielectric constant of the soil. Probes can be installed at varying depths in vertical wells or in angled wells as was done by Rimon *et al*. (2007). Concerns with vertical wells include that the probes may not make adequate contact with the natural soil or that the natural soil may be disturbed by the drilling techniques, thus influencing results. Rimon *et al.* (2007) utilized flexible time domain reflectometry (FTDR) probes installed in wells angled at 35° to 45°. Lithology of the site was very similar to the SCIF 4 site examined in this study, consisting of unconsolidated sand with silt and clay interbeds. The probes were integrated into flexible sleeves which were hydraulically expanded by filling them with resin, thus pressing the probes against the angled borehole and ensuring adequate surface contact with the natural soil. The angled boreholes ensured each probe (at successive depths) was overlain by a completely undisturbed soil column.

Researchers agree that no vadose zone monitoring or analysis technique is flawless or without its own level of uncertainty, and thus a combination of estimation methods is recommended (Scanlon *et al.*, 2002; Arauzo *et al.*, 2010). As such, after evaluation of available resources, this research employed a combination of soil moisture monitoring, water storage recession rate monitoring, and passive capillary lysimeters to provide an estimate of infiltration rates and potential semiarid groundwater recharge which is substantiated by multiple datasets and methods.

The literature pertaining to xeric (arid and semiarid) bioretention is sparse (Pomeroy *et al.*, 2008; Houdeshel *et al.*, 2012). However, a few researchers have examined general potential recharge in semiarid climates. Gee *et al.* (2007) measured recharge of 1 to 200 mm/year in an 18 m deep lysimeter in a semiarid climate in Hanover, WA. Using the zero-flux plane method, researchers in western Australia estimated recharge of 34 to 139 mm/year (Scanlon *et al.*, 2002). Using Darcy's Law, researchers in an arid region of New Mexico estimated recharge of 37 mm/year (Scanlon *et al.*, 2002).

In the absence of more applicable data, the results of these studies, although not specific to bioretention, may serve as comparative data for approximately verifying potential recharge from the semiarid bioretention examined in this study.

BACKGROUND

Study Area

Field Site #1: University of Utah Campus, Salt Lake City Utah

The primary field site for the study consisted of a bioretention cell designed during the fall of 2011 and constructed in March of 2012 on the site of an existing detention basin southeast of the Humanities Building (Bldg. 45, CTIHB) on the University of Utah campus. The site was nicknamed “SCIF 4” because it was the group’s fourth project completed with funding from the University of Utah Sustainable Campus Initiative Fund (SCIF). Due to its central campus location and close proximity to heavy foot traffic, the project served as a visible example of bioretention implementation. The increased visibility highlighted the research benefits of LID stormwater best management practices to the University and the wider community. Consideration was given to the potential for future studies at this site. The design incorporated a variety of plants for potential future nutrient removal studies in addition to added data collection opportunities for studies already in progress. The layout, including a single inlet with a well-defined catchment area, was ideal for many potential bioretention research studies.

Field Site #2: Mountview Park, Cottonwood Heights Utah

In the fall of 2011, a second field site was designed for the newly constructed Mountview Park in Cottonwood Heights, Utah. Construction of the park began in the fall of 2011, and with approval of the Cottonwood Heights City Engineer, the bioretention portion of the park was completed in May, 2012. The project was executed in cooperation with the City of Cottonwood Heights, Gilson Engineering, and Miller Paving. Funding for the project was provided by a 104b grant through the U.S. Geological Survey (USGS) with matching funds from the City of Cottonwood Heights and Gilson Engineering. An informative sign detailing the purpose, conceptual design, and cooperative efforts of involved parties was installed next to the site to educate the passersby.

The purpose of the site was to serve as the first public demonstration of bioretention in Utah and to support future research studies. Although preliminary data was collected from the site, analysis results presented in this thesis are with regard to the SCIF 4 site only. References to the Mountview Park site are included as supporting material in the interest of completeness in presenting the progress of bioretention design and development in Utah.

Design and Construction

Field Site #1: University of Utah Campus, Salt Lake City Utah

The existing detention basin was excavated to a depth of 4 ft and subsequently backfilled with gravel and soil layers up to the preexisting level. A cross-sectional view of the bioretention cell is shown in Figure 1. The design includes a 0.6 m (2 ft) top soil layer above a 0.6 m (2 ft) subsurface reservoir layer. The gravel reservoir is composed of Utelite 3/8" medium grade aggregate with a porosity of 53% (HWA GeoSciences Inc., 2009). Utelite is an expanded shale, clay and slate (ESCS) ceramic aggregate suitable for use in filtering and planting applications.

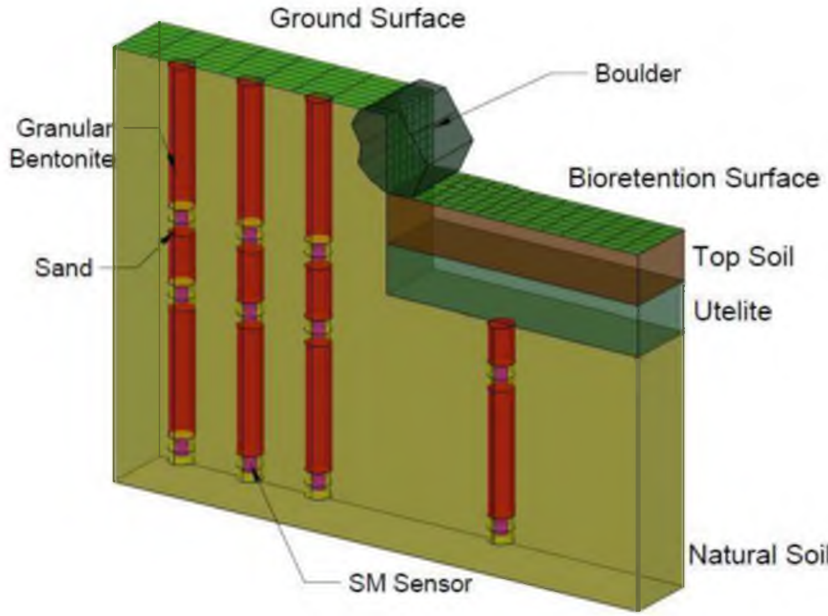


Figure 1. Isometric View of the Bioretention Cells, Showing Soil Moisture Wells

The Utelite reservoir has a storage capacity of approximately 32.1 m^3 (8,480 gal). Additional runoff collects in surface depression storage [approximately 35.6 m^3 (1,260 gal)] up to the point of overflow into the orifice structure.

The design also includes an Utelite forebay that allows water to rapidly percolate to the storage reservoir. The forebay extends laterally in a 5-ft radius from the basin inlet, and extends vertically to the reservoir layer.

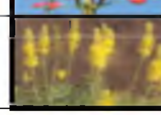
Biological conditions are often as important as physical conditions to the success of the bioretention cell. The selected media mixture and vegetation in the bioretention cell should allow for a diverse range of future studies regarding water quality, evapotranspiration, or to quantify any additional treatment provided by the plants at the site. The vegetation has been carefully selected for the semiarid climate of the Salt Lake valley and closely matches selected native species used in existing bioretention sites on the University of Utah campus; this will allow for multisite studies in the future. The cell was planted with a native grass and shrub community with vegetative species listed in Table 1. Placement of the plant species within the cell is shown in Figure 2. The bioretention cell was designed to be completely irrigation free, requiring no supplemental water intake for vegetation survival. The design is intended to function such that the vegetation consumes the water in the storage layer below the surface, thus reducing runoff pollution transport and stormwater loading to traditional infrastructure.

Field Site #2: Mountview Park, Cottonwood Heights Utah

Schematics of the park and analyses of the watershed hydrology were obtained from the Cottonwood Heights City Engineer (Mr. Brad Gilson) for use in the design process. Plans of the final design, including all appropriate dimensioning, placement of wells, and locations of plants were supplied to the Cottonwood Heights City Engineer for approval prior to construction of the site in May, 2012. The research team coordinated material selection and well drilling, and provided personnel for construction activities including well installation, planting, and installing instruments. The contracted construction company (Miller Paving) provided in-kind assistance in the form of heavy equipment, personnel, gravel and soil spreading, and time for excavation.

Five drainage basins flow to an outfall at the northwest corner of the parking lot, as shown in Figure 3. The bioretention cell was sized to fit in available space near the outfall of the drainage area. A 0.3 m (12 in) diameter concrete storm sewer connected the cell at the surface level to a nearby overflow basin to allow drainage in an emergency overflow scenario. The cell area was approximately 229 m^2 (2470 ft^2).

Table 1. Vegetation Species Planted in the Bioretention Cells

Species	Common Name	Plant Type	Image	Site
Cercocarpus ledifolius	Curleaf Mountain	Evergreen Shrub		Mountview Park
Cercocarpus montanus	Beechleaf Mountain	Tree Shrub		SCIF 4, Mountview Park
Schizachyrium scoparium	Little Bluestem Grass	Bunchgrass		SCIF 4, Mountview Park
Bouteloua gracilis	Blue Grama Grass	Bunchgrass		SCIF 4, Mountview Park
Sorgastrum nutans	Indian Grass	Bunchgrass		SCIF 4, Mountview Park
Ericameria nauseosa	Rubber Rabbitbrush	Shrub		SCIF 4, Mountview Park
Atriplex canescen s	Saltbush	Shrub		SCIF 4, Mountview Park
Artimesia tridentata	Big Sagebrush	Evergreen Shrub		SCIF4, Mountview Park
Chrysothamnus viscidiflorus	Rabbitbrush	Shrub		SCIF 4, Mountview Park
Monardella odoratissima	Mountain Beebalm	Perennial		SCIF 4
Penstemon eatonii	Firecracker Penstemon	Perennial		SCIF 4
Stanleya pinnata	Prince's Plume	Perennial		SCIF 4

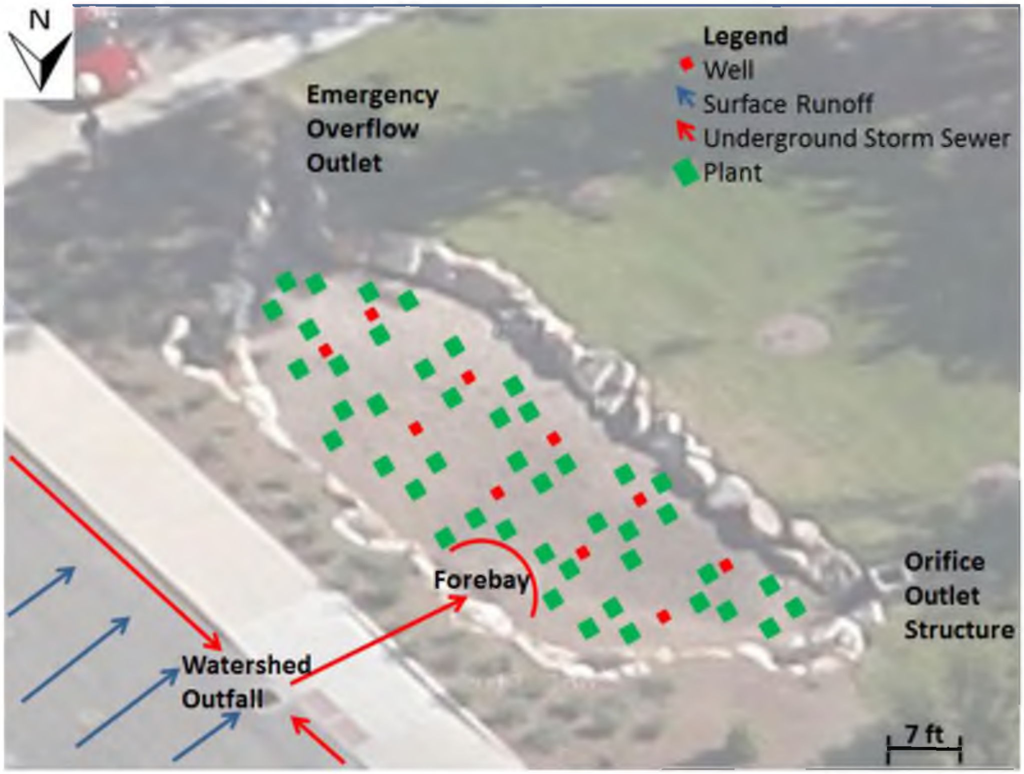


Figure 2. SCIF 4 Well and Plant Layout

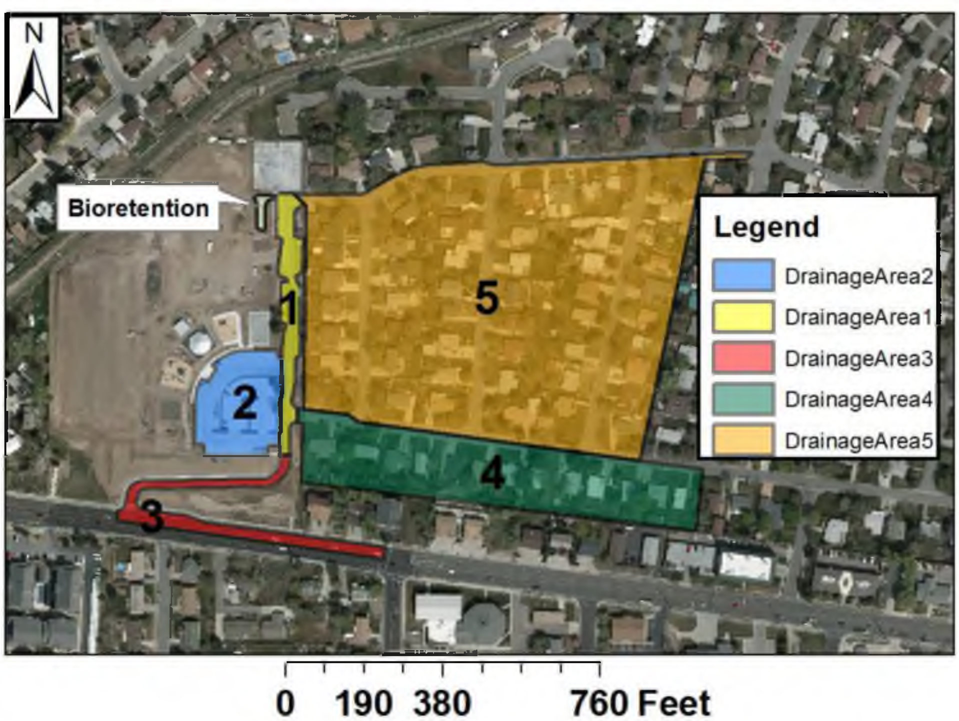


Figure 3. Mountview Park Drainage Basin Map
(Source: Modified from Gilson Engineering)

The cell was excavated to a depth of 1.2 m (4 ft) and subsequently backfilled with storage and soil layers up to the preexisting level. The design included a 0.6 m (2 ft) top soil layer above a 0.6 m (2 ft) subsurface reservoir layer. A cross-sectional view of the design is identical to the SCIF 4 design shown in Figure 1, with one exception; due to cost constraints, the gravel reservoir was built with ¾" gravel rather than the 3/8" medium grade Utelite aggregate used in the SCIF 4 site.

The design also includes a gravel forebay that allows water to rapidly percolate to the storage reservoir. The forebay extends laterally 1.5 m (5 ft) from the cell inlet, and extends vertically to the reservoir layer.

Combined, the underground gravel reservoir and surface depression storage of the overflow retention pond have a capacity of approximately 212.1 m^3 (56,029 gal). Overflow is diverted into traditional infrastructure and discharged into a nearby canal on the northwest side of the park.

The cell was planted with a mixture of native grasses, shrubs, and woody vegetation identical to the plants used in the SCIF 4 site, with specific species listed in Table 1. Configuration of the vegetation and wells within the cell is shown in Figure 4.

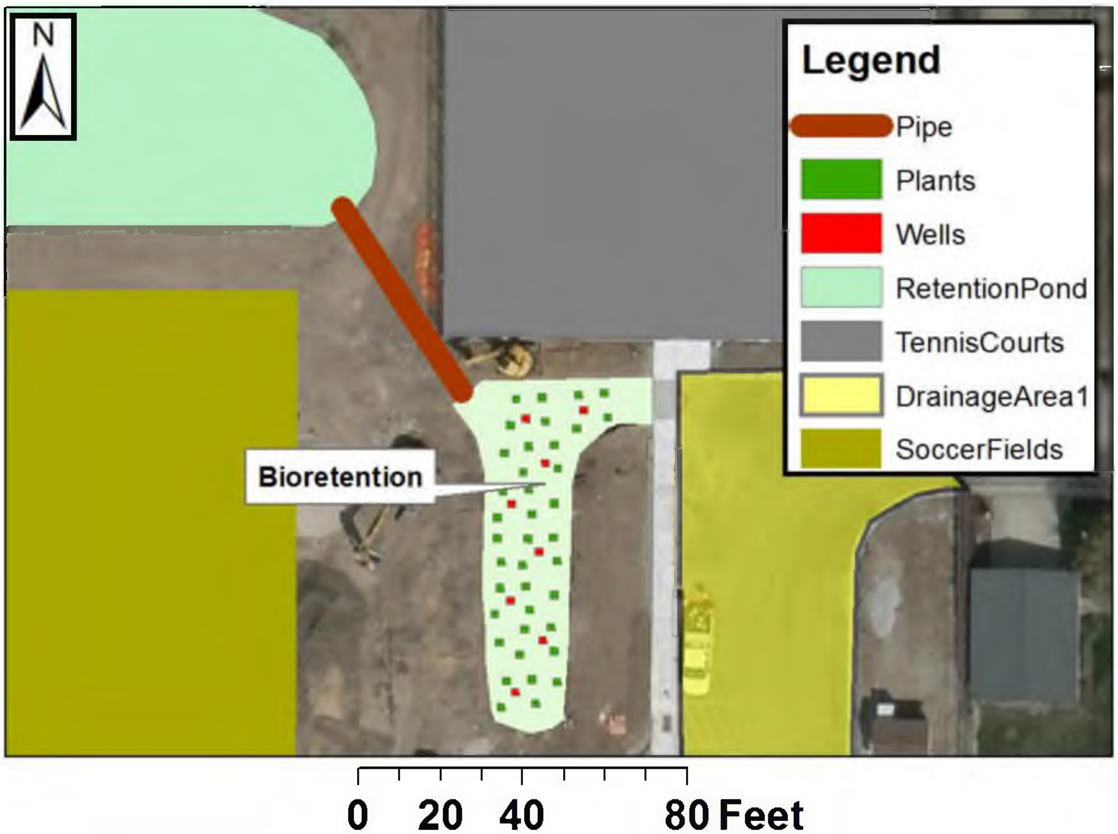


Figure 4. Mountview Park Bioretention Plant and Well Layout

EXPERIMENTAL METHODOLOGY

Hydrologic Observation

Field Site #1: University of Utah Campus, Salt Lake City Utah

The watershed upstream of the bioretention cell is a portion of the parking lot located directly to the east of the site, as shown in Figure 5.

All runoff is routed into the bioretention cell through a single 38 cm (15 in) diameter plastic storm sewer pipe. This single inlet pipe was ideal for measuring flow volume using a Level Troll 500 pressure transducer installed in the bottom of the pipe.

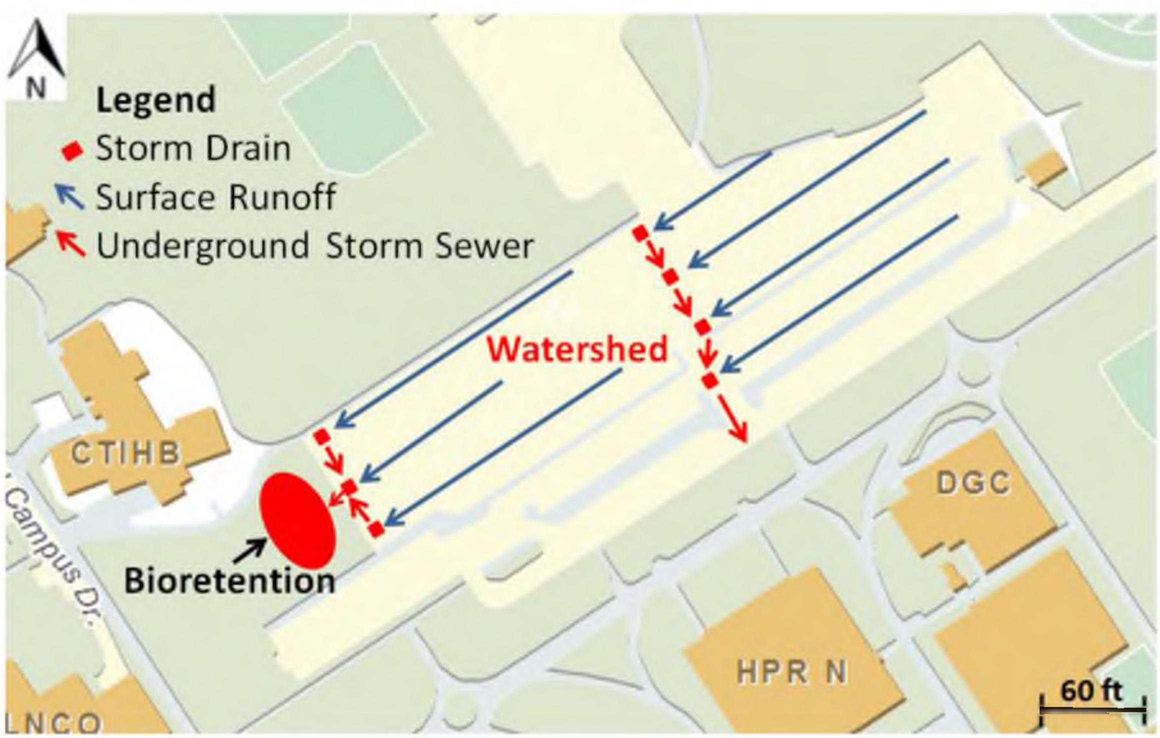


Figure 5. SCIF 4 Watershed Delineation

The existing detention basin was excavated 4 ft down from the existing grade. At that point, ten 5 cm (2 in) diameter wells were drilled in two rows, with 3 m (10 ft) between each well. The wells were drilled to an absolute depth of 3.6 m (12 ft) referenced from the original basin grade. A soil moisture sensor was installed at the 3.6 m (12 ft) depth encapsulated by a 0.3 m (1 ft) layer of backfilled sand. The wells were backfilled with a 1.5 m (5 ft) layer of moderately compacted hydrated granular bentonite, up to the 2 m (6.5 ft) level. A second soil moisture sensor was installed at the 1.8 m (6 ft) level encapsulated in 0.3 m (1 ft) of sand, and the remainder of the well was backfilled with hydrated granular bentonite to the bottom of the Utelite layer. The sand layers facilitate lateral seepage of water into the well column while the bentonite layers compact and expand to seal the well, thus preventing the well from acting as an artificial vertical conduit. All drill casings below the Utelite layer were removed. Once this process was completed for each well, a 3.1 cm (1.25 in) diameter polyvinylchloride (PVC) pipe was inserted permanently above each well. The lower 61 cm (2 ft) of the PVC pipes were perforated to allow the water level within the Utelite layer to equalize within the PVC wells. Lastly, the basin was backfilled first with a 61 cm (2 ft) layer of Utelite aggregate surrounding the PVC wells, and then with a 61 cm (2 ft) layer of native backfill soil.

Several sensors were installed to determine the infiltration rates through the backfilled layers and natural subsoils. HOBOnode soil moisture sensors were installed in the wells at vertical locations as illustrated in Figure 6. The sensors measure volumetric soil water content by sensing the dielectric constant of the soil. The sensor probes were buried in the soil and wired to 2.4 GHz transmitters on the basin surface.

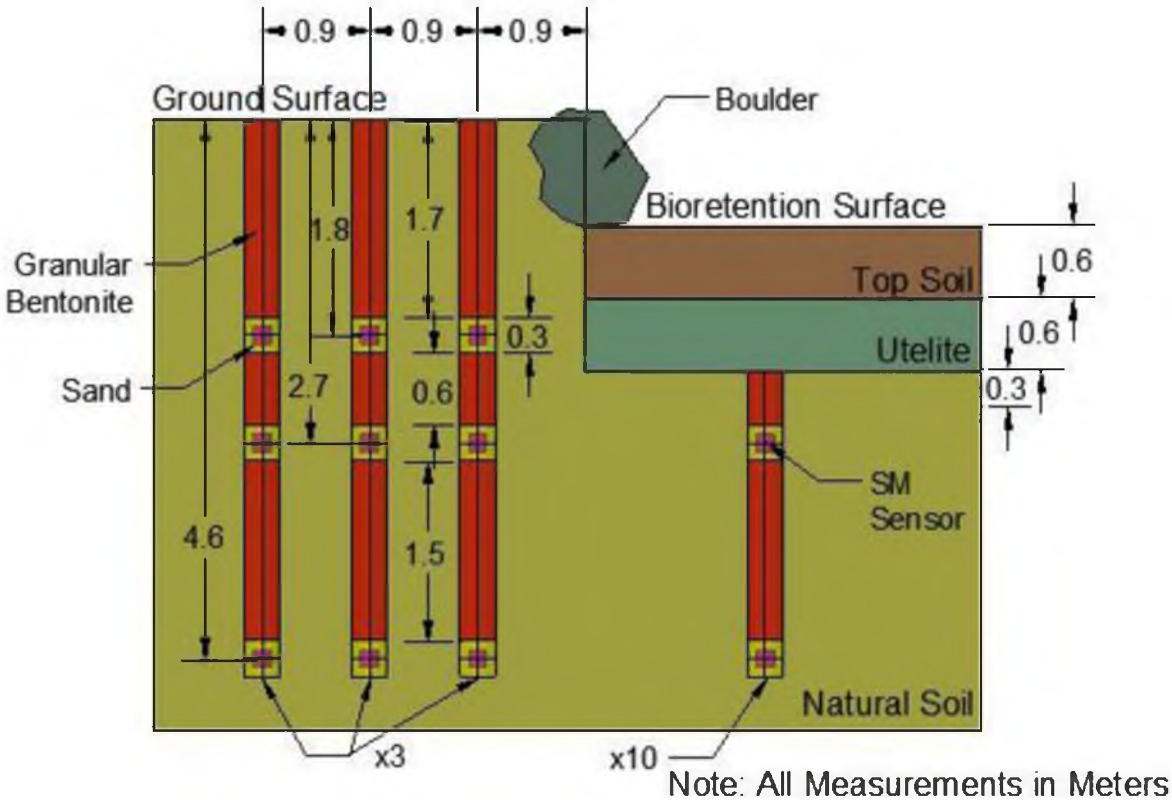


Figure 6. Soil Moisture Sensor Well Design

Solinst Model 3001 F15/M5 Levelogger Junior pressure transducers were lowered into the PVC wells on tethers, as shown in Figure 7. These depth monitors were installed at the bottom of the Utelite layer inside the perforated PVC casing which allowed water to fill the pipe at the same level as the surrounding Utelite layer. The sensors are 22 mm (0.875 in) in diameter and 140 mm (5.5 in) long and are suitable for sensing water depth levels up to 5 m (15 ft). The 316L stainless steel housing and operational temperature range of -20˚C to +80˚C (-4˚F to +176˚F) made these sensors a suitable choice for the application. Up to 32,000 data points can be recorded at user defined (0.5 sec up to 99 hrs) intervals during any given recording period. Pressure data is automatically compensated with simultaneous temperature readings, resulting in an accuracy of 0.1%

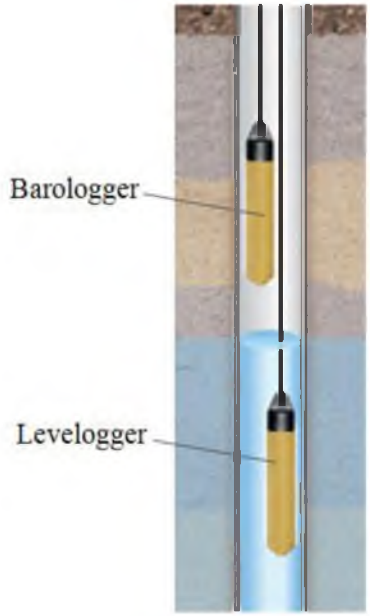


Figure 7. Levelogger and Barologger Installation
(Source: Modified from http://solinst.com)

FS (full scale of measurement). Solinst Barologger transducers were used in conjunction with the Leveloggers to further improve accuracy by compensating for differential atmospheric pressure changes in the air column above the water level in the wells. Barologgers were installed in two of the PVC wells. The wells were capped with perforated PVC lids. The sensors were retrieved via the tethers on a biweekly basis for data downloading.

Pressure data were converted to water depths and provided an indication of the storage level in the Utelite reservoir at each well location. This data, combined with the soil moisture data, was the primary indication of the infiltration rates and potential for groundwater recharge throughout the cell.

Three passive capillary lysimeters, constructed by Decagon Devices, Inc. were installed in a line at 4.5 m (15 ft) intervals down the center of the cell. The lysimeters provided a measurement of volumetric drainage in the natural subsoils below the Utelite reservoir. A 60 cm (23.6 in) long undisturbed soil monolith was captured inside the sensor's stainless steel diversion control tube (DCT). The DCT was installed above the sensor's wick, measurement reservoir, and sampling reservoir. As the water from the Utelite reservoir drains through the soil monolith in the DCT, it is wicked into the measurement reservoir where a level sensor detects each millimeter of drainage flushed into the sampling reservoir. The sensor is wired to a logger on the cell's surface. Although no water quality analysis was conducted, sampling for water quality analysis is possible via syringe from a tube extending to the surface of the cell from each lysimeter sampling reservoir.

Field Site #2: Mountview Park, Cottonwood Heights Utah

The watershed consists of the park's parking lots and nearby Cloverdale and Village Green paved roadways, as illustrated in Figure 3. In total, the watershed is 76,323 m^2 (18.86 acres) consisting of 8,012 m^2 (1.98 acres) of contributing impervious area. All inflow to the cell is directed through two side-by-side rectangular concrete channels monitored with Stingray ultrasonic level-velocity sensors made by Greyline Instruments, Inc.

Eight wells were drilled in an identical fashion (i.e., identical depths and backfill layers) to those drilled in the SCIF 4 site. Three of the wells were outfitted with HOBOnode soil moisture sensors at 3.6 m (12 ft), 2.7 m (9 ft), and 1.8 m (6 ft) depths (referenced from the final basin grade). The remaining five wells were outfitted with two soil moisture sensors at depths of 3.6 m (12 ft) and 1.8 m (6 ft). In total, 19 soil moisture sensors were installed.

In order to monitor the water movement and level in the underground gravel reservoir, six perforated PVC wells were installed with Levelogger and Barologger transducers in the same manner as was done for the SCIF 4 site.

Like the SCIF 4 site, three passive capillary lysimeters were installed in a line along the center of the basin to provide an additional measure of infiltration.

ANALYSIS

Site Geology and Basin Fill Aquifers

When analyzing the infiltration of surface water into subsurface media, and the subsequent flow of groundwater, it is important to have an understanding of the local geology and factors affecting the groundwater flow. In the western arid and semiarid regions of the United States, most groundwater recharge occurs in mountains and flows through bedrock to the sand, silt, and gravel basins nearby. Such regions are often referred to as basin and range systems where unconsolidated sedimentary fill deposits define the lithology in the basins adjacent to mountainous bedrock (Schwartz and Zhang, 2003). The Basin and Range aquifer system, consisting in part of the Salt Lake valley, generally fits this description. As such, within the valley, the lithology consists of layers of deposited sediment constituting an unconfined aquifer system, between land surface and bedrock about 1 km (0.6 mi) below, which is largely fed by primary recharge from the Wasatch Mountains. Secondary recharge may occur further down gradient in the basin. At some location within the basin, referred to as a discharge area, the groundwater actually tends to flow upward. These regions are illustrated generally (Thiros and Manning, 2004) in Figure 8 and with respect to the Wasatch Front in Figure 9 using data obtained from the Utah Automated Geographic Reference Center (State of Utah, 2012).

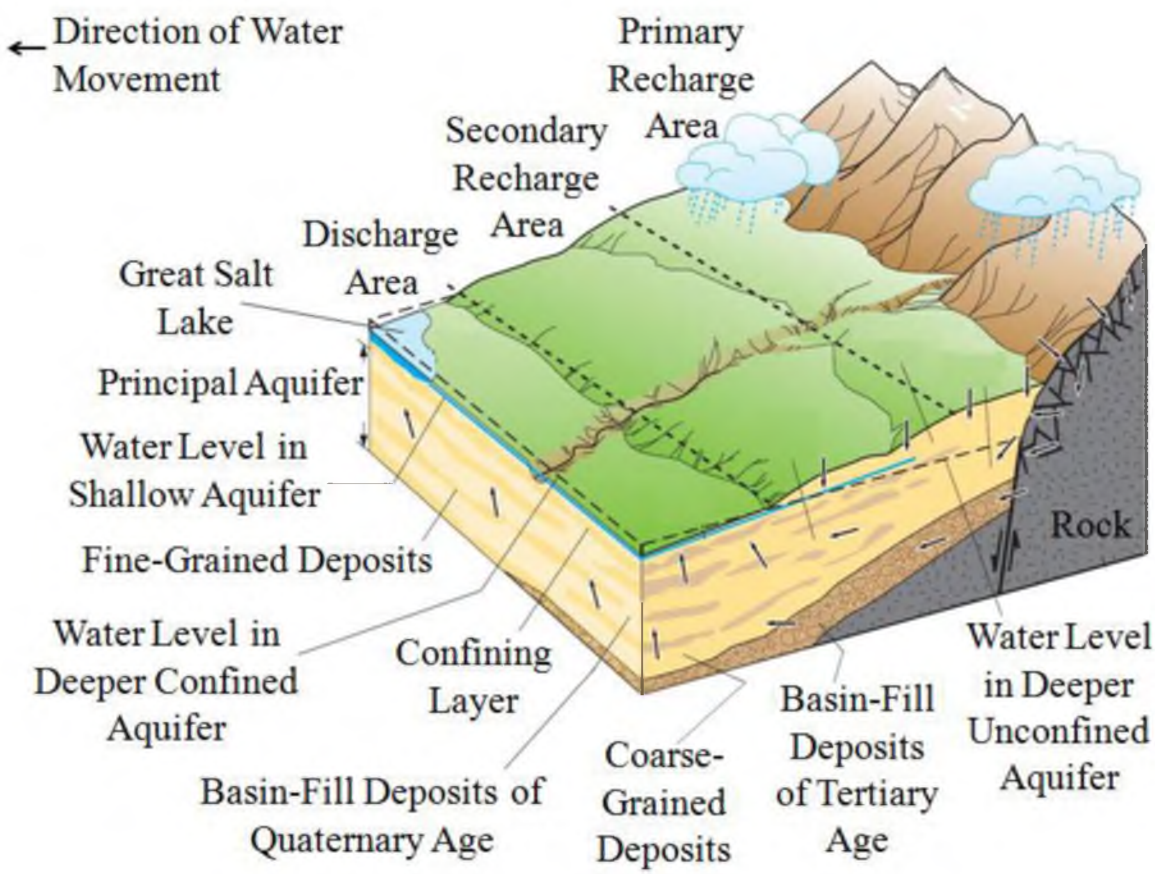


Figure 8. Generalized Block Diagram Showing the Basin-Fill Deposits and Groundwater Flow System in the Salt Lake Valley, Utah
(Source: Modified from Thiros and Manning, 2004)

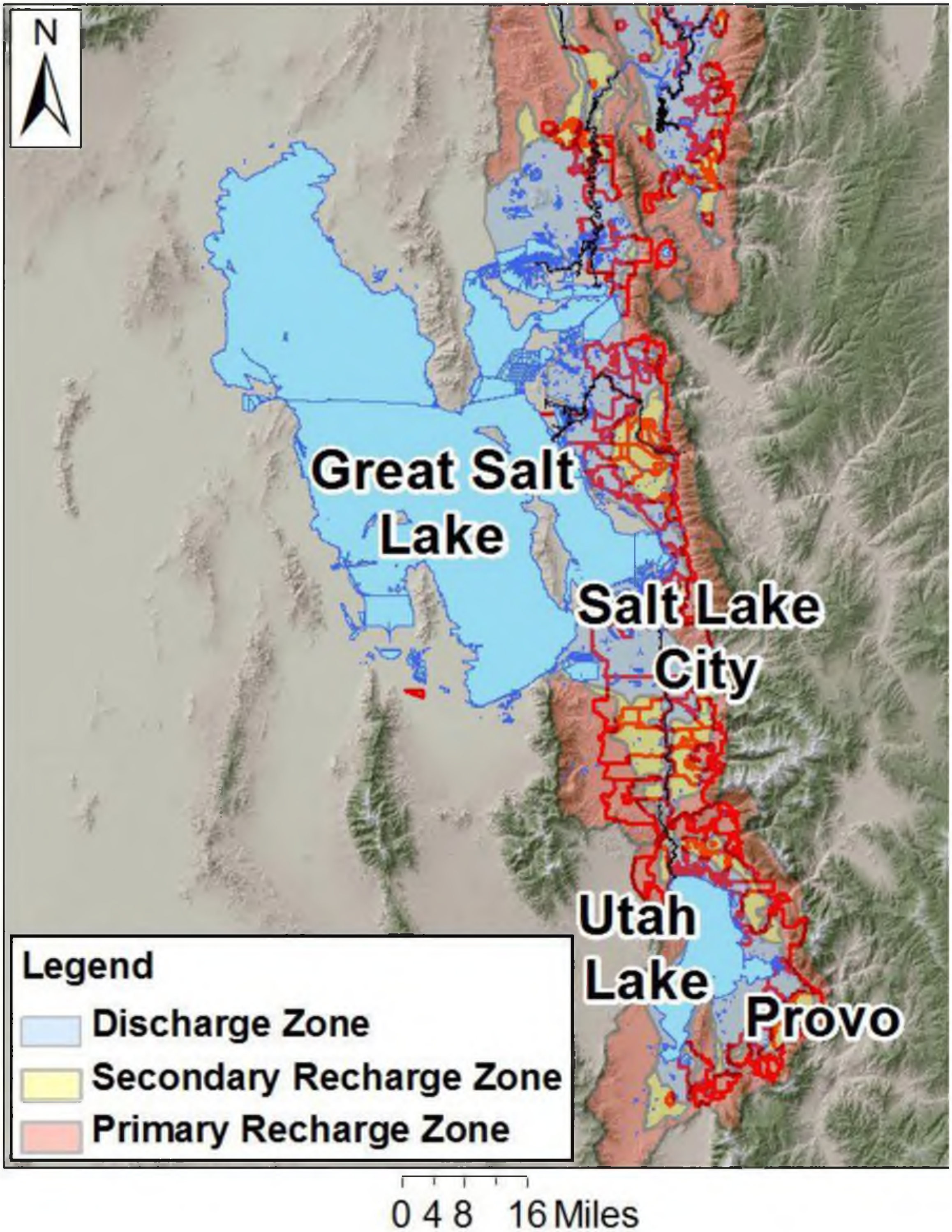


Figure 9. Recharge and Discharge Zones Along the Wasatch Front

In the Salt Lake valley, the transition from secondary recharge to discharge is approximately near the natural topographic divide aligned with Highland Drive (2000 East); Groundwater east of this divide generally flows downward as recharge and groundwater west of this divide generally flows upward toward the Jordan River as discharge. The SCIF 4 bioretention site lies within the primary recharge region and the Mountview Park bioretention site lies within the secondary recharge region, as shown in Figure 10, Figure 11, and Figure 12.

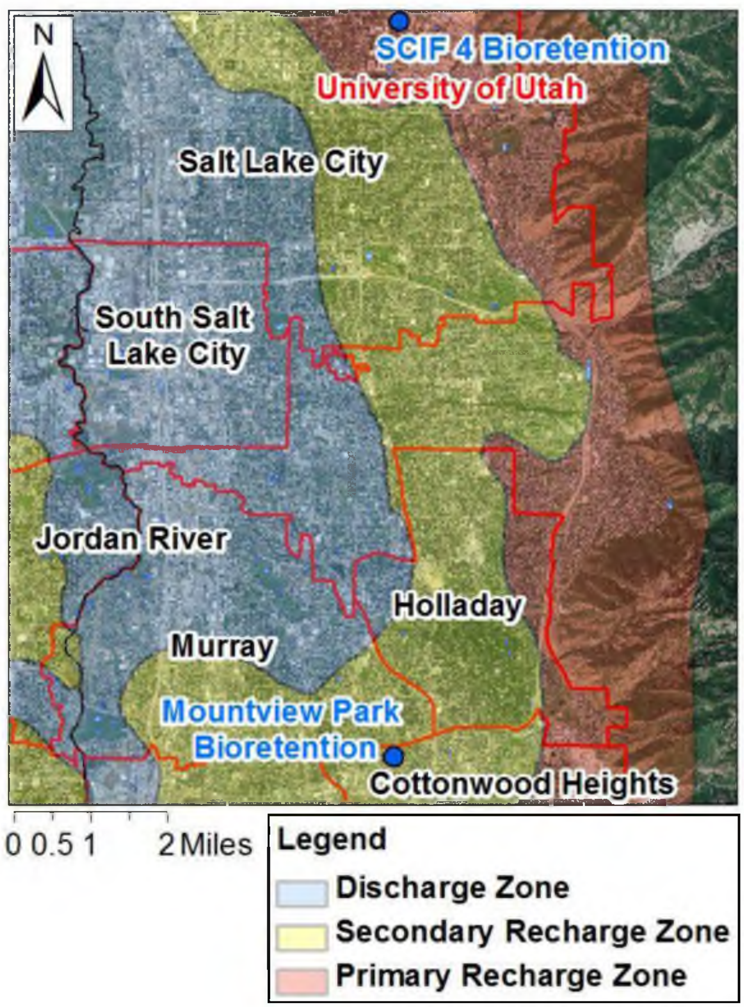


Figure 10. SCIF 4 and Mountview Park Bioretention Sites and Associated Recharge Zone Boundaries

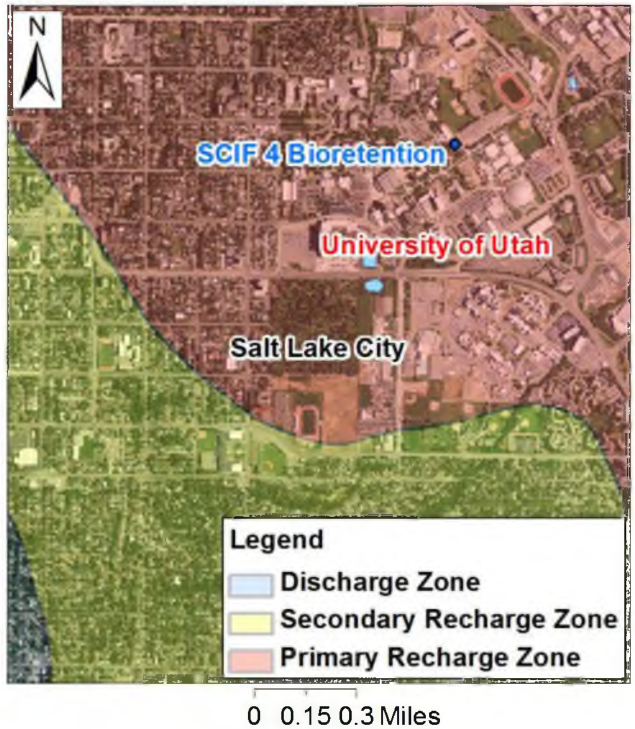


Figure 11. SCIF 4 Bioretention Site, Recharge Zones, and Discharge Zones

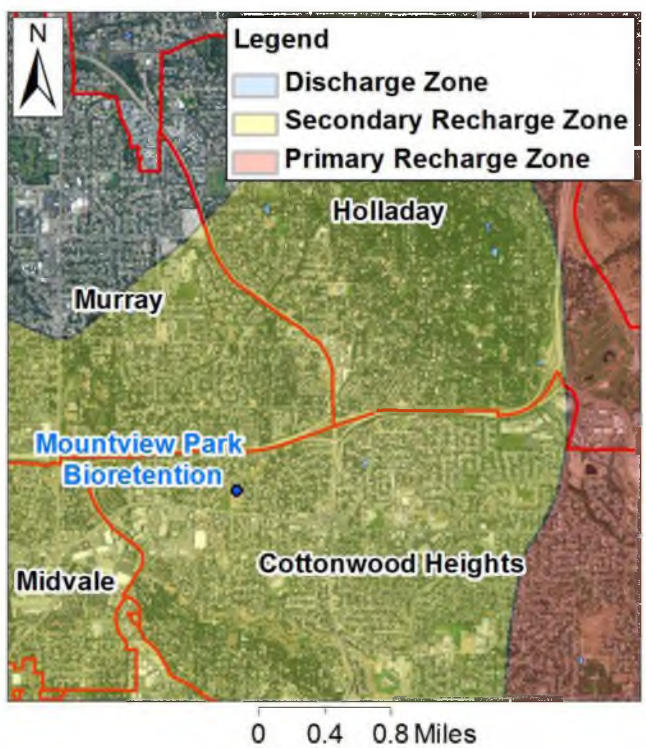


Figure 12. Mountview Park Bioretention Site, Recharge Zones, and Discharge Zones

The U.S. Geological Survey (USGS) maintains a network of groundwater wells throughout the State of Utah. Water level data is available from an interactive mapping tool located on the Utah Active Water Level website (U.S. Geological Survey, 2012). USGS well #404531111510101, located approximately 0.9 km (0.5 mi) southwest of the SCIF 4 bioretention site, averages a depth of groundwater below land surface of approximately 129 ft (U.S. Geological Survey, 2012). USGS well #403742111503201, located approximately 0.3 km (1000 ft) northeast of the Mountview Park bioretention site, averages a depth of groundwater below land surface of approximately 36.5 m (120 ft) (U.S. Geological Survey, 2012). However, other wells (i.e., USGS well #403713111501901) within approximately 1.2 km (0.7 mi) southeast of the Mountview Park site average a groundwater depth below land surface of about 6 m (20 ft). This highly variable nature of the groundwater table is likely due to the “valley fill” lithology, and shows the direct impact that site selection may have on potential recharge.

Matlab Graphical User Interface (GUI)

A Graphical User Interface (GUI) was programmed in Matlab to allow streamlined and repeatable calculations and visualization of the data. The GUI contains functionality to load data from any number of the sensors at the site. The load functions read data in Microsoft Excel formats as produced by the sensors. The sensors are represented as buttons overlain on an aerial image of the site for easy reference of the spatial location of the sensor. A plot of the loaded data is displayed in the GUI and can also be displayed in a standalone window, copied to the clipboard, or saved to hard disk.

Various analysis options become visible in the GUI depending on which sensor dataset the user chooses to analyze. For example, when the inflow data is plotted, options become available to allow the user to select whether any or all of the flow depth, flow velocity, volume, or cumulative volume are calculated and plotted. When soil moisture data is plotted, options become available to allow the user to select which wells and depths to plot simultaneously and whether or not the data should be plotted in raw or normalized format. Options also become available to allow the user to "stack" multiple soil moisture plots on top of each other for easier viewing in one plot.

Volume Reduction

Field Site #1: University of Utah Campus, Salt Lake City Utah

The depth of water flowing through the 38.1 cm (15 in) diameter inflow pipe was recorded for each storm. The data were used to calculate flow rate using Manning's equation for open channel flow through a partially full circular pipe,

$$Q = \frac{K}{n} A R^{\frac{2}{3}} \sqrt{S}\,, \qquad (1)$$

where Q [L^3/T] is the volumetric flow rate, n is Manning's roughness coefficient (0.009 for plastic), K is 1.49 for U.S. customary units and 1.0 for metric units, A [L^2] is the cross-sectional flow area, S [L/L] is the pipe bottom slope (1/20 for the SCIF 4 inflow pipe), and R [L] is the hydraulic radius defined as

$$R = \frac{A}{P}, \qquad (2)$$

where A [L^2] is the cross-sectional flow area and P [L] is the wetted perimeter. For the case where the pipe is less than half full, the flow area was calculated as

$$A = \frac{r^2(\theta - \sin\theta)}{2}, \tag{3}$$

and the wetted perimeter was calculated as

$$P = r\theta\ , \tag{4}$$

where r [L] is the radius of the pipe (0.19 m for the SCIF 4 inflow pipe) and θ [rad] is the central angle between lines drawn from the pipe center to the water surface at each side. For this case, theta was calculated as

$$\theta = 2\sin^{-1}\left[\frac{r-h}{r}\right], \tag{5}$$

where h [L] is simply equal to the measured depth of flow, denoted by the variable y. For the case where the pipe was more than half full, the flow area was calculated as

$$A = \pi r^2 - \frac{r^2(\theta - \sin\theta)}{2}, \tag{6}$$

and the wetted perimeter was calculated as

$$P = 2\pi r - r\theta \,, \tag{7}$$

For this case, theta was calculated using equation (5) with h defined as the distance from top dead center of the pipe to the water surface, and given by

$$h = 2r - y \,, \tag{8}$$

where y [L] is the measured depth of flow. Furthermore, using the continuity equation

$$Q = vA \,, \tag{9}$$

where Q [L^3/T] is the volumetric flow rate, v [L/T] is the average flow velocity, and A [L^2] is the cross-sectional flow area, Manning's equation was solved for the flow velocity as stated in equation (10).

$$v = \frac{K}{n} R^{\frac{2}{3}} \sqrt{S} \,, \tag{10}$$

Additionally, the average flow volume at each time step was calculated as

$$V = Qt\ , \tag{11}$$

where t [sec] is the time step over which the volume was calculated. Cumulative volume [L^3] was calculated as

$$V_{cumulative} = V_t + V_{cumulative,t-1}\ , \tag{12}$$

where V_t is the average flow volume at the current time step and $V_{cumulative,t-1}$ is the cumulative volume at the prior time step.

Matlab functions were written to read the measured flow data and calculate the flow rate, flow velocity, flow volume, and cumulative flow volume using equations (1) through (12).

Infiltration

Pressure data from each Levelogger well were retrieved at two week intervals throughout the study duration. The data were converted to water depths and compensated with barometric pressure measurements to provide an indication of the storage levels in the Utelite layer at each well location. The data were plotted and analyzed using the aforementioned Matlab GUI. A custom data cursor was programmed in the GUI to show the formatted date and time for any selected event on the plot. In this graphical manner, the time steps at which the storage levels began to rise, peaked, and subsided were selected. The dates and times of these events for each of the six Levelogger sensors and for each storm event were recorded and subsequently analyzed in an Excel spreadsheet.

The infiltration rate is nonlinear by nature due to the fact that the hydraulic head in the storage layer decreases with time. In order to maintain consistency in the infiltration rate calculations and in order to avoid introducing error into the calculations by selecting intermediate points from the plots, an average rate was calculated based on the most easily recognizable time events on the plots: the peak time and the steady state time. Specifically, the time of peak was subtracted from the steady state time to obtain a duration over which the infiltration occurred. Similarly, water levels at the time of peak and steady state time were recorded. Average infiltration rates were calculated by

$$\bar{I}_{LL} = \frac{(d_{peak} - d_{steady\ state})}{(t_{peak} - t_{steady\ state})}, \tag{13}$$

where $\bar{I}_{LL}$ is the average Levelogger infiltration rate, d_{peak} is the water level at the peak time, t_{peak}, and $d_{steady\ state}$ is the water level at the steady state time, $t_{steady\ state}$.

Infiltration rates were also calculated from the soil moisture data. As the infiltrating wetting front advances through the subsoils, the sensors installed at various depths register spikes in soil moisture content, with the spikes registered by the deepest sensors lagged behind the shallowest sensors by the duration of the infiltration. Knowing the measured depths at which the sensors were installed, the infiltrating distance was calculated. The average soil moisture sensor infiltration rates were calculated as

$$\bar{I}_{SM} = \frac{(z_{deep} - z_{shallow})}{(t_{deep} - t_{shallow})}, \tag{14}$$

where $\bar{I}_{SM}$ is the average soil moisture sensor infiltration rate, z_{deep} is the depth of the deep soil moisture sensor, $z_{shallow}$ is the depth of the shallow soil moisture sensor, $t_{deep}$is the time at which the wetting front registered on the deep sensor, and $t_{shallow}$ is the time at which the wetting front registered on the shallow sensor.

Again, like equation (13), equation (14) results in an average infiltration rate. In the saturated zone, the groundwater flow can be calculated by measuring the total hydraulic head at various depths with piezometers and then solving the saturated groundwater flow equation

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t}, \tag{15}$$

where h is the total hydraulic head, K_i(i = x, y, and z) are the saturated hydraulic conductivities in the respective directions, and S_s is the specific storage of the saturated media. Total hydraulic head h is given by

$$h = z + \Psi, \tag{16}$$

where z is the elevation head. The infiltration beneath the bioretention site is characterized by a wetting front advancing through the unsaturated zone. In the vadose zone, the unsaturated hydraulic conductivity K_{us} is a function of the pressure head and the change in volumetric water content is the change in storage. Consequently, the unsaturated groundwater flow equation, given here in the three dimensional, anisotropic, heterogeneous form as

$$\frac{\partial}{\partial x}\left(K_r(\Psi)K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_r(\Psi)K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_r(\Psi)K_z\frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial t}, \qquad (17)$$

is nonlinear as it depends on the volumetric water content and the total hydraulic head. In equation (17), θ is the volumetric water content, h is the total hydraulic head, Ψ is the pressure head (also referred to as the matric potential), K_i(i = x, y, and z) are the saturated hydraulic conductivities in the respective directions, and K_r is the relative hydraulic conductivity. Note that the unsaturated hydraulic conductivity is a fraction of the saturated hydraulic conductivity as is illustrated by the definition of the relative hydraulic conductivity ($0 < K_r < 1$) as

$$K_r(\Psi)=\frac{K_{us}(\Psi)}{K_s}, \qquad (18)$$

where K_s is the saturated hydraulic conductivity, and K_{us} is the unsaturated hydraulic conductivity.

Various forms of equation (17) are solved by finite element analysis (FEA) modeling packages such as MODFLOW or HYDRUS. Such a model would require knowledge of total hydraulic head in defining the boundary conditions. As such, to accurately model total hydraulic head in the unsaturated zone, one must make separate measurements of the elevation head and matric potential. In modeling, the water-retention (a.k.a. $\theta(\Psi)$) curve for the unsaturated media must also be known. The water-retention curve describes the nonlinear dependence of θ on the pressure head (which is negative in unsaturated groundwater flow). Generally, as the volumetric water content of a soil decreases, Ψ becomes more negative. Matric potential measurements could be acquired using a tensiometer, and combined with volumetric soil water content readings, the $\theta(\Psi)$ curve could be derived. Alternatively, empirical relationships developed by van Genuchten (1980) are often used in practice to represent the $\theta(\Psi)$ curve. The van Genuchten equation is given as

$$s_e = \frac{1}{[1 + (\alpha|\Psi|)^{\beta}]^{\gamma}}, \tag{19}$$

where s_e is the effective saturation (a dimensionless soil moisture content), α and β are soil specific parameters, and $\gamma = 1 - \frac{1}{\beta}$. The parameters α and β can be referenced from literature for the soil, or can be determined by fitting a site-specific measured $\theta(\Psi)$ curve with a calculated $\theta(\Psi)$ curve. Development of a three-dimensional groundwater model for a similar semiarid bioretention site was developed by Jennifer Steffen (Steffen, 2012) and was beyond the scope of this study.

To avoid the complexity of a three-dimensional model, a simpler one-dimensional form of Darcy's Law (which is used to derive equations (15) and (17)) can be used to calculate the local vertical flow beneath the bioretention site. As shown here

$$q_z = -K_z(\Psi)\frac{\Delta h}{\Delta z}, \tag{20}$$

where q_z is the Darcy velocity vector in the vertical direction, $K_z(\Psi)$ is the hydraulic conductivity in the vertical direction, and $\frac{\Delta h}{\Delta z}$ is the gradient of total hydraulic head in the vertical direction, the flow is dependent on measurements of the unsaturated hydraulic conductivity (i.e., measurements of matric potential) and measurements of total hydraulic head (which also require measurements of matric potential) at vertical locations distanced by Δz in the soil profile. At the time of construction of the bioretention site analyzed in this study, resources were not available to allow installation of tensiometers at the depths for which soil moisture measurements were feasible. As a result, no direct matric potential measurements were acquired and instead, infiltration rates were calculated as averages using soil moisture and Levelogger data and equations (13) and (14).

An additional measurement of infiltration was provided by three Gee passive capillary lysimeters installed in the center of the bioretention site. Direct readings of volumetric deep drainage were output by the sensors and plotted using the Matlab GUI. The deep drainage for each storm event was calculated as the cumulative sum of the drainage at each time step.

RESULTS

As was previously stated, although preliminary data was collected from the Mountview Park site, analysis results presented herein are with regard to the SCIF 4 site only.

Volume Reduction

Results of the inflow volume calculations using Manning's equation for open channel flow are summarized in Table 2 for each storm event. An example of the calculated cumulative volume is illustrated in Figure 13 for the 8/31/12 storm event. The inflow dataset for the 5/26/12 storm event was corrupted and thus unusable in the analysis. The dataset for the 10/25/12 storm event is only half complete due to an error in the data which was likely caused by lodging of debris in the sensor. The results are reviewed further in the Discussion section.

Table 2. Cumulative Inflow Results

Storm Event	Precipitation (mm)	Cumulative Inflow (m^3)	Cumulative Inflow (gal)
5/26/12	9.7	-	-
8/31/12	6.9	29.49	7,790
9/1/12	3.8	21.05	5,561
9/25/12	5.3	22.64	5,981
10/12/12	20.1	231.20	61,077
10/25/12	9.7	19.82 (Sensor Malfunction)	5,236

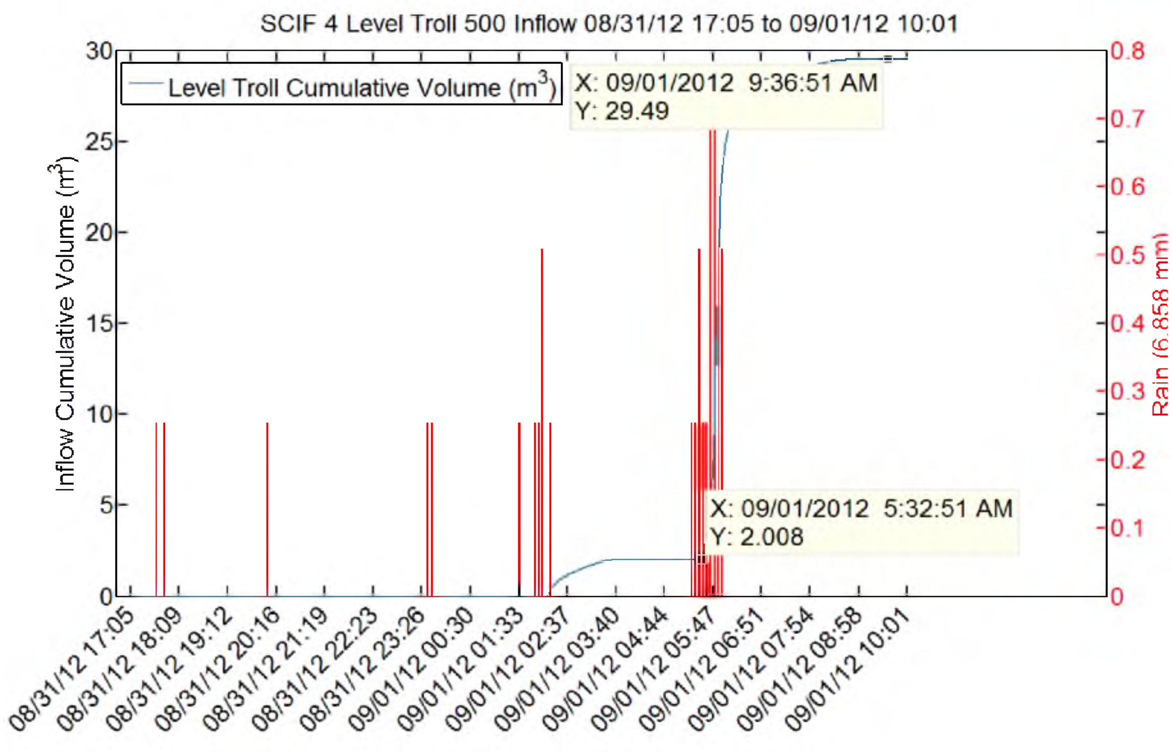


Figure 13. Cumulative Inflow, 8/31/12 Storm Event

Infiltration

Vertical Infiltration Rates

Multiple methods and datasets were used to calculate vertical infiltration rates at multiple locations throughout the site. Firstly, the recession rates of the water levels in the storage layer were calculated using each of the six Levelogger datasets. Secondly, the infiltration rates in the topmost 0.6 m (2 ft) of underlying subsoil were calculated using the Levelogger datasets and the soil moisture data from sensors located at the 0.6 m (2 ft) depth. Thirdly, infiltration rates in the deep subsoil were calculated using data from the soil moisture sensors located at the 1.8 m (6 ft) and 3.7 m (12 ft) depths. Figure 14 shows the Levelogger data for the 5/26/12 storm event. As shown, the water levels were plotted against the rain event, indicating the response time of the storage layer. Figure 14 is an example of the many different plots that were generated for each storm event. The image shows custom data tips displayed at the peak and steady state times for the Levelogger well nearest the inlet of the basin. In a similar fashion, timestamps were plotted for all six Levelogger wells individually. Only one image is shown here; additional plots are included for completeness in Appendix A.

Average infiltration rates calculated from the Levelogger datasets are plotted in Figure 15 for six storm events between May and October of 2012. The 25th percentile, median, and 75th percentile values were calculated and are plotted in Figure 16 with error bars indicating the maximum and minimum values.

Average infiltration rates in the topmost 0.6 m (2 ft) of subsoil were calculated from soil moisture rise times as shown in the example plot of Figure 17 for the 5/26/12 storm event.

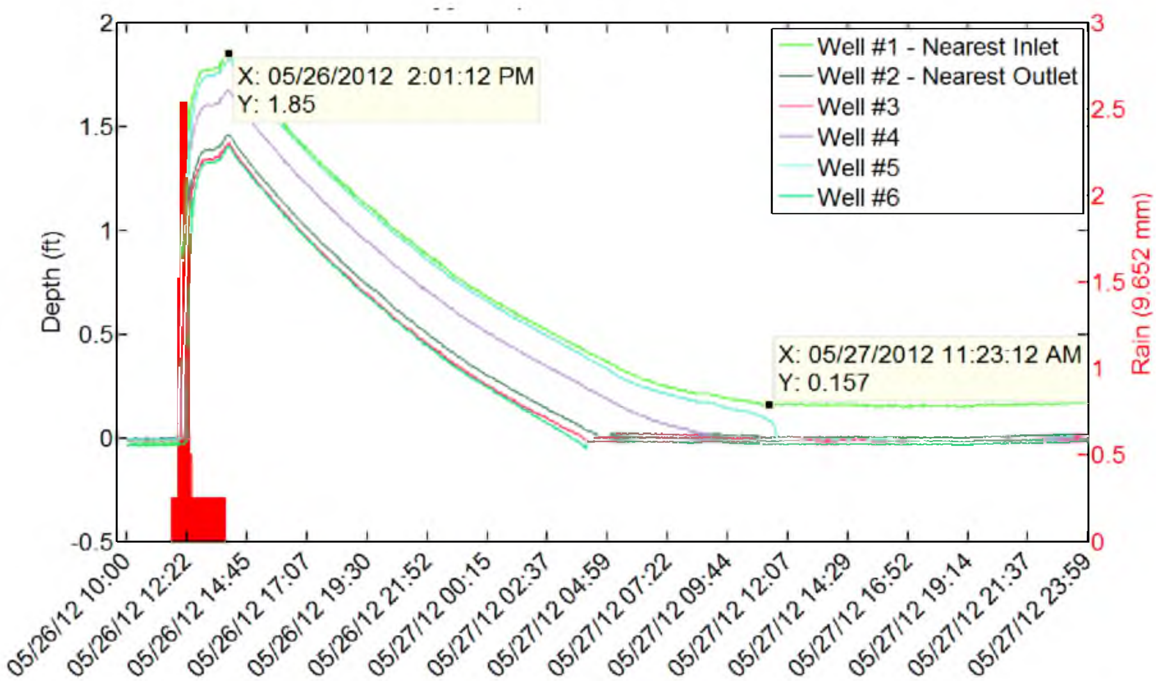


Figure 14. Storage Layer Water Depth from Levelogger Sensors, 5/26/12 Storm Event

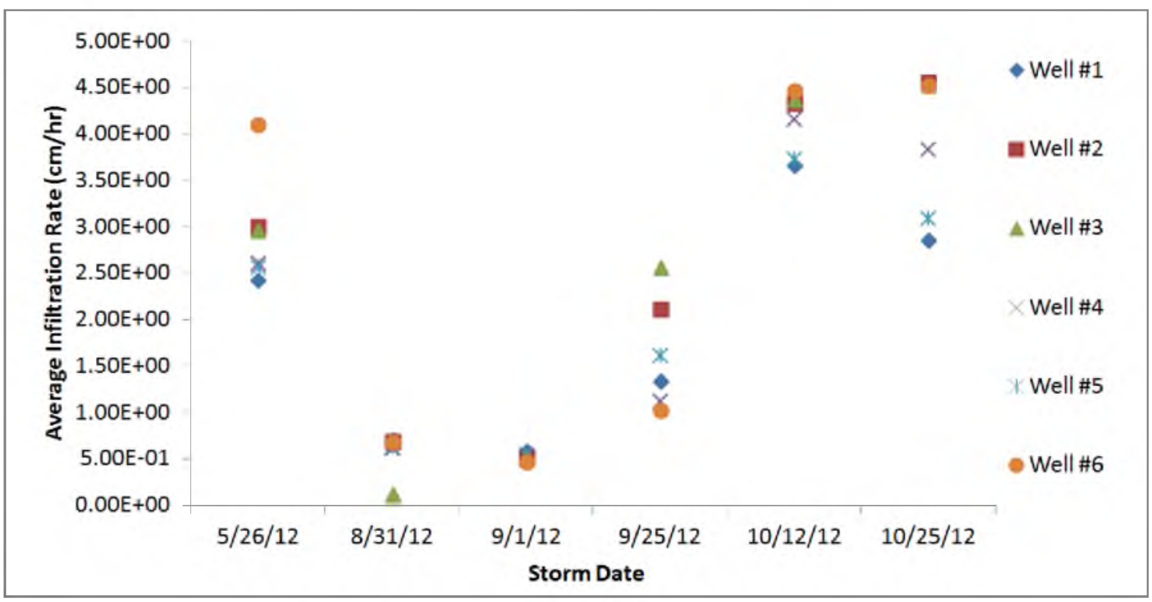


Figure 15. Average Vertical Infiltration Rates Calculated from Levelogger Datasets

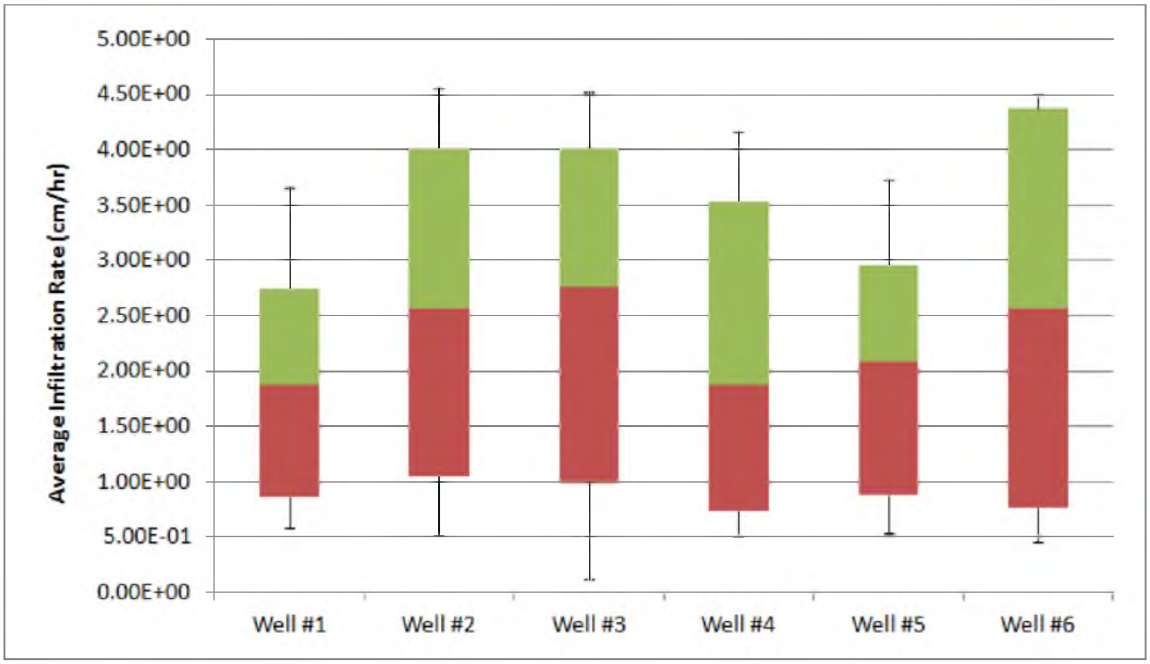


Figure 16. Box Plot for Average Vertical Infiltration Rates Calculated from Levelogger Datasets; Error Bars Indicate Maximum and Minimum Values

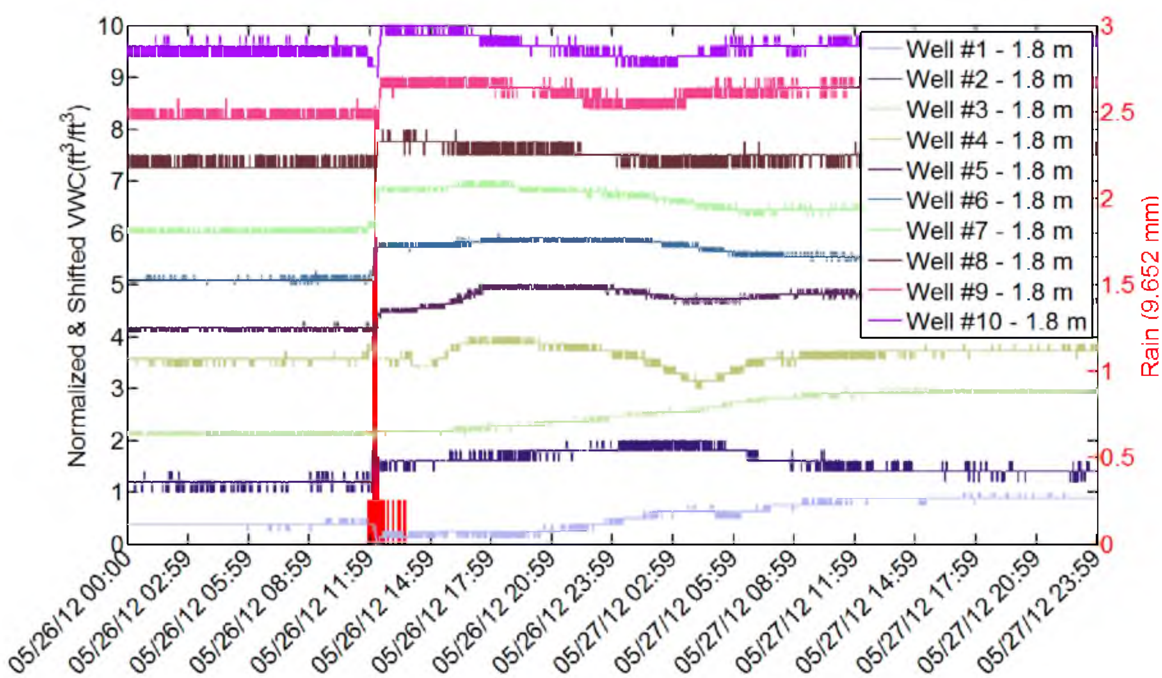


Figure 17. Soil Moisture Data, Wells 1-10, 1.8 m Depth, 5/26/12 Storm Event

Infiltration rates are plotted in Figure 18. The 25th percentile, median, and 75th percentile values were calculated and are plotted in Figure 19, with error bars indicating the maximum and minimum values.

These rates were calculated using the time at which the soil moisture sensors located at the 1.8 m (6 ft) depth (0.6 m below the Utelite storage layer) showed a spike in soil moisture. The starting times for each calculation were taken as the time at which the nearest Levelogger sensor began to show a rise in storage level. The variation in calculated rates between Figure 15 and Figure 18, and the dependence on the methods employed is addressed further in the Discussion section.

Average infiltration rates for the 2.4 m (8 ft) of subsoil between the 1.8 m (6 ft) and 3.7 m (12 ft) soil moisture sensors were calculated from plots such as that shown in Figure 20 (note that the data tip timestamps for the rise of each curve are omitted here for clarity). The calculated rates are plotted in Figure 21. Additional plots of the soil moisture data for each storm event are included in Appendix A.

The 25th percentile, median, and 75th percentile values were calculated and are plotted in Figure 22. As a redundant measure of infiltration performance, three passive capillary lysimeters captured direct measurements of volumetric drainage in the subsoils. Lysimeters 1 and 3 were located near the ends of the basin, with lysimeter 2 located in the center. Data from lysimeter 2 were not obtained for some storms due to a sensor malfunction, so lysimeter 2 was discarded from the analysis. The plotted cumulative infiltration for an example storm on May 26th, 2012 is shown in Figure 23. Infiltration rate results for two of the lysimeters are shown in Figure 24, with cumulative drainage results illustrated for each storm event in Figure 25.

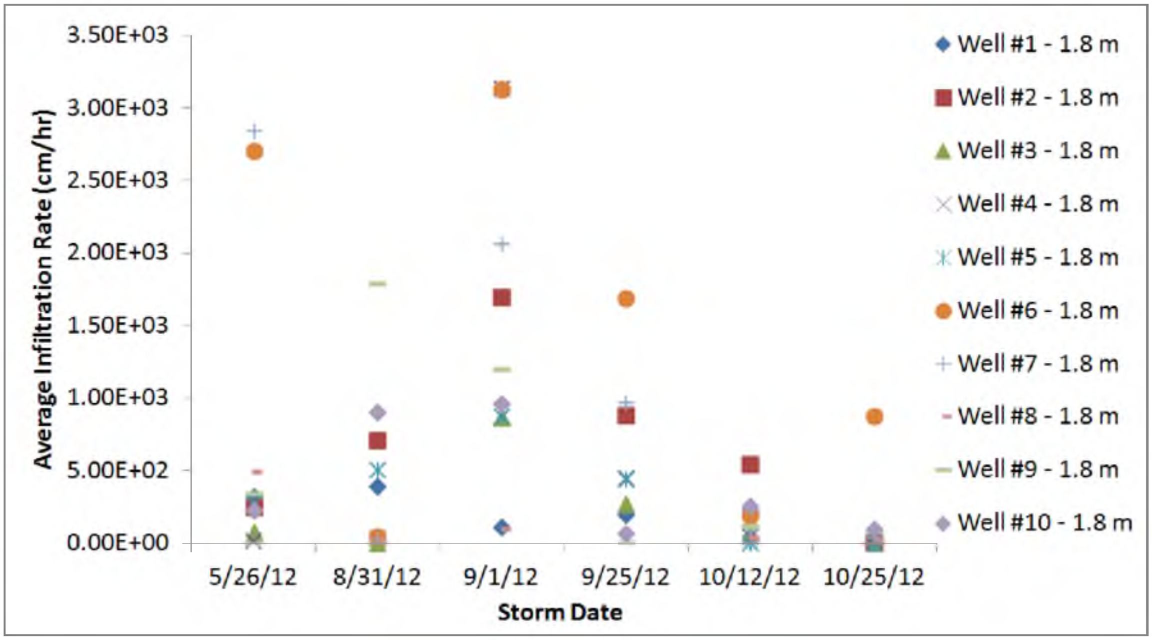


Figure 18. Average Vertical Infiltration Rates Calculated from Soil Moisture Sensors at the 1.8 m Depth (0.6 m Below the Ultelite Storage Layer)

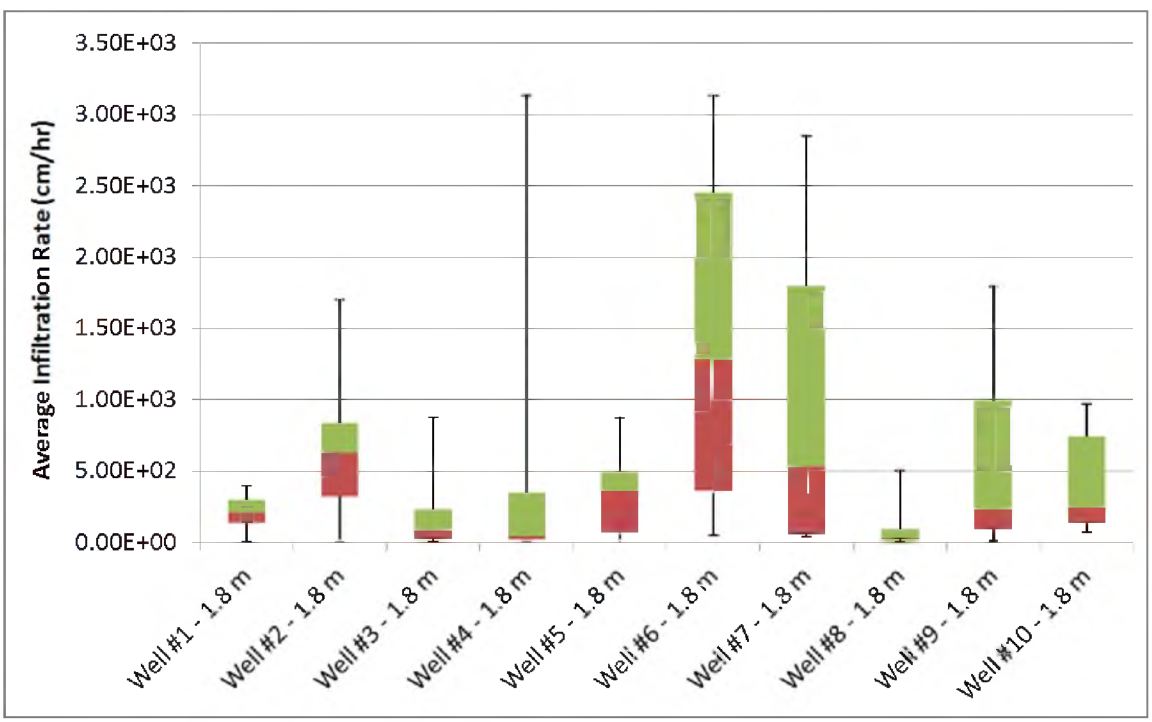


Figure 19. Box Plot for Average Vertical Infiltration Rates Calculated from Soil Moisture Sensors at the 1.8 m Depth (0.6 m Below the Ultelite Storage Layer)

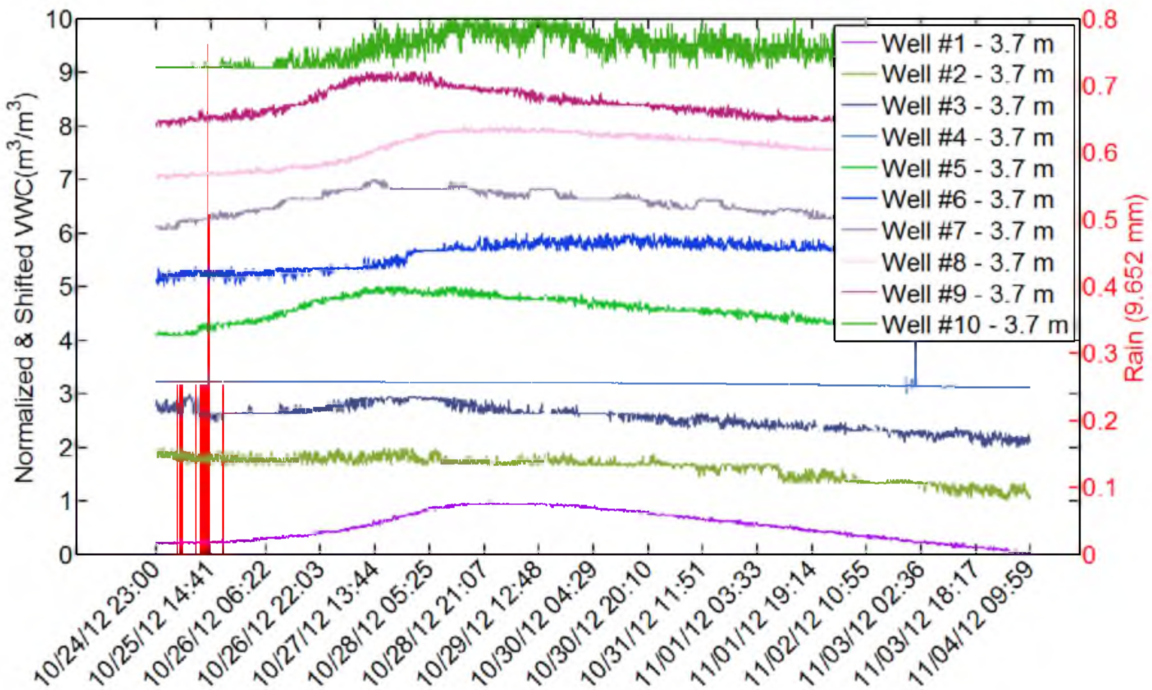


Figure 20. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 10/25/12 Storm Event

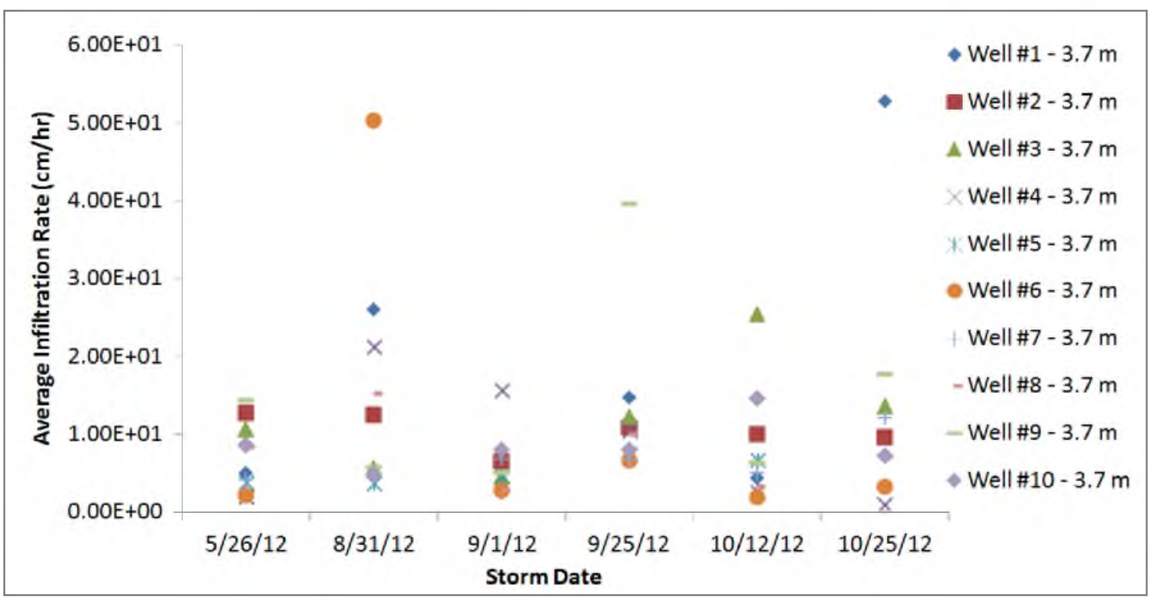


Figure 21. Average Vertical Infiltration Rates Calculated from Soil Moisture Sensors at the 1.8 m (0.6 m Below the Utelite Storage Layer) and 3.7 m Depths (2.4 m Below the Utelite Storage Layer)

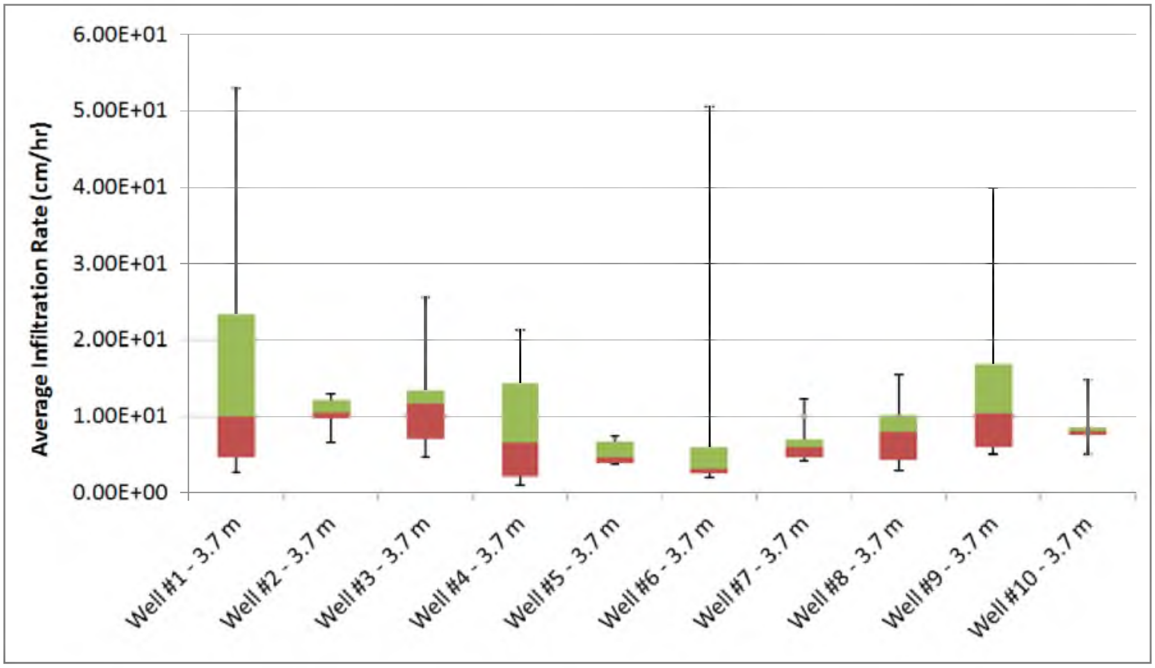


Figure 22. Box Plot for Average Vertical Infiltration Rates Calculated from Soil Moisture Sensors at the 1.8 m (0.6 m Below the Utelite Storage Layer) and 3.7 m Depths (2.4 m Below the Utelite Storage Layer)

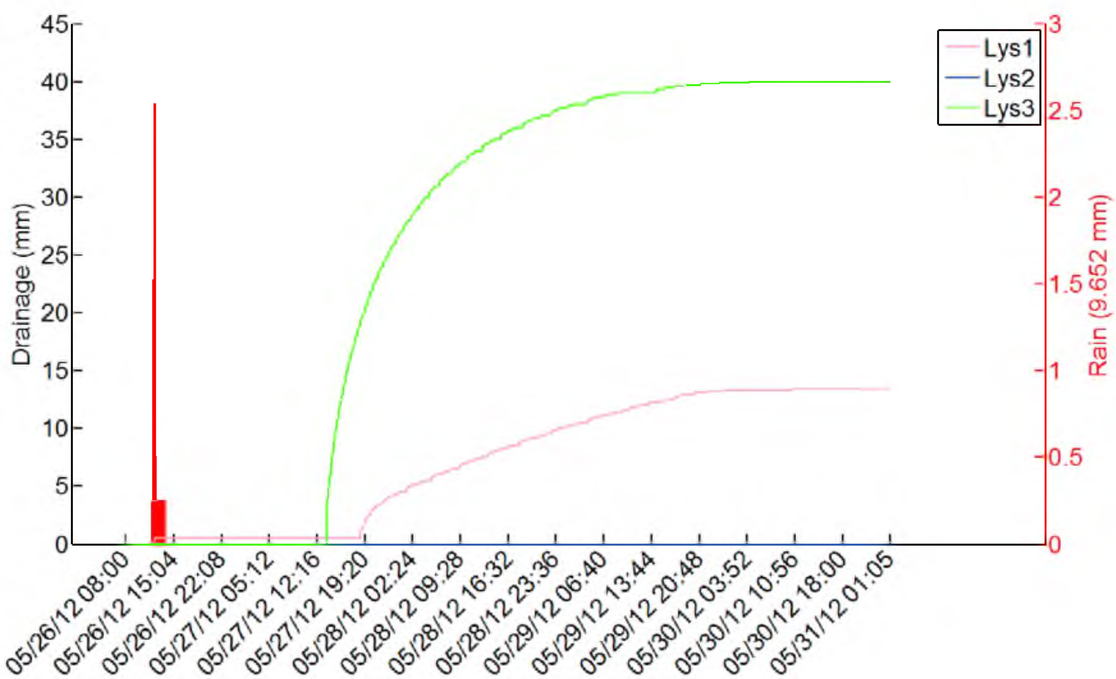


Figure 23. Lysimeter Cumulative Drainage for the 5/26/12 Storm Event

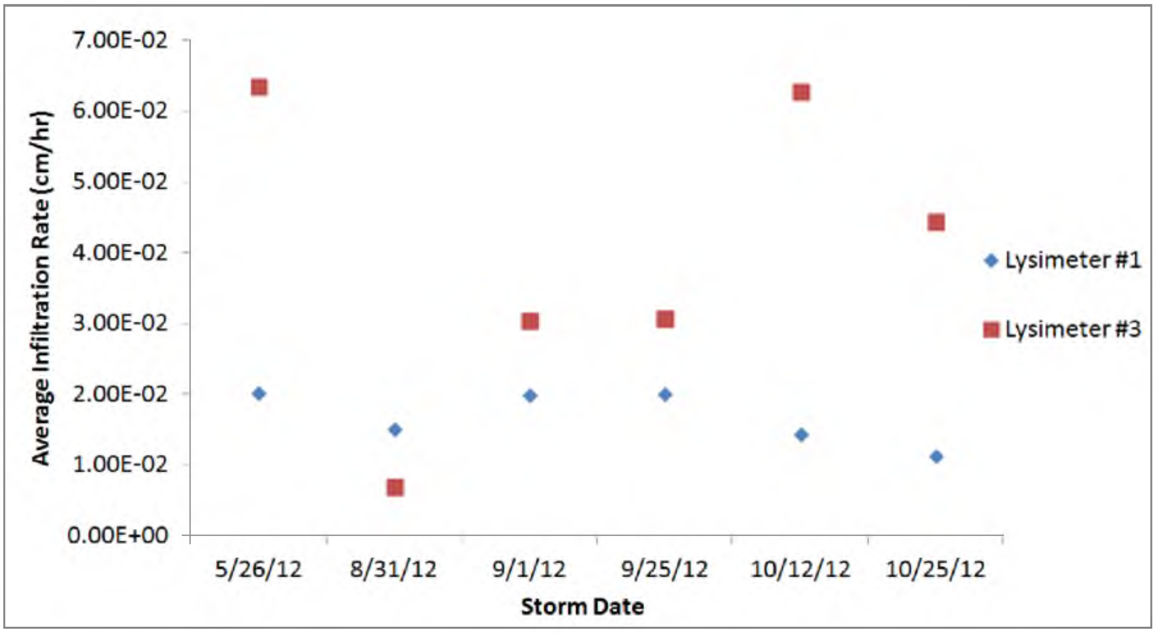


Figure 24. Lysimeter Average Vertical Infiltration Rates

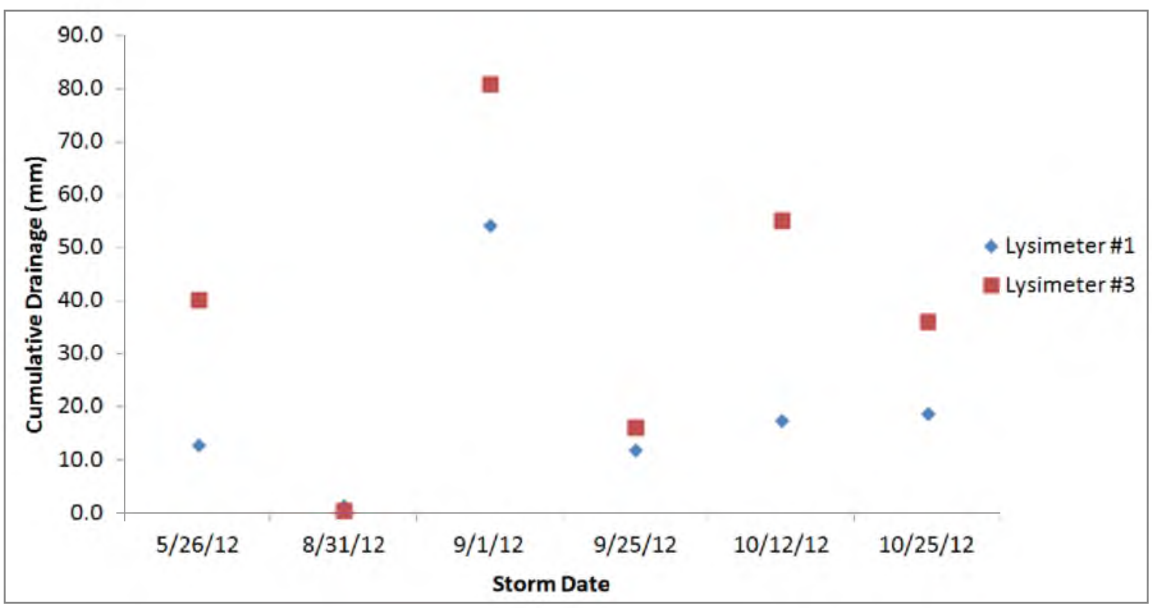


Figure 25. Lysimeter Cumulative Drainage

Horizontal Infiltration Rates

It should be noted that the term "infiltration" technically refers to transport between surface and subsurface; it is used throughout this thesis in a more general sense including subsurface lateral seepage which may be more strictly referred to as "exfiltration". This simplification was made in an effort to prevent confusion among readers and in order to maintain consistent terminology between sections of this thesis.

With the available data, no perfect method was available to calculate horizontal infiltration rates. As such, a few substantial assumptions underlie the results presented in this section. Namely, the soil moisture peaks at sensors of equal depth inside and outside the basin were used in the rate calculations, assuming one-dimensional horizontal flow between the sensors. The implications of these assumptions are further addressed in the Discussion section.

As illustrated in Figure 26, horizontal infiltration rates at the 1.8 m depth (level with the Utelite storage layer) were generally between 10 and 20 cm/hr, with outliers as high as 140 cm/hr in a few storm events. The box plot of Figure 27 illustrates the range of calculated values. Figure 28 and Figure 29 show that infiltration rates at the 2.7 m depth fell in the range of approximately 10 cm/hr to 75 cm/hr with outliers as high as 550 cm/hr. At the 4.6 m depth, infiltration rates were generally between 10 and 20 cm/hr with outliers as high as about 100 cm/hr as shown in Figure 30 and Figure 31.

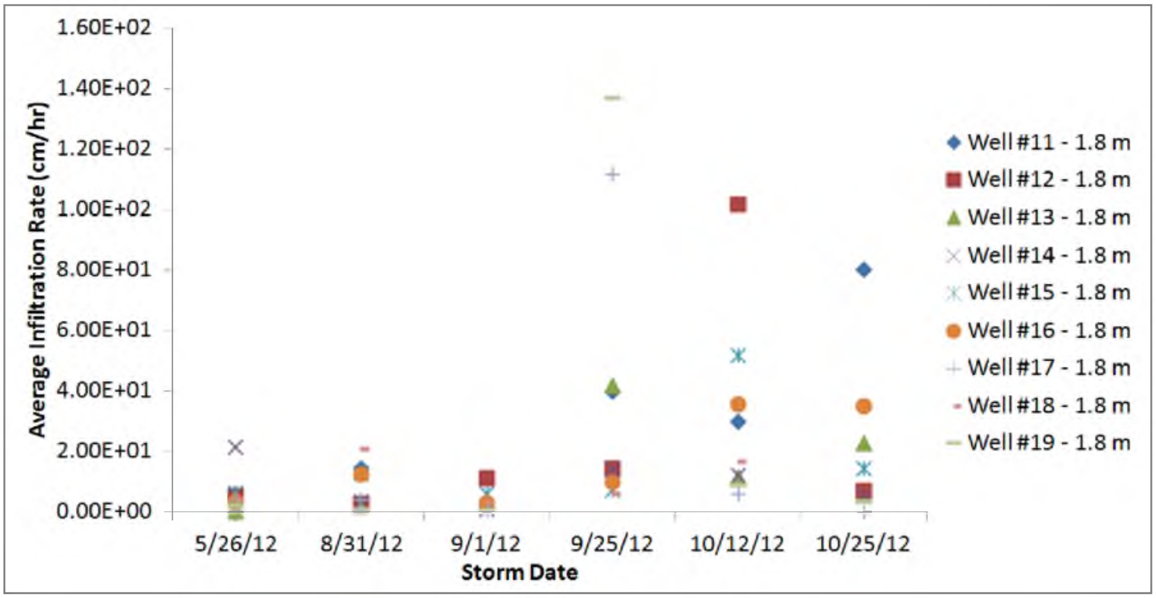


Figure 26. Average Horizontal Infiltration Rates Calculated from Soil Moisture Sensors at the 1.8 m Depth Outside the Basin

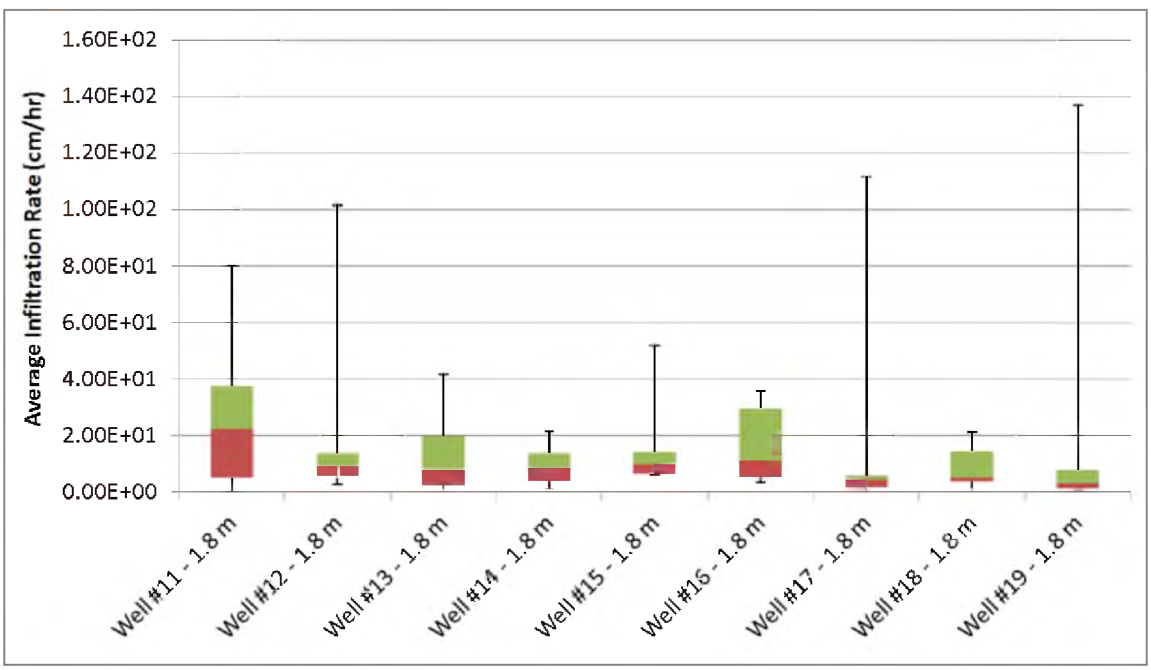


Figure 27. Box Plot for Average Horizontal Infiltration Rates Calculated from Soil Moisture Sensors at the 1.8 m Depth Outside the Basin

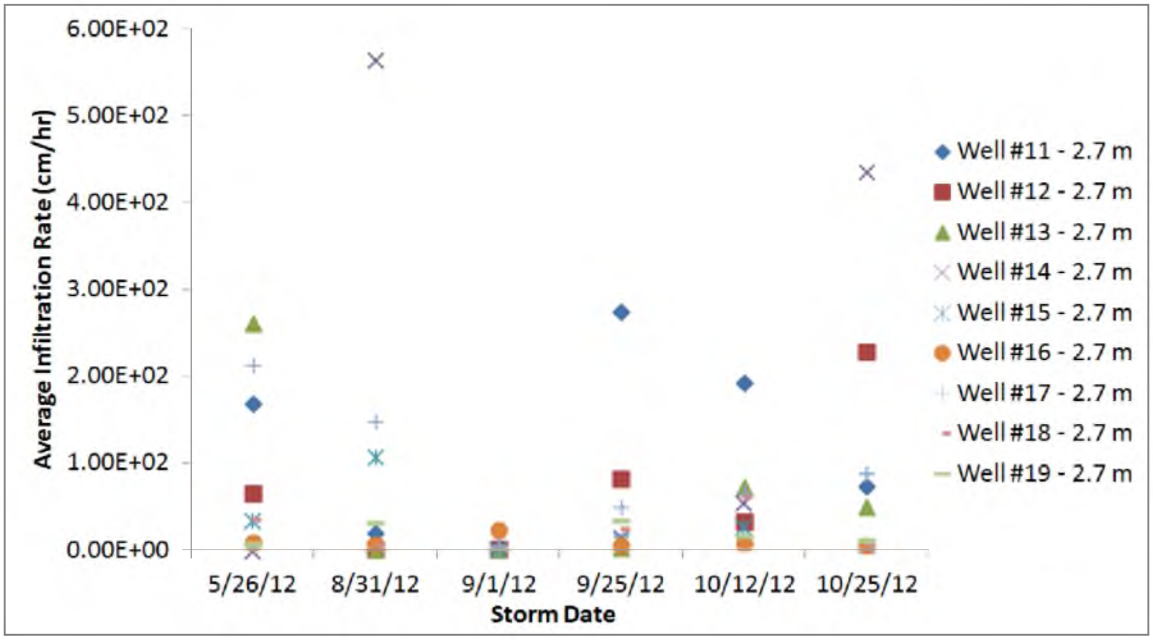


Figure 28. Average Horizontal Infiltration Rates Calculated from Soil Moisture Sensors at the 2.7 m Depth Outside the Basin

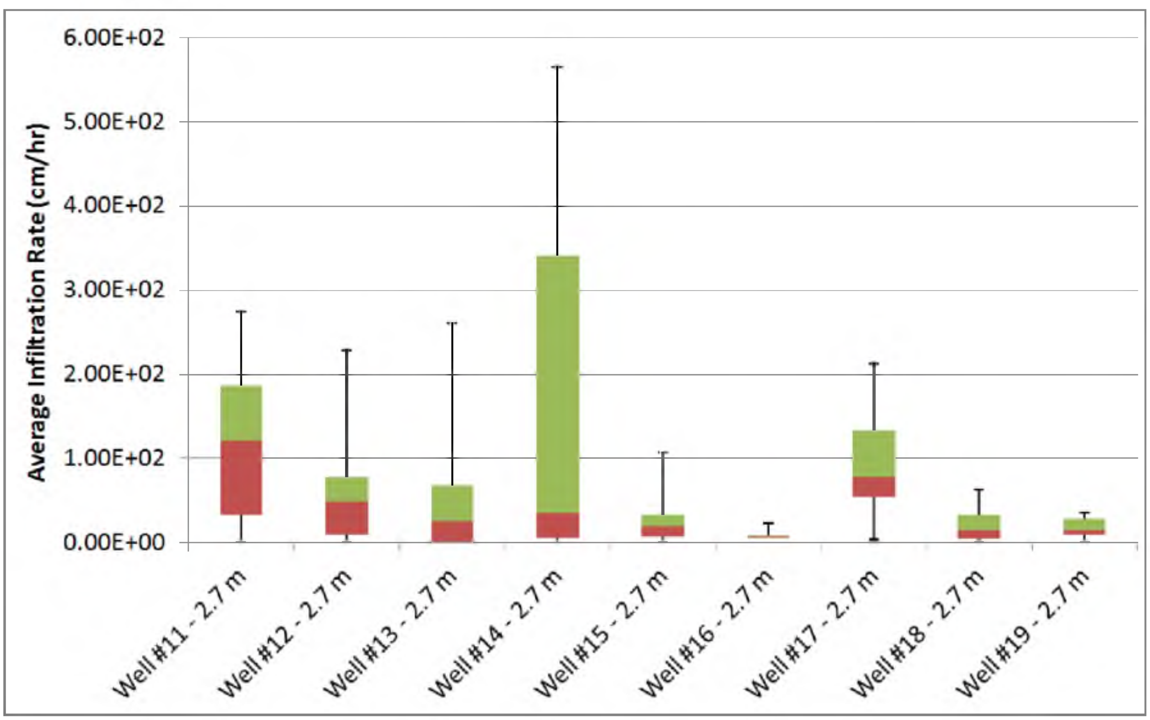


Figure 29. Box Plot for Average Horizontal Infiltration Rates Calculated from Soil Moisture Sensors at the 2.7 m Depth Outside the Basin

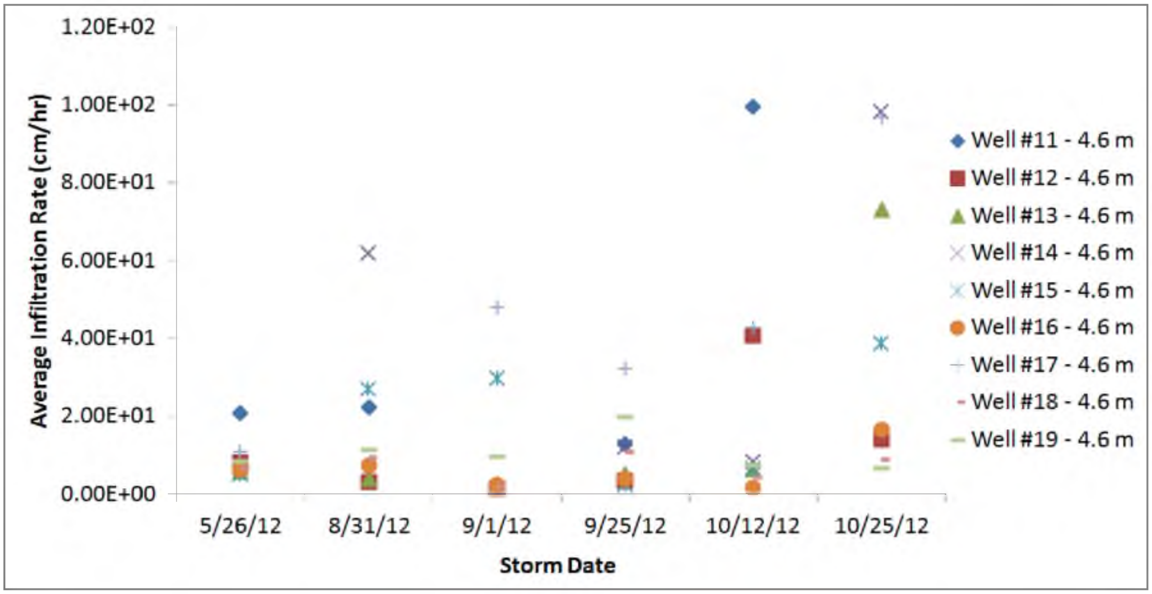


Figure 30. Average Horizontal Infiltration Rates Calculated from Soil Moisture Sensors at the 4.6 m Depth Outside the Basin

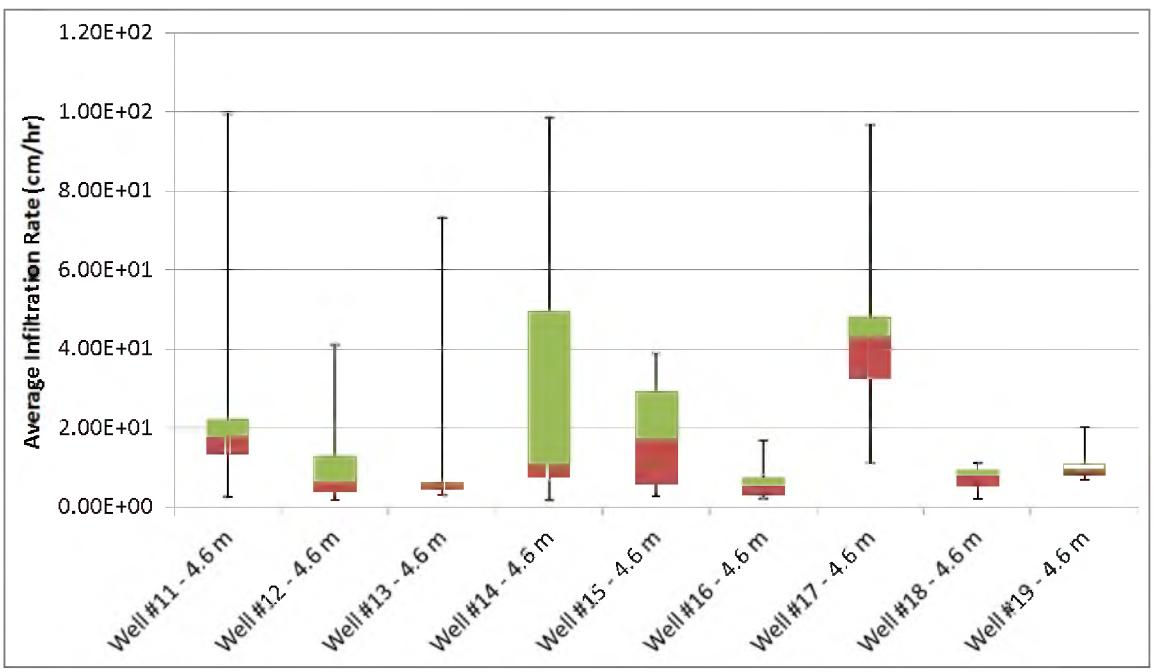


Figure 31. Box Plot for Average Horizontal Infiltration Rates Calculated from Soil Moisture Sensors at the 4.6 m Depth Outside the Basin

DISCUSSION

Volume Reduction

The bioretention cell proved to be capable of retaining and infiltrating substantial volumes of stormwater due to its underground storage capacity of approximately 37 m^3 (9,774 gal) and relatively high infiltration rates characteristic of the underlying sandy soils. An important component of the design was the Utelite forebay which allowed the majority of influent to immediately percolate down to the storage layer; substantial overflow from the forebay onto the surface of the basin and temporary surface ponding was only observed during the 10/12/12 storm event and during a few subsequent larger storm events. The highly porous forebay conveyed the water rapidly underground, enhancing the system's ability to retain large volumes of water.

As was shown in Table 2, the 8/31/12, 9/1/12, and 9/25/12 storm events produced reasonable inflow volumes equal to 67%, 86%, and 66% respectively of the maximum volumes expected from simple hand calculations based on the watershed area and precipitation. The 10/25/12 storm event dataset clearly showed a sensor malfunction halfway through the event. The 19.82 m^3 of inflow recorded up until that point was reasonable for the amount of precipitation prior to that time step; one could reasonably anticipate a total inflow volume in the 35 m^3 to 45 m^3 range, which would still be within the basin's storage capacity considering the total Utelite storage volume and infiltration rates. The 10/12/12 storm event dataset showed an inflow volume of 231 m^3 which seems unreasonably high based on what could be expected from simple hand calculations. However, the precipitation event was substantially larger than any other observed event, thus causing a much more substantial and sustained inflow over a much longer duration (consistently flowing at an average depth of 5 cm for 8 hrs before receding). The dataset was examined for possible sensor errors and none were identified. It is hypothesized that the large inflow during this storm was also partially attributable to runoff from the second half of the parking lot uphill of the storm drains used as the up-gradient boundary of the watershed. The runoff from this upper parking lot was likely so substantial that it overran the storm drains and connecting gutters, entered the study watershed, and flowed to the bioretention basin inflow pipe. In effect, this would mean flow would have originated from an area almost double the delineated watershed area, and the 231 m^3 inflow volume would then be feasible. During this storm event, surface ponding could be observed throughout the basin for at least 24 hrs afterwards, but no direct overflow to the traditional infrastructure was observed.

None of the six storm events resulted in overflow to the traditional infrastructure, although a few larger events which occurred in November 2012 may have caused some overflow as evidenced by debris trails observed near the outlet after those storms.

Infiltration

Vertical Infiltration Rates

Generally, infiltration rates calculated from the Levelogger data are in agreement across each of the six well locations (as seen by the close groupings in Figure 15) with slight variation in absolute value across storm events. Even so, the six storm events examined show rates that are between approximately 0.5 cm/hr and 5 cm/hr across the board, which is considered good agreement for this study because of the methods used and the oftentimes highly heterogeneous nature of underlying subsoils.

The results calculated for the topmost 0.6 m (2 ft) of subsoil as shown in Figure 18 indicate infiltration rates on the order of 500 cm/hr with outliers in soil moisture well # 6 as high as 3,000 cm/hr. These rates seem very high at first compared to the overall recession rates calculated with the Levelogger datasets, and would be representative of a coarse sand material as shown in Table 3. However, such high values could be expected in the 0.6 m of subsoil directly beneath the storage layer because the overlying total hydraulic head is largest during the short timeframe over which the average is calculated, and the infiltrating distance (0.6 m) is small. Additionally, the basin subsoils are very heterogeneous as they are largely composed of backfilled materials. Mixtures of clay, loam, silt, and sand were observed during construction of the site.

Table 3. Typical Hydraulic Conductivities for Earthen Materials

	K (m/s)			K (cm/s)			K (cm/hr)		
Material	Low	High	Average	Low	High	Average	Low	High	Average
Gravel	3.00E-04	3.00E-02	1.52E-02	3.00E-02	3.00E+00	1.52E+00	1.08E+02	1.08E+04	5.45E+03
Coarse Sand	9.00E-07	6.00E-03	3.00E-03	9.00E-05	6.00E-01	3.00E-01	3.24E-01	2.16E+03	1.08E+03
Medium Sand	9.00E-07	5.00E-04	2.50E-04	9.00E-05	5.00E-02	2.50E-02	3.24E-01	1.80E+02	9.02E+01
Fine Sand	2.00E-07	2.00E-04	1.00E-04	2.00E-05	2.00E-02	1.00E-02	7.20E-02	7.20E+01	3.60E+01
Silt, Loess	1.00E-09	2.00E-05	1.00E-05	1.00E-07	2.00E-03	1.00E-03	3.60E-04	7.20E+00	3.60E+00
Till	1.00E-12	2.00E-06	1.00E-06	1.00E-10	2.00E-04	1.00E-04	3.60E-07	7.20E-01	3.60E-01
Clay	1.00E-11	4.70E-09	2.36E-09	1.00E-09	4.70E-07	2.36E-07	3.60E-06	1.69E-03	8.48E-04
Marine Clay	8.00E-13	2.00E-09	1.00E-09	8.00E-11	2.00E-07	1.00E-07	2.88E-07	7.20E-04	3.60E-04

Adapted from Table 3.4 in *Fundamentals of Groundwater* by Franklin W. Schwartz, Hubao Zhang

The results for the deeper subsoil indicate average infiltration rates generally between 1 cm/hr and 17 cm/hr with outliers as high as 50 cm/hr. The results more closely match those obtained from the Levelogger datasets but span a slightly larger range. Rates in this range generally indicate fine sandy subsoils with some potentially silty or loamy areas, as was confirmed through observation during construction. Again, these data are closely grouped for each storm event as shown in Figure 21, indicating acceptable agreement in calculated values across a wide range of spatially varied measurement locations. These data also show more consistent infiltration rates from storm to storm than were calculated from the Levelogger datasets (i.e., any given well produced consistent calculated infiltration rates for each of the six storm events).

The variance in the infiltration rates of the deeper subsoil can be seen in Figure 22. Generally, most soil moisture wells produced a range of infiltration rates which varied by less than an order of magnitude. Namely, wells numbered 1, 5, 6, 7, 8, 9, and 10 produced rates which varied by no more than 10 cm/hr across all measurements. Such close agreement between measurements is deemed very good given the methods used, the highly heterogeneous subsoils, and the substantial variation (i.e. orders of magnitude) in hydraulic conductivity which can often be expected across spatial areas even as small as this study site. Wells numbered 2, 3, and 4 produced calculated infiltration rates which varied slightly more but were still very good (between 1cm/hr and 17 cm/hr).

Results from the lysimeters produced infiltration rates two orders of magnitude less than those calculated from the Levelogger data and soil moisture data. Whereas the Levelogger data and soil moisture data produced reasonable results characteristic of materials ranging from silt to medium sand, the lysimeters produced results characteristic of till or clayey material. These differences are likely due to compaction of the lysimeter soil monolith core during installation. The 60 cm diameter diversion control tube had to be gently pushed into the ground with an excavator bucket to capture the soil core. In doing so, it was observed that the soil became substantially compacted within the tube. Consequently, the calculated infiltration rates through the lysimeters are likely not representative of the true infiltration rates of the surrounding soils. Additionally, due to the compaction of the core, the total volumetric drainage through the lysimeters never exceeded 90 mm^3 during any storm event. This volume is lower than expected for the volume of water entering the basin, and further highlights the potential errors introduced due to compaction of the core sample. These discrepancies highlight potential problems with using the Gee passive capillary lysimeters in this application and particularly with the installation method used in this study. Additionally, it is hypothesized that the lysimeters did not effectively capture the infiltrating moisture but instead were affected by preferential flow paths that may have developed external to the diversion control tube, thus allowing much of the water to bypass the lysimeters. This again highlights potential problems with the lysimeter installation. With an improved installation method, the Gee lysimeters could potentially be used in similar applications with better results. As such, the lysimeter results are included for completeness, but should be considered with caution.

Horizontal Infiltration Rates

Horizontal infiltration rates at the 1.8 m depth, 2.7 m depth, and 4.6 m depth were generally less than 100 cm/hr with the majority of the data points falling in the 1 cm/hr to 20 cm/hr range. These results were expected as they are similar to the calculated vertical infiltration rates in the area. Again, the calculated values are representative of loamy materials with fine and coarse sand mixtures, as is shown in Table 3 and as was verified during construction of the sites. At the 2.7 m depth, the results showed a larger percentage of data points between 100 cm/hr and 300 cm/hr. This could be partially due to the profile of the wetting front as it progresses laterally and downward in an arcing fashion from the basin.

Overall, the data show trends that indicate the wetting front takes 1 to 2 days (24 to 48 hrs) to reach the 1.8 m (6 ft) depth and 7 to 14 days to reach the 3.7 m (12 ft) depth below the bioretention basin. The datasets from sensors outside the basin indicate that the wetting front generally takes 1 to 2 days (24 to 48 hrs) to progress horizontally to each of the well columns spaced 0.9 m (3 ft) apart. Without additional sensors located at larger lateral distances from the basin, it is unclear exactly where the lateral extent of the wetting front ceases, but the data does clearly show that the wetting front progresses at least 3 m (10 ft) laterally in three days (72 hrs).

CONCLUSIONS

The design, construction, and instrumentation of two new bioretention cells on the University of Utah campus and in Cottonwood Heights, Utah have been presented in this thesis. Details of the experimental methodology were covered. Analysis results were reported and discussed only for the SCIF 4 site on the University of Utah campus.

The SCIF 4 bioretention cell has thrived in a mostly irrigation free environment; any irrigation received was from unintentional runoff from nearby sprinkler systems. The site required no supplemental water intake for vegetation survival. By design, the vegetation consumes the water in the storage layer, thus reducing runoff pollution and stormwater loading to traditional infrastructure.

Analysis Results

Overall, the site demonstrated substantial improvement in volume retention and infiltration over the conditions observed at the basin prior to conversion of the site to a bioretention facility. For all storm events examined, nearly 100% of the inflow volume was retained and either infiltrated, lost through evapotranspiration, or utilized by plants. Thus, it is recommended that volume reduction credits be offered in future legislation for similar semiarid bioretention sites. The credits should be based not only on surface ponding volume, but also on underground storage volume, as this research has shown the site's ability to quickly convey large inflow volumes to underground storage.

Analysis of data collected between May and November of 2012 showed that both vertical and horizontal infiltration rates were generally between 0.5 cm/hr and 20 cm/hr on the average for the loamy and sandy subsoils beneath the bioretention site. Calculated infiltration rates were variable as was expected for the heterogeneous subsoils examined, with vertical rate outliers as high as 3000 cm/hr. The data illustrate the highly heterogeneous nature of unconsolidated earthen materials, resulting in hydraulic conductivity values that typically range by several orders of magnitude across a spatial extent as large as the University of Utah campus.

Analysis results also clearly showed that the infiltrating wetting front beneath the bioretention basin takes 1 to 2 days (24 to 48 hrs) to reach the 1.8 m (6 ft) depth and 7 to 14 days to reach the 3.7 m (12 ft) depth depending on the spatial location within the basin. The datasets from sensors outside the basin indicate that the wetting front generally takes 1 to 2 days (24 to 48 hrs) to progress horizontally to each of the well columns spaced 0.9 m (3 ft) apart. The data does clearly show that the wetting front progresses at least 3 m (10 ft) laterally in 3 days (72 hrs) time, but without additional sensors located at larger lateral distances from the basin, it remains unclear exactly where the lateral extent of the wetting front ceases. As such, it is recommended that bioretention cells constructed in semiarid climates and with similar subsoils be located at least 6.1 m (20 ft) away from infrastructure such as building foundations and retaining walls to prevent unintentional seepage or damage to the infrastructure. The same recommendation applies for locating semiarid bioretention cells near slopes or graded surfaces to prevent unintentional erosion or slope failure.

The results indicate suitable infiltration performance of the semiarid bioretention design implemented in this study. The Utelite forebay was an integral component, allowing much of the inflow volume to rapidly percolate to the underground storage layer with minimal surface ponding in most storm events. As such, it is recommended that semiarid bioretention cells utilize engineered topsoil layers only as a means of improving water quality; natural soil backfill was sufficient for infiltration performance at the SCIF 4 site analyzed in this study.

On a larger scale, the project serves as a visible example of successful implementation of decentralized stormwater management and low impact development methods in Utah's semiarid climate. The project supports current research being conducted by the University of Utah Civil and Environmental Engineering Department, with potential for additional bioretention research studies in the future.

Benefits to the State

Oftentimes, legal, social, and political barriers prevent the implementation of low impact development methods, such as bioretention, across a greater scale within a watershed or region. Specifically, the effects of bioretention and decentralized stormwater management on groundwater recharge are often viewed as potential risks to a project because of unknown vertical and lateral infiltration volumes. The results of this research study will help educate citizens, policy makers, and water resources professionals on the effects of bioretention on infiltration and potential groundwater recharge in Utah's semiarid climate. It is hoped that this will lead to improved designs, modified policies, and improved longterm effectiveness of bioretention systems in Utah.

In addition, due to the Mountview Park project's integration within a community setting, it has served as a notably visible example of bioretention implementation in Utah's semiarid climate. The increased visibility has highlighted the benefits of stormwater research applied in a community setting. It also has served as an example project to accompany the soon to be released State of Utah Nonpoint Source Stormwater Management Plan.

Outreach and Education

The bioretention sites are being incorporated into university education. Drs. Pomeroy and Burian teach courses in Stormwater Management and Design, Sustainable Urban Water Engineering, and Urban Watershed Management, all of which have or will use the sites and the research data for class exercises, team projects, and lecture material to help educate the next generation of urban water engineers in Utah.

Additionally, it is anticipated that the projects will be included in two half-day bioretention workshops presented in October, 2013. The workshops are planned as part of a current National Science Foundation (NSF) research project being conducted at the University of Utah by Dr. Pomeroy. Both sessions will be presented in conjunction with the University of Utah chapter of the American Water Resources Association (AWRA) and the Utah Rivers Council and will address design, plant selection, and environmental benefits of bioretention in Utah. One of the workshops will be targeted to engineering professionals; the other workshop will be targeted to policy makers. The SCIF 4 site has been used in a number of campus tours for community leaders, policy makers, and student groups, and it was used in demonstrations and activities presented by the Urban Water Research Group to high school students in May and November, 2012.

The new bioretention sites presented in this research will be incorporated into the existing Green Infrastructure Network (GrIN) operated by the University of Utah Urban Water Research Group, led by Drs. Pomeroy and Burian. The bioretention sites will be incorporated into the GrIN website (currently under development) as well as made into locations for field visits and seminars in the Salt Lake City metropolitan area. The data from the study has been disseminated to the professional urban water engineering community in Utah through stormwater and water management related conferences and workshops. For example, preliminary results were presented at the World Environmental and Water Resources Congress (EWRI) in Albuquerque, NM in May 2012, and final results will be presented at the EWRI Congress in Cincinnati Ohio in May, 2013.

Future Research Needs

Continuation of this research is essential in order to further understand the impact of bioretention in semiarid climates on the overall water budget and environment. There exists substantial opportunity for future studies to continue the work that was begun in this study. The two newly constructed bioretention cells will serve as valuable field sites and long term case studies. Future research questions may include:

1. Are these facilities better than traditional centralized facilities at reducing stormwater runoff volume in semiarid climates? Or do the benefits stem from using them in addition or in combination with traditional infrastructure?

   Need: Comparative data from traditional grey infrastructure, possibly from a metropolitan area with a similar climate, such as Denver Colorado.

2. Can actual groundwater recharge from semiarid bioretention be modeled? Do these facilities actually recharge groundwater or do they simply reduce the peak rate and volume of stormwater runoff?

   Need: Produce and validate a numerical groundwater model using the two sites and the data collected in this study. Additional appropriate techniques might include the Zero-Flux Plane (ZFP) method or various isotopic tracer methods as described by Scanlon *et al.* (2002) for thick vadose zones.

3. How far away does seasonal groundwater need to be from the bottom of the bioretention before it reduces the infiltration and groundwater recharge effectiveness?

   Need: Produce and validate a numerical groundwater model using the two sites and the data collected in this study. Model multiple groundwater levels and study the effect of the water table on the bioretention infiltration effectiveness.

4. Is infiltration and potential groundwater recharge effectiveness reduced at the interface with the native subsoils?

   4a. Does clogging and compaction have an effect?

   4b. What is the minimum porosity needed of the underlying soils for effective infiltration and potential groundwater recharge?

   Need: During construction of the next Utah bioretention field facility, collect samples and soil compaction data and measure the porosity at locations across the facility. Construct the facility such that the interface of storage media and subsoils is accessible for long term data collection.

5. How does maintenance of these facilities compare to traditional infrastructure?

Need: Record detailed maintenance log of the bioretention facilities for a period of one year. Obtain comparative data for traditional retention/detention facilities, and compare with the bioretention data.

6. What is the impact of vegetation configuration on biodiversity (i.e. macro invertebrate species richness)? Determination of bioretention's associated impacts on biodiversity in semiarid climates will allow for increased perception of benefits as compared to traditional stormwater management practices.

Need: Sample species richness at the two bioretention facilities used in this study at intervals over the course of a year. Compare the species richness at each site with nearby control sites, and with each other.

APPENDIX A

ADDITIONAL DATA PLOTS

Additional plots are included as Figure 32 through Figure 51.

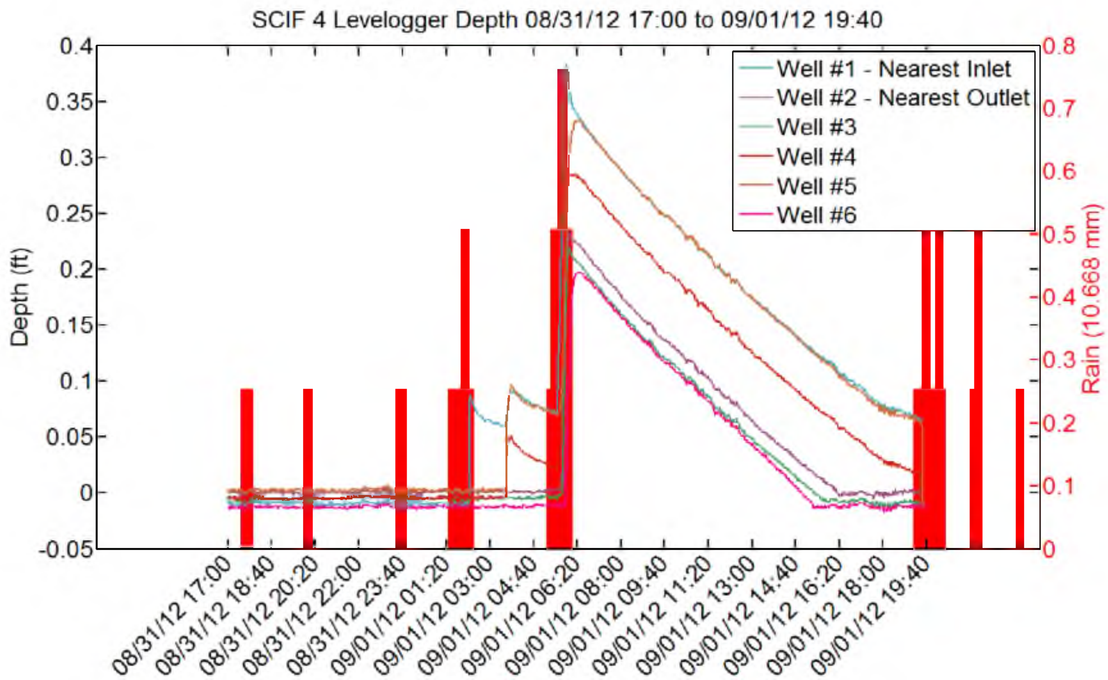


Figure 32. Storage Layer Water Depth from Levelogger Sensors, 8/31/12 Storm Event

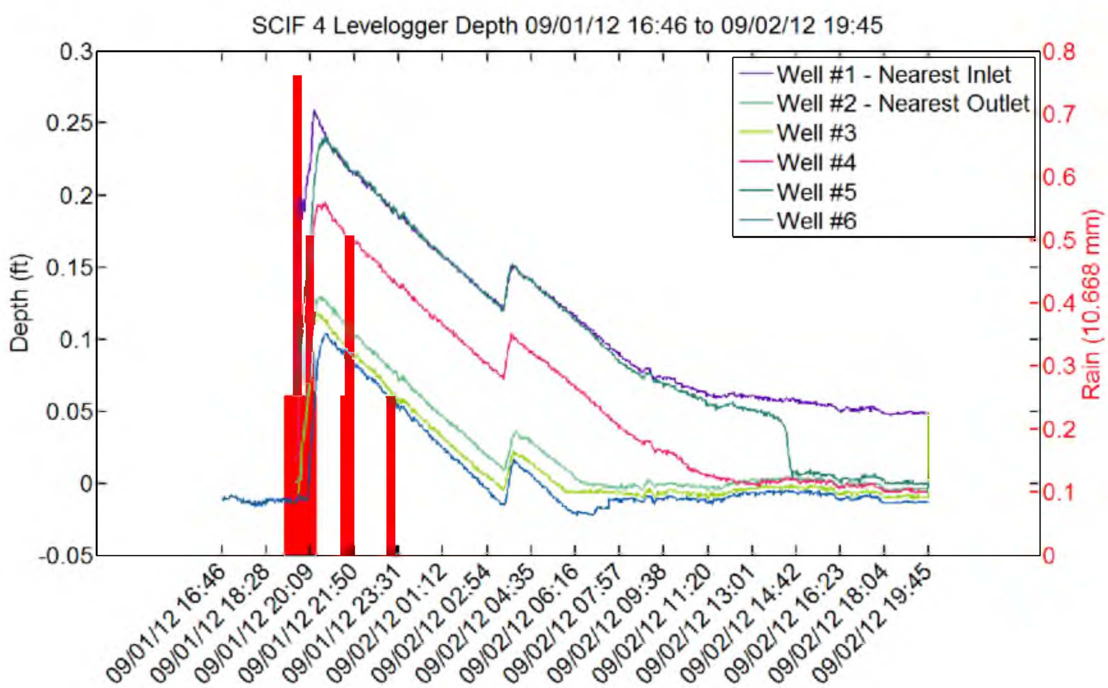


Figure 33. Storage Layer Water Depth from Levelogger Sensors, 9/01/12 Storm Event

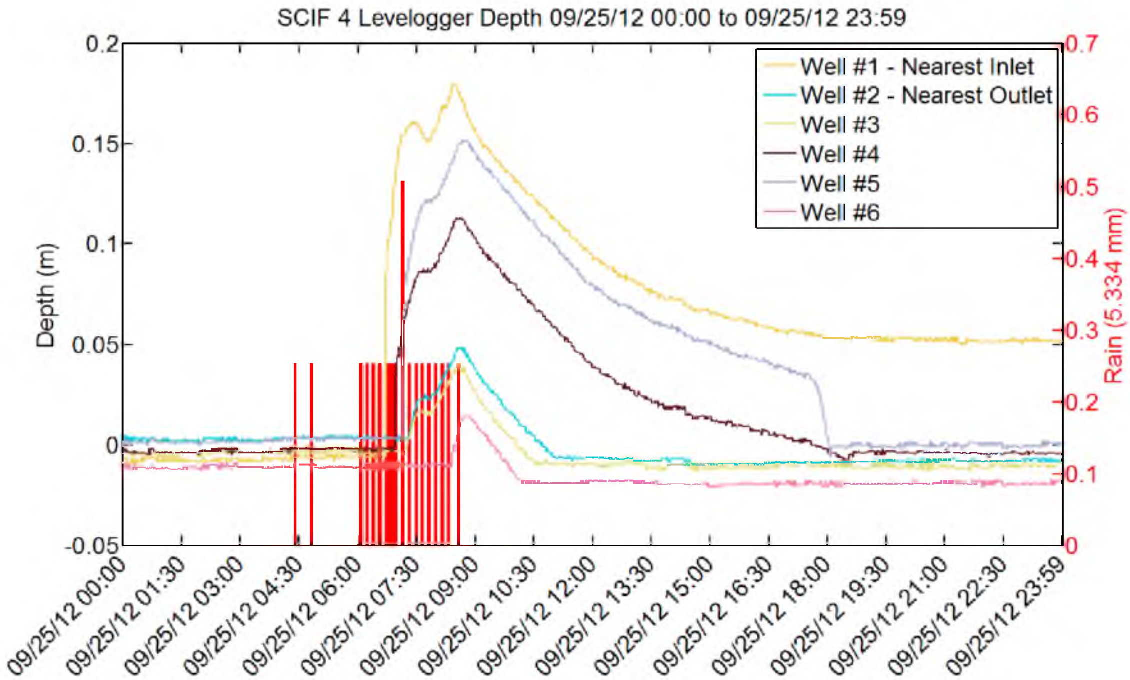


Figure 34. Storage Layer Water Depth from Levelogger Sensors, 9/25/12 Storm Event

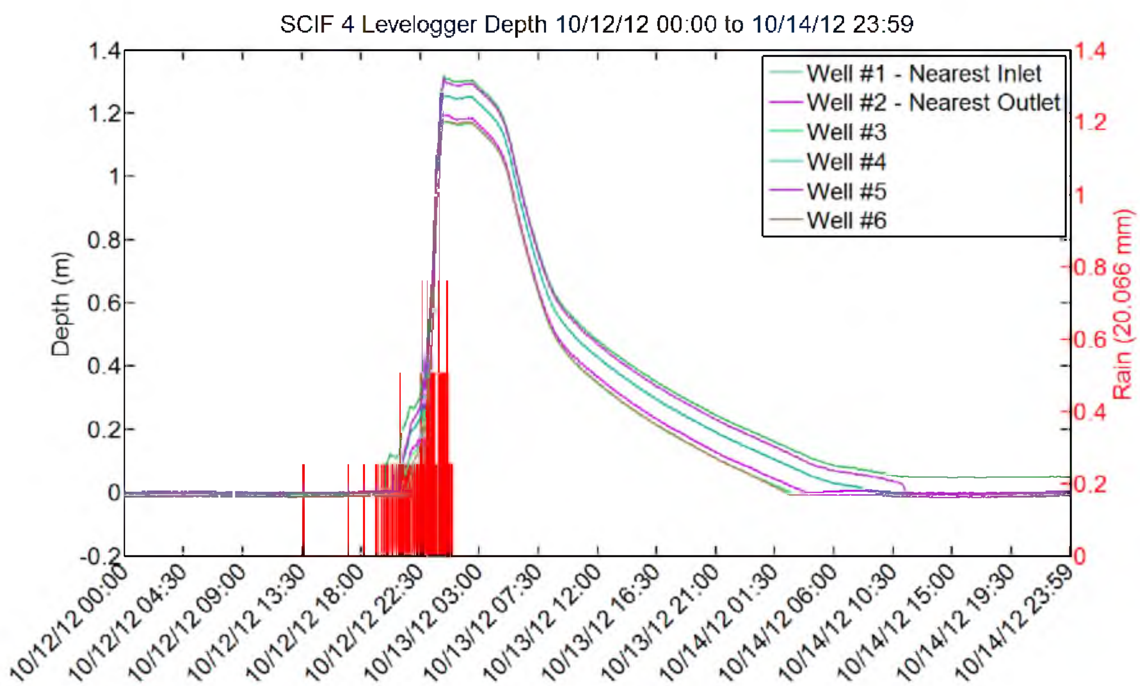


Figure 35. Storage Layer Water Depth from Levelogger Sensors, 10/12/12 Storm Event

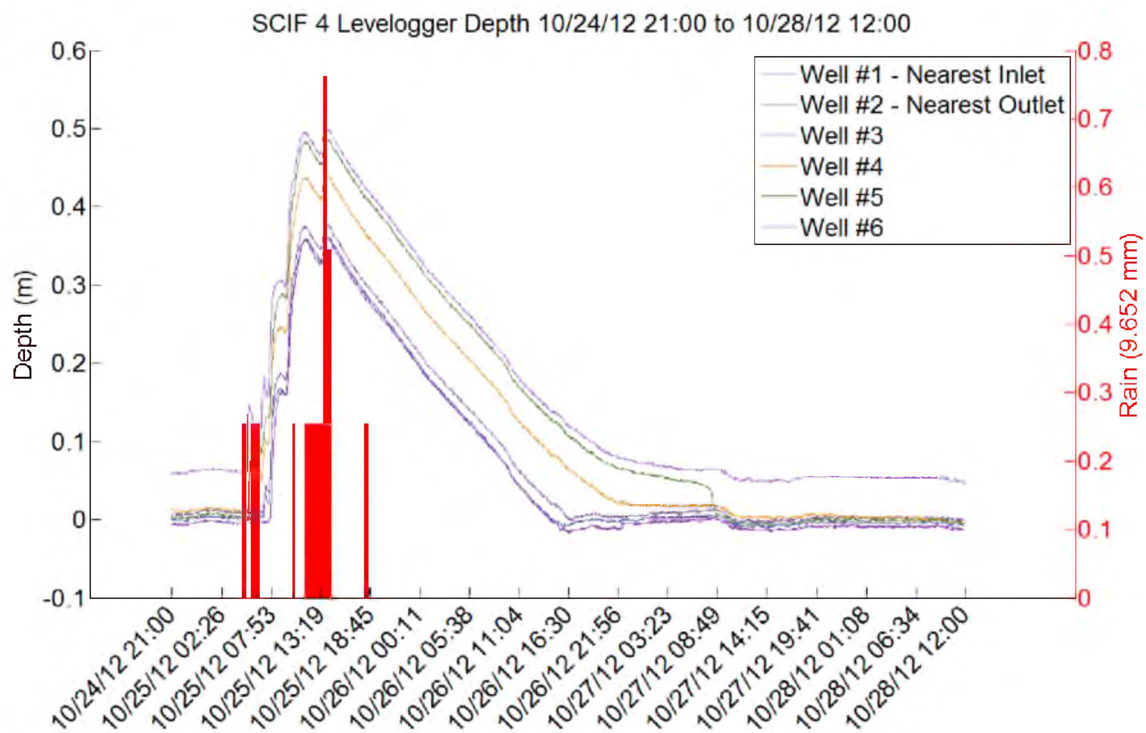


Figure 36. Storage Layer Water Depth from Levelogger Sensors, 10/25/12 Storm Event

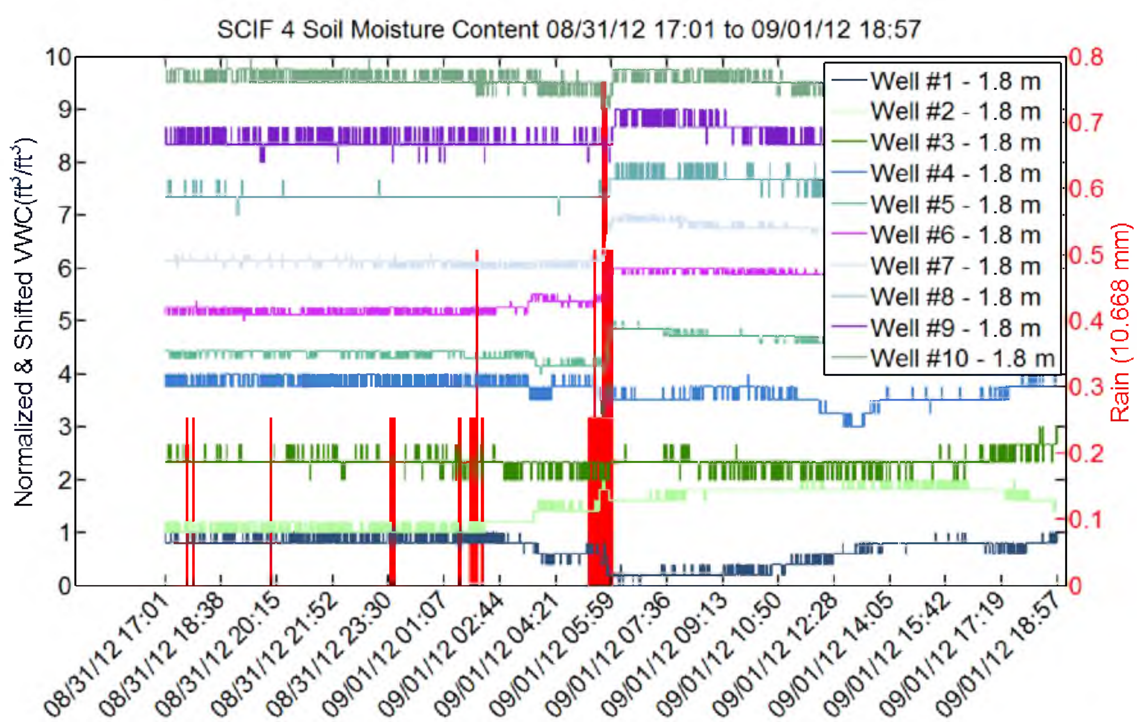


Figure 37. Soil Moisture Data, Wells 1-10, 1.8 m Depth, 8/31/12 Storm Event

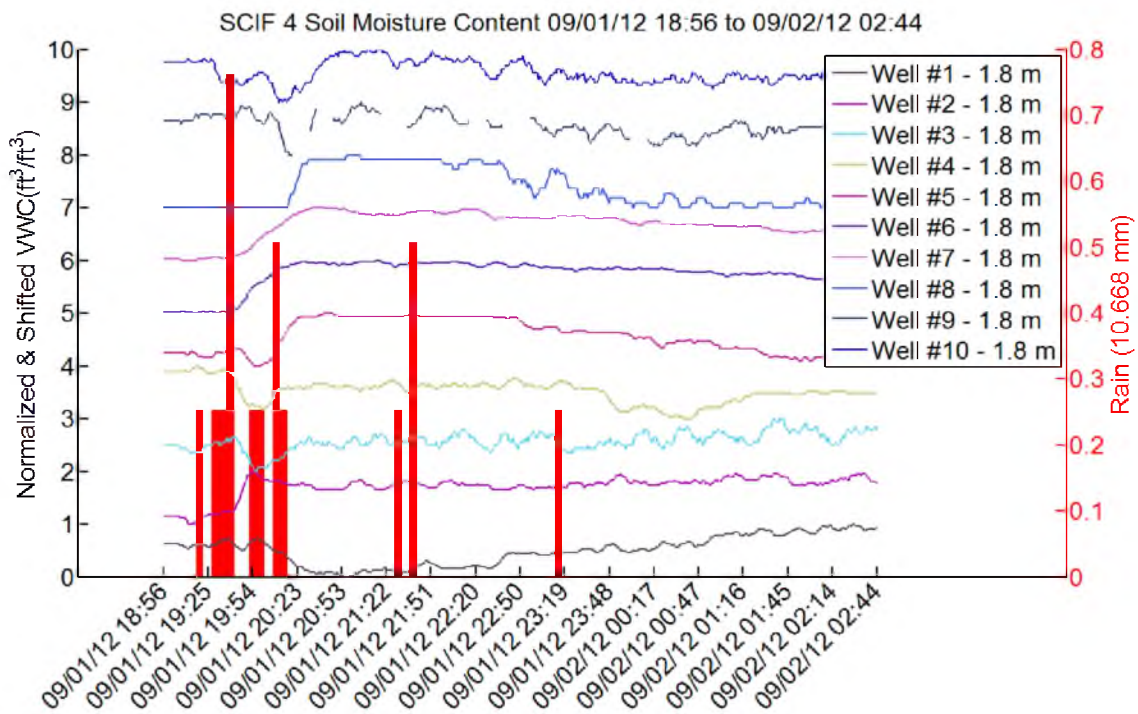


Figure 38. Soil Moisture Data, Wells 1-10, 1.8 m Depth, 9/01/12 Storm Event

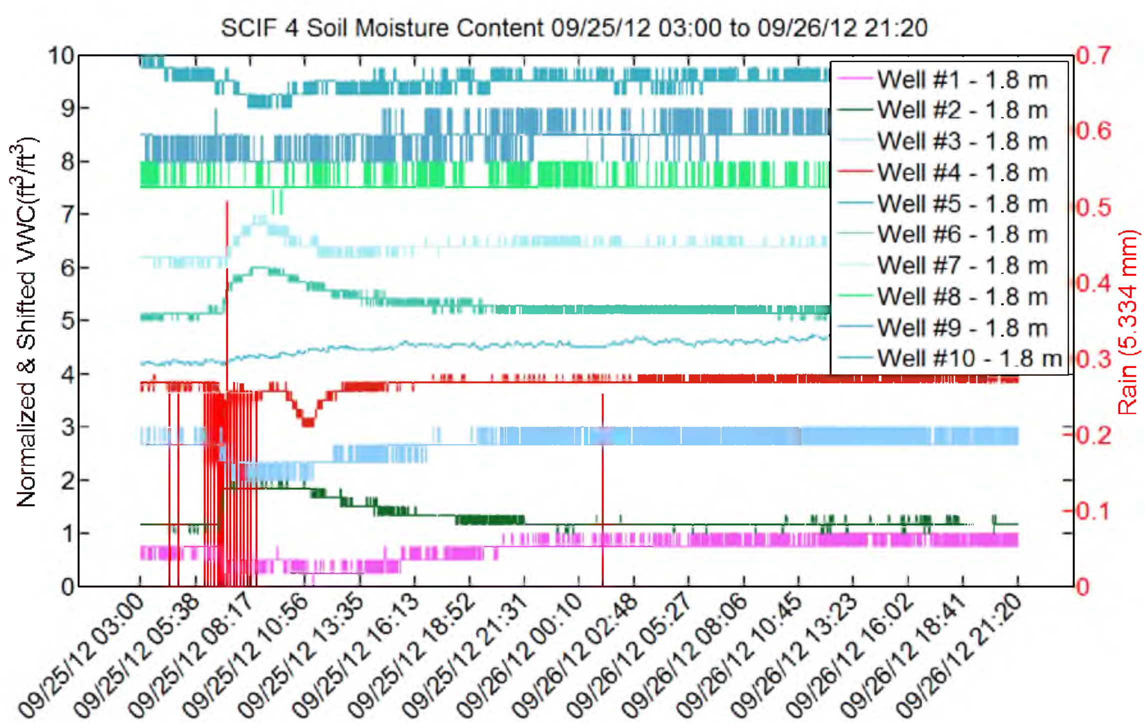


Figure 39. Soil Moisture Data, Wells 1-10, 1.8 m Depth, 9/25/12 Storm Event

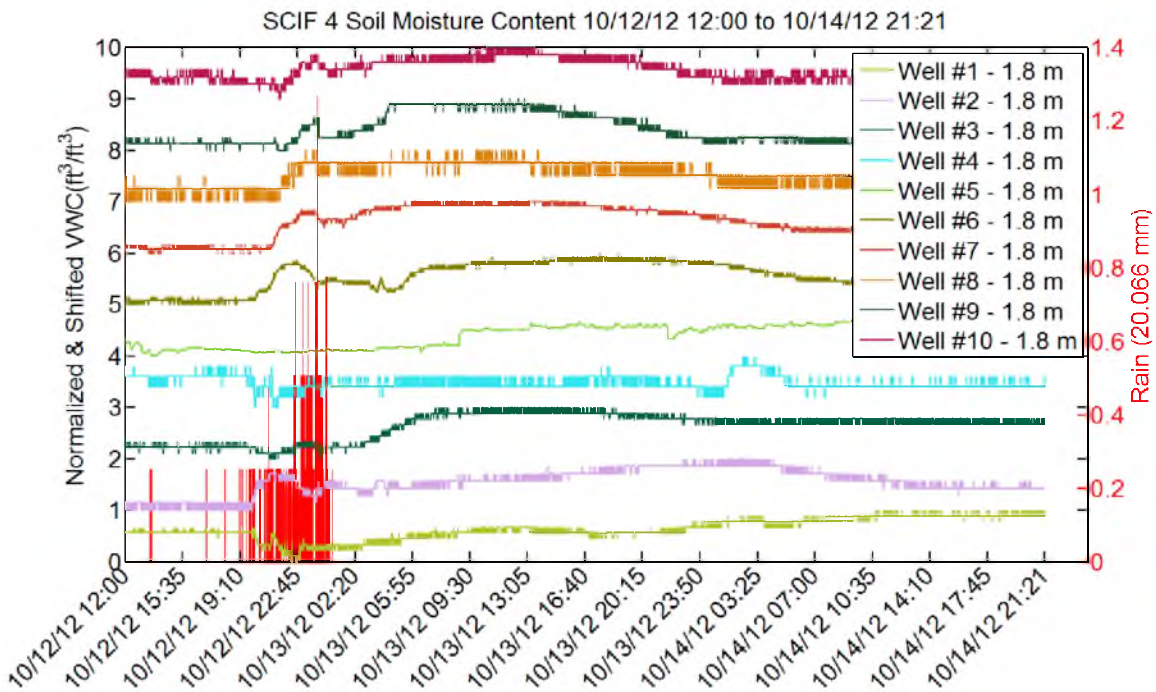


Figure 40. Soil Moisture Data, Wells 1-10, 1.8 m Depth, 10/12/12 Storm Event

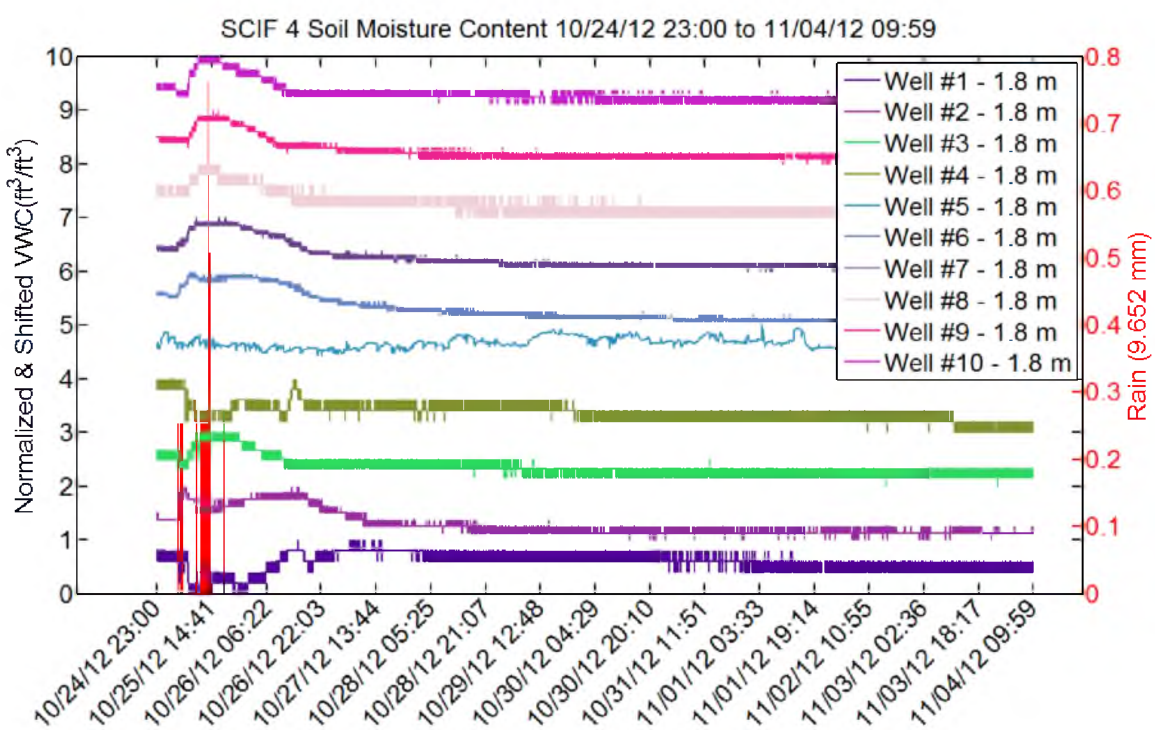


Figure 41. Soil Moisture Data, Wells 1-10, 1.8 m Depth, 10/25/12 Storm Event

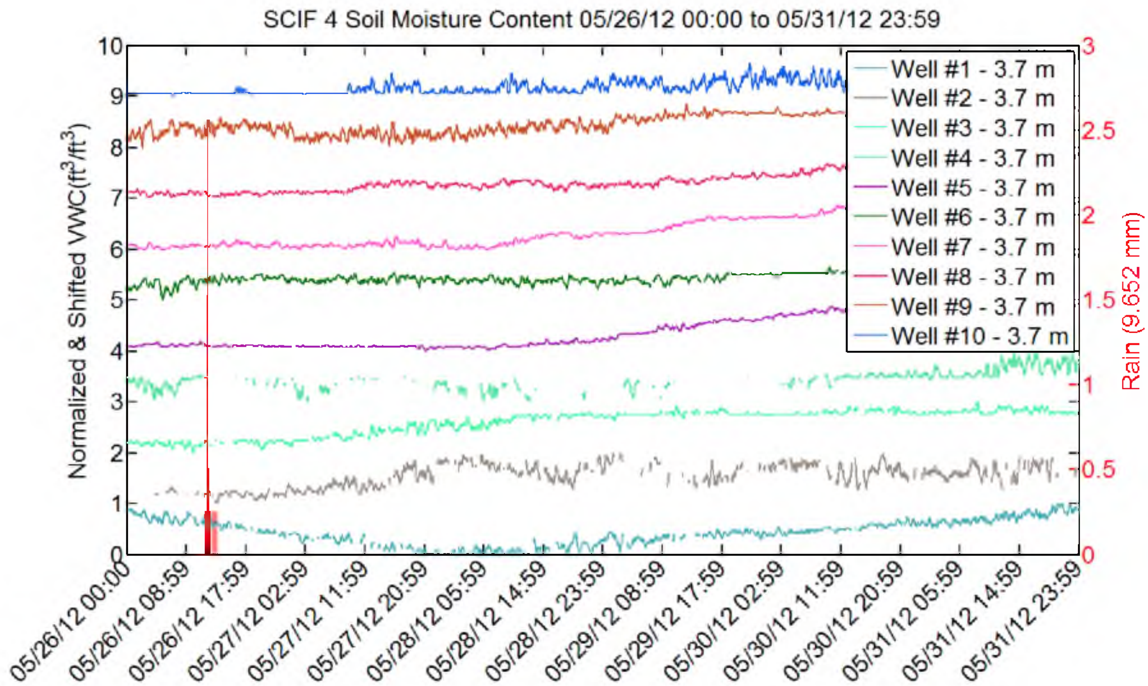


Figure 42. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 5/26/12 Storm Event

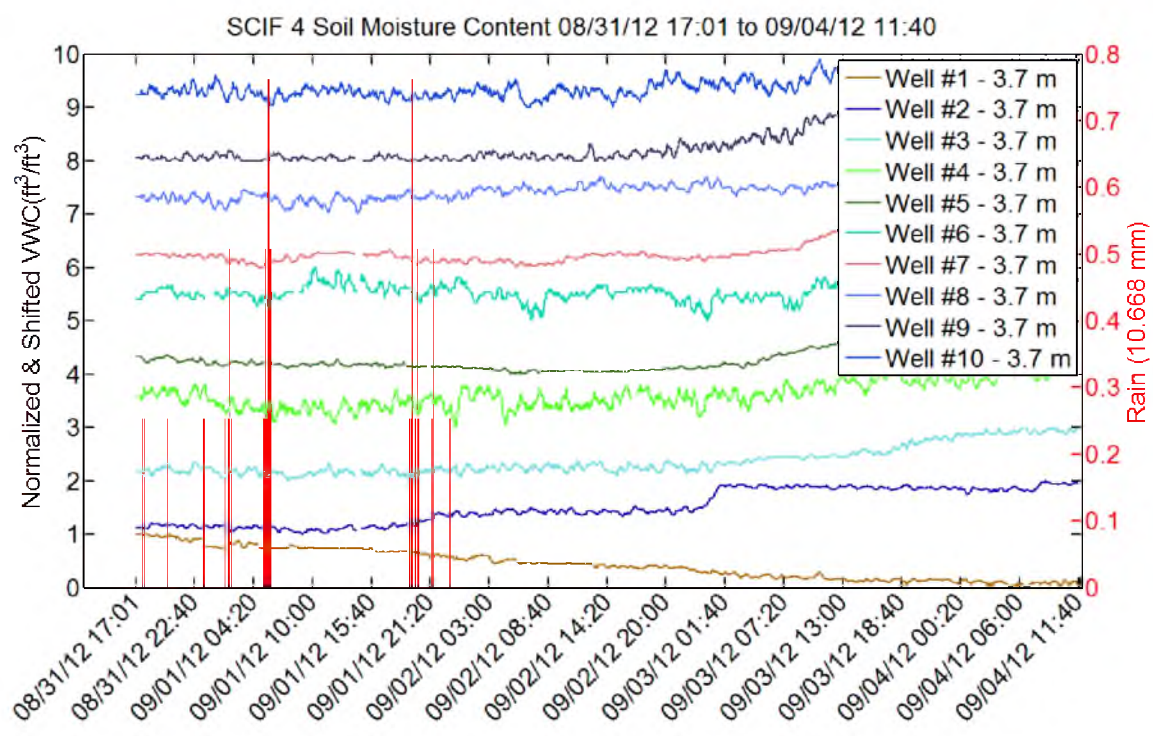


Figure 43. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 8/31 & 9/1 Storm Events

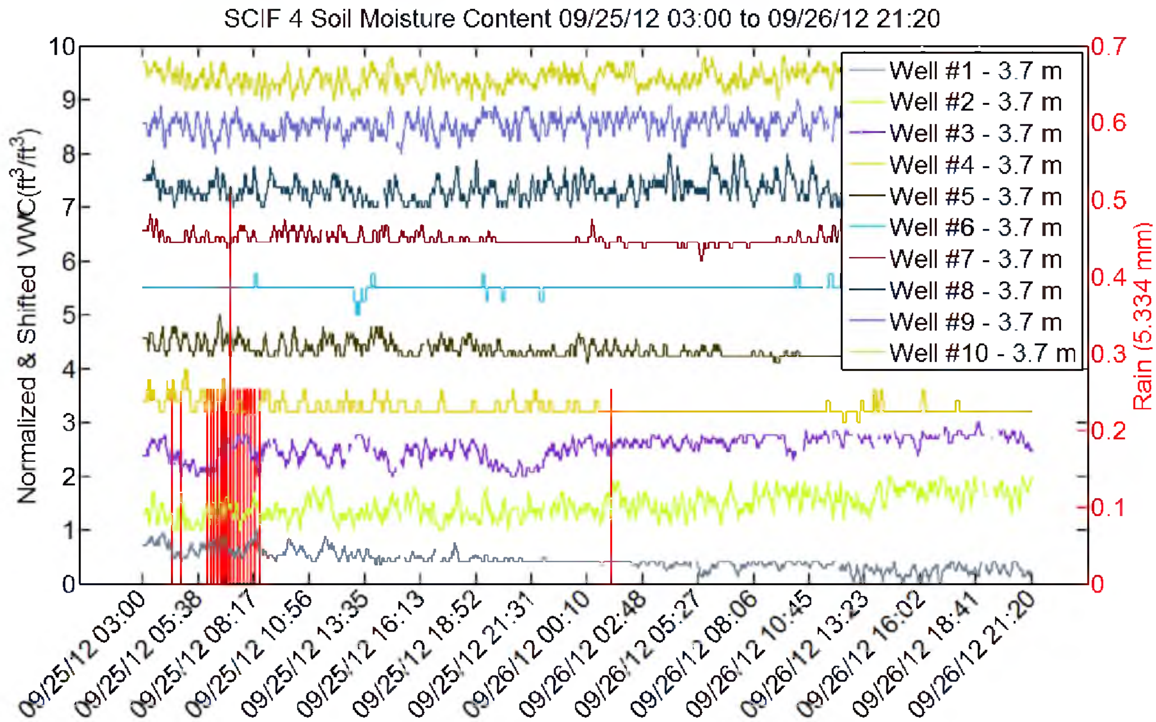


Figure 44. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 9/25/12 Storm Event

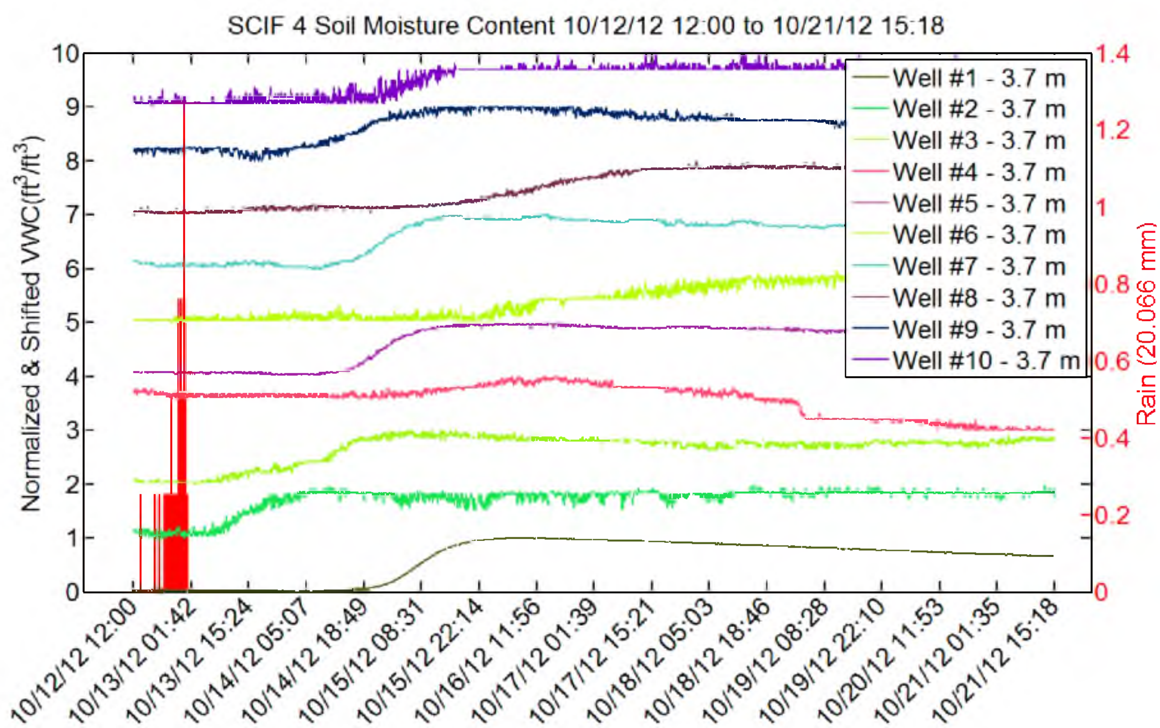


Figure 45. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 10/12/12 Storm Event

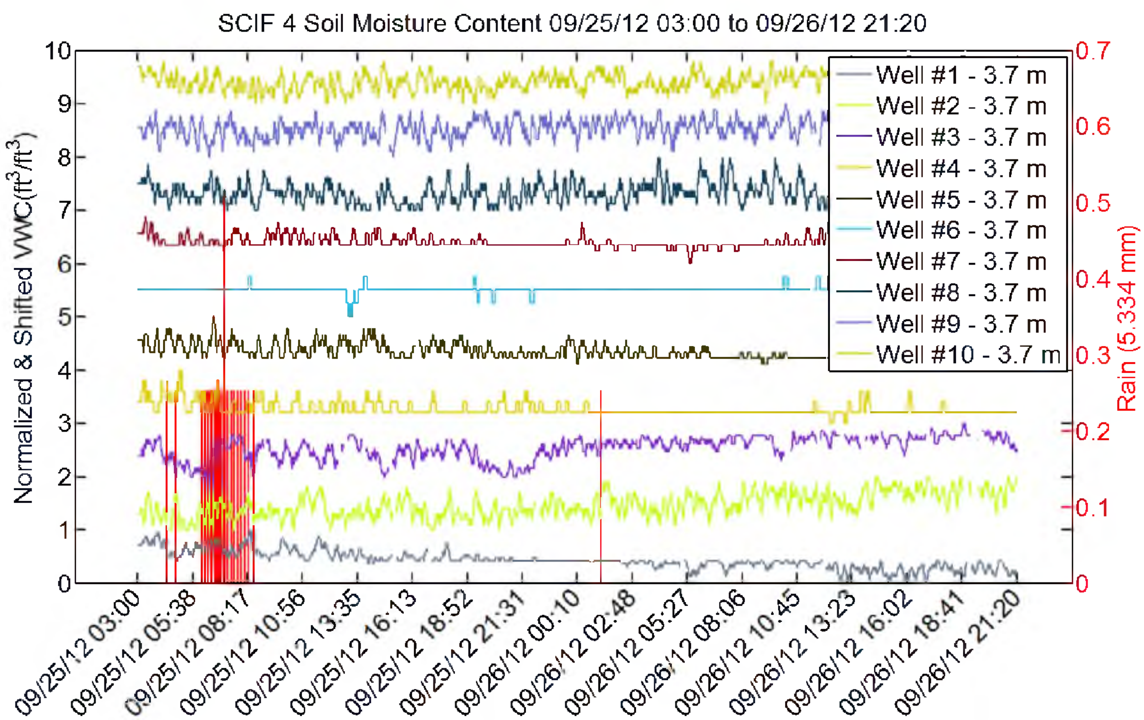


Figure 46. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 9/25/12 Storm Event

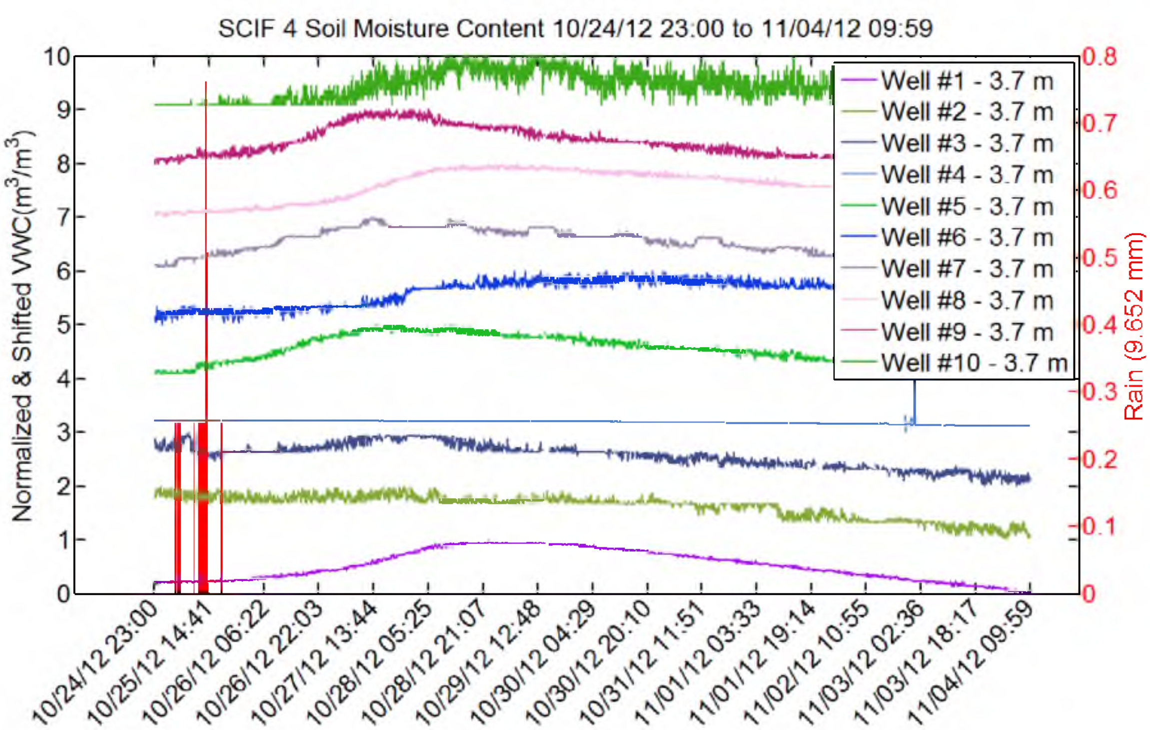


Figure 47. Soil Moisture Data, Wells 1-10, 3.7 m Depth, 10/25/12 Storm Event

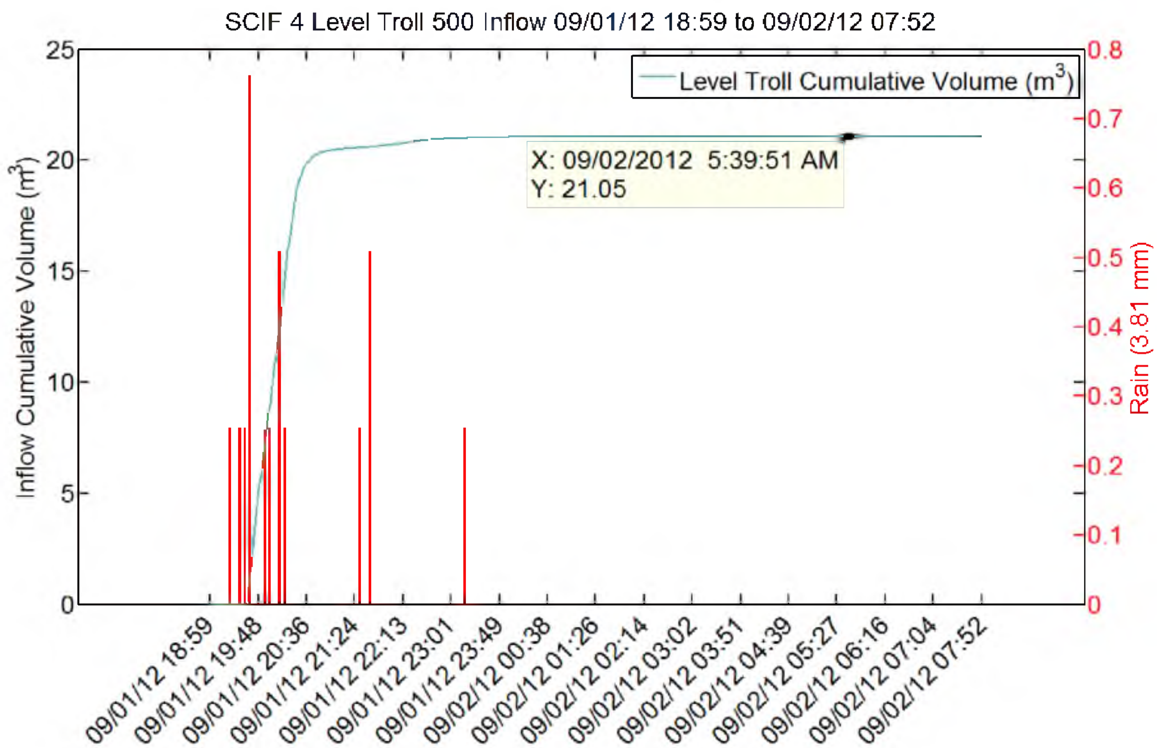


Figure 48. Cumulative Inflow, 9/1/12 Storm Event

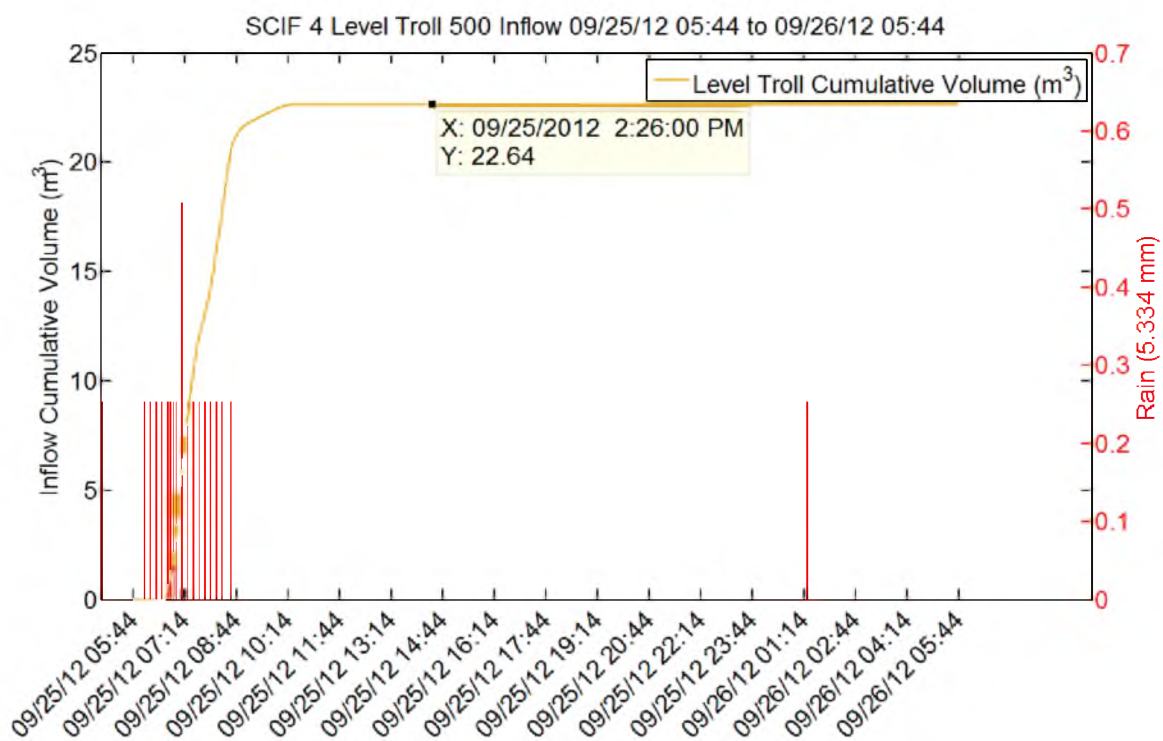


Figure 49. Cumulative Inflow, 9/25/12 Storm Event

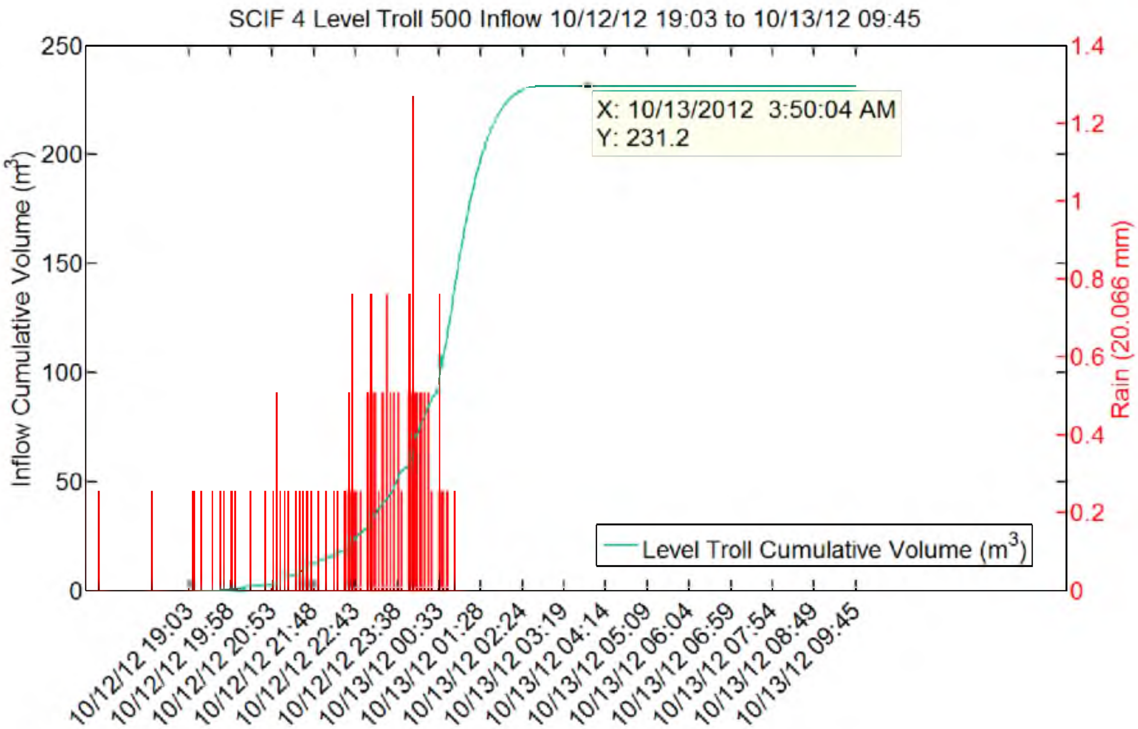


Figure 50. Cumulative Inflow, 10/12/12 Storm Event

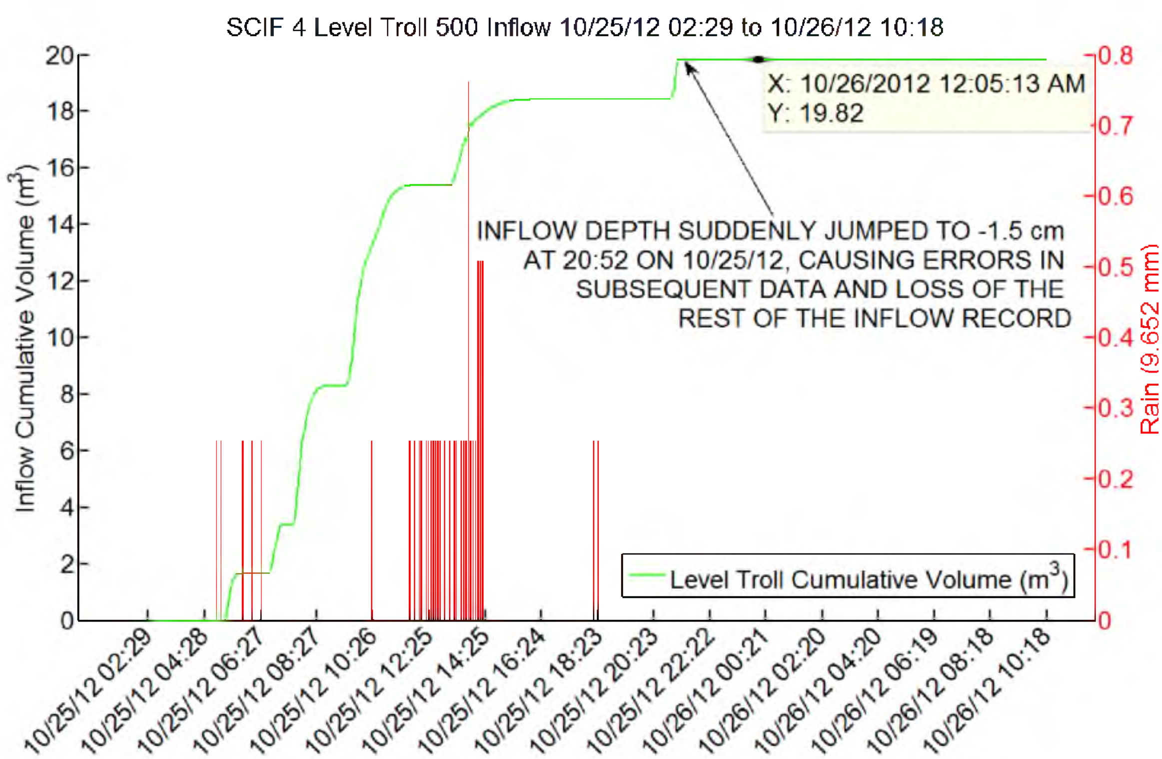


Figure 51. Cumulative Inflow, 10/25/12 Storm Event

APPENDIX B

BUDGET AND WHOLE LIFE COSTS

Field Site #1: University of Utah Campus, Salt Lake City Utah

The project budget is outlined in Table 4.

Budget justification. Excavation costs were determined from standard hourly equipment and operator rates quoted by University of Utah Facilities Management. Labor and personnel cost estimates were determined based on design engineering, graduate student, and faculty labor rates and estimated hourly contributions to the project. Utelite aggregate, topsoil, and vegetation costs were justified with supplier quotes; estimates were used for the costs of plants which were not readily available. Instrumentation costs were based on supplier quotes with estimated miscellaneous costs.

Whole life costs. In 2005 and 2009, a suite of spreadsheet tools was developed under partnership with the Water Environment Research Foundation (WERF) to facilitate whole life cost estimation of stormwater best management practices (BMP). Tools are available for nine different BMPs including extended detention basins, cisterns, retention ponds, swales, permeable pavements, curb contained bioretention, in-curb planter vaults, rain gardens, and green roofs. Users have the option of accepting default inputs but are encouraged to provide as much site-specific information as possible. Outputs include summaries of total costs, cumulative costs, and present values of projected costs. A case study was prepared to compare actual whole life costs of the newly constructed bioretention cell on the University of Utah campus to the costs estimated by the WERF whole life cost tools. This study provides valuable insight into the capital costs associated with the design, construction, and maintenance of a bioretention facility in the semiarid climate of the Salt Lake valley.

Table 4. SCIF 4 Bioretention Budget

Cost Item	Unit Cost	Unit	ACTUAL INCURED COSTS Quantity	Cost
Excavation				
Operator & Equipment	-	-	-	$6,270.00
Soil Disposal, etc.	-	-	-	$1,200.00
Re-Sodding (Sod + Labor)	-	-	-	$1,150.00
		Excavation Total:		**$8,620.00**
Well Drilling (EarthProbe)				
Daily Rig Rate	$1,500.00	Ea.	2	$3,000.00
Mobilization/Demobilization	$175.00	Ea.	2	$350.00
Equipment Decontamination	$100.00	Ea.	2	$200.00
Soil Sample Liners	$8.00	Ea.	57	$456.00
Sand/Bentonite	$15.00	Ea.	20	$300.00
Expendable Drive Points	$25.00	Ea.		$0.00
		Well Drilling Total:		**$4,306.00**
Storage Layer				
Utelite 3/8" Medium Grade Aggregate	$28.85	Yd^3	100	$2,690.29
Aggregate Delivery Charge	$360.00	Yd^3	2	$720.00
Utelite DONATION	$28.85	Yd^3	50	-$1,442.50
		Storage Layer Total:		**$1,967.79**
Vegetation			Quantity	
CERCOCARPUS MONTANUS	$16.00	Ea.	4	$64.00
beechleaf mountain mahogany				
SCHIZACHYRIUM SCOPARIUM	$6.10	Ea.	6	$36.60
little bluestem grass				
BOUTELOUA GRACILIS	$6.10	Ea.	15	$91.50
blue gramma grass				
SORGHASTRUM NUTANS	$5.25	Ea.	0	$0.00
indian grass				

Table 4 continued

Cost Item	Unit Cost	Unit	ACTUAL INCURED COSTS Quantity	Cost
CHRYSOTHAMNUS NAUSEOSUS	$4.75	Ea.	4	$19.00
rubber rabbitbrush				
ATRIPLEX CANESCENCE	$5.95	Ea.	4	$23.80
saltbush				
Monardella odoratissima	$3.80	Ea.	12	$45.60
Mountain Beebalm				
Penstemon eatonii	$5.95	Ea.	12	$71.40
Firecracker Penstemon				
Stanleya pinnata	$3.80	Ea.	12	$45.60
Prince's Plume				
FREIGHT-SL VALLEY	$59.00	Ea.	2	$99.00
delivery charges				
Vegetation Totals:			**69**	**$496.50**
Instrumentation				
W-SMC, HOBOnode	$213.00	Ea.	30	$6,390.00
Model 3001 LT Levelogger Edge Junior	$400.00	Ea.	9	$3,510.00
Model 3001 Barologger Edge, Solinst	$487.00	Ea.	2	$949.65
FREIGHT, Equipco (Solinst)	$40.00	Ea.	1	$40.00
Gee Passive Capillary Lysimeter G-2	$1,250.00	Ea.	3	$3,750.00
Data Logger Em50	$440.00	Ea.	1	$440.00
FREIGHT, Drain Gauges	$210.00	Ea.	1	$250.35
Level TROLL 500	$1,111.50	Ea.	1	$1,111.50
Rugged Twist-Lock cable	$396.15	Ea.	1	$396.15
Sign, Public Education	$275.00	Ea.	1	$275.00
Misc.	$300.00	Ea.		$319.90
Instrumentation Total:				**$17,432.55**
TOTAL COST:				**$32,822.84**

The longterm economic feasibility of LID projects is often questioned. As new bioretention facilities are constructed, cost data pertaining to the life cycle of the field facilities is becoming available, and unique opportunities exist to study the economic feasibility through whole life cost analysis. In support of this study's outreach goals, it is anticipated that this whole life cost case study will serve as an example to stakeholders of the economic feasibility of bioretention in the semiarid region of the Salt Lake valley. Throughout the design and construction phases of the project, detailed accounts of capital and operation/maintenance costs were recorded for comparison to cost estimates calculated using the WERF whole life cost tools.

The WLC comparison included capital costs such as base facility costs as well as associated capital costs. Line items including drainage area, mobilization, excavation/grading, disposing of excavated material, engineered substrate backfill, inflow structure, topsoil, vegetation, landscaping, and signage/education materials were factored into the base facility cost calculation as shown in Table 5 through Table 8.

Table 5. Construction and Well Drilling Costs

Facility Base Costs	Unit	Unit Cost	Quantity	Cost
Excavation/Grading (Operator & Equipment)	LS	$ 6,270	1	$ 6,270.00
Haul/Dispose of Excavated Material	LS	$ 1,200	1	$ 1,200.00
Sod/Planting	SF	$ 1	1000	$ 1,150
Topsoil	CY	$ 25	100	$ 2,500
Bark Mulch	CY	$ 20	5	$ 100
Well Drilling Daily Rig Rate	EA	$ 1,500	2	$ 3,000
Well Drilling Mobilization/Demobilization	EA	$ 175	2	$ 350
Well Drilling Equipment Decontamination	EA	$ 100	2	$ 200
Well Drilling Soil Sample Liners	EA	$ 8	57	$ 456
Well Drilling Sand/Bentonite	EA	$ 15	20	$ 300

Table 6. Vegetation Costs

Facility Base Costs	Unit	Unit Cost	Quantity	Cost
Vegetation: CERCOCARPUS MONTANUS (beechleaf mountain mahogany)	EA	$ 16	4	$ 64
Vegetation: SCHIZACHYRIUM SCOPARIUM (little bluestem grass)	EA	$ 6	6	$ 37
Vegetation: BOUTELOUA GRACILIS (blue gramma grass)	EA	$ 6	15	$ 92
Vegetation: ARTEMISIA TRIDENTATA (big sagebrush)	EA	$ 6	8	$ 48
Vegetation: CHRYSOTHAMNUS NAUSEOSUS (rubber rabbitbrush)	EA	$ 5	4	$ 19
Vegetation: ATRIPLEX CANESCENCE (saltbush)	EA	$ 6	4	$ 24
Vegetation: Monardella odoratissima (Mountain Beebalm)	EA	$ 4	12	$ 46
Vegetation: Penstemon eatonii (Firecracker Penstemon)	EA	$ 6	12	$ 71
Vegetation: Stanleya pinnata (Prince's Plume)	EA	$ 4	12	$ 46
Vegetation: FREIGHT (delivery charges)	LS	$ 50	2	$100
Vegetation: 31600P8, DEWITT FABRIC, LANDSCAPE PRO 5-8X250	LS	$ 261	1	$261

Table 7. Engineered Substrate Backfill Costs (Utelite Storage Layer)

Facility Base Costs	Unit	Unit Cost	Quantity	Cost
Soil Amendment or Engineered Substrate Backfill	CY	$ 27	100	$2,691
Soil Amendment or Engineered Substrate Backfill Haul Charge	EA	$ 360	2	$ 720

Table 8. Instrumentation Costs

Facility Base Costs	Unit	Unit Cost	Quantity	Cost
Instrumentation: W-SMC, HOBOnode w/ Soil Moisture Sensor, Onset	EA	$ 213	30	$6,390
Instrumentation: W-RCVR-USB, HOBOnode Receiver - USB, Onset	EA	$ 220	1	$ 220
Instrumentation: FREIGHT, Onset	EA	$ 40	1	$ 40
Instrumentation: Model 3001 LT Levelogger Edge Junior, M5/F15, Solinst	EA	$ 390	9	$3,510
Instrumentation: Model 3001 Barologger Edge, Solinst	EA	$ 475	2	$ 950
Instrumentation: Std Comm Package (USB)	EA	$ 198	1	$ 198
Instrumentation: FREIGHT, Equipco (Solinst)	LS	$ 40	1	$ 40
Instrumentation:Level TROLL 500 Pressure Transducer, In-Situ Inc.	EA	$ 1,112	1	$1,112
Instrumentation: Rugged Twist-Lock cable, In-Situ Inc.	EA	$ 396	1	$ 396
Instrumentation: TROLL Com Bundle USB direct connect (programming cat	EA	$ 469	1	$ 469
Instrumentation: Drain Gauge Gee Passive Capillary Lysimeter G-2	EA	$ 1,250	3	$3,750
Instrumentation: Data Logger Em50	EA	$ 440	1	$ 440
Instrumentation: FREIGHT, Drain Gauges	LS	$ 250	1	$ 250

Project management, engineering design time, surveying, utility location, and construction/inspection permits and fees were factored into the associated capital cost calculation as shown in Table 9. Maintenance costs included routine maintenance activities as well as corrective and infrequent activities as shown in Table 10. Line items such as vegetation management, trash removal, and minor debris removal were factored into the routine maintenance costs. Corrective items such as inflow/outflow structure unclogging, sediment removal, topsoil tilling, and erosion management were factored into the infrequent maintenance calculations as shown in Table 11.

Results of the case study indicate estimated whole life costs calculated by the WERF tools closely resemble actual costs incurred during the life cycle of the constructed bioretention facility. Total facility base costs were calculated to be $38,103 with calculated associated capital costs of $15,115, resulting in a total facility cost of $53,218 as shown in Table 12. These results included estimates of design and management time, as well as time for data collection and research efforts directly pertaining to the facility. For comparison, results obtained by using the simplified costing method within the WERF spreadsheet are shown in Table 13. Overall, a net present value of $154,457 was calculated assuming a facility lifetime of 20 years as shown in Table 14. Net present value is plotted in Figure 52.

In order to provide an indication of the whole life costs without the research costs included, the analysis was repeated excluding instrumentation costs, well drilling costs, and those maintenance costs which were directly related to research activities. The results indicate a total capital cost of $31,147, regular maintenance costs of $900 per year, and corrective and infrequent maintenance costs of $1,663.

Table 9. Associated Costs

Associated Capital Costs		Unit Cost	Quantity	Cost
Project Management	HR	$ 30	40	$ 1,200
Engineering: Preliminary	HR	$ 100	40	$ 4,000
Engineering: Final Design	HR	$ 100	20	$ 2,000
Topographic Survey	HR	$ 100	2	$ 200
Landscape Design	HR	$ 100	2	$ 200
Permitting Fees	LS	$ 150	1	$ 150
Construction Inspection	LS	$ 150	1	$ 150
Contingency (e.g., 30%)	LS	$ 2,715	1	$ 2,715
Construction Labor	HR	$ 15	300	$ 4,500

Table 10. Regular Maintenance Costs

REGULAR MAINTENANCE ACTIVITIES	Months Between Events	Cost per Event	Total Cost per Year	Included in WLC Calculation Chosen option
Reporting & Information Management	0	$60	$2,880	$ 2,880.00
Vegetation Management with Trash & Minor Debris Removal	1	$75	$900	$ 900.00
Data Collection	0	$75	3600	$ 3,600.00
Annual Totals, Regular Maintenance Activities				$7,380

Assumptions: Data collection and reporting once per week.
Minor debris removal once per month.

Table 11. Infrequent Maintenance Costs

CORRECTIVE AND INFREQUENT MAINTENANCE ACTIVITIES	Years between Events	Cost per Event	Total Cost per Year	Included in WLC Chosen option
Till TopSoil	1	$160	$160	$ 160.00
Unclog Inflow/Outflow Structures	0.08	$15	$180	$ 180.00
Replace Gravel/Sediment Removal	4	$3,850	$963	$ 962.50
Manage Erosion	0.08	$30	$360	$ 360.00
Corrective and Infrequent MaintenanceActivities				$1,663
Maintenance Costs as a percent of Capital Cost:				17%

Assumption: Unclog inflow/outflow structures and manage erosion once per month.

Table 12. Engineer's Itemized Costing Method Results

CAPITAL COSTS	Total Cost
Total Facility Base Cost	$ 38,103
Total Associated Capital Costs (e.g., Engineering, Land, etc.)	$ 15,115
Capital Costs	**$53,218**

Assumption: New construction as opposed to retrofit.

Table 13. Alternative Simplified Costing Method Results

Method A: Simple Cost Based on Drainage Area		
Cost Based on Drainage Area	**Model Default**	**Chosen Option**
Effective Drainage Area (DA) (acres)	0.80	1.50
Suggested Garden Size (SF)	2,500	4,600
Base Facility Cost ($/acre effective DA)	$ 42,254	$ 42,254
Base Facility Cost	**$ 33,900**	**$ 63,400**
Engineering & Planning (default = 25% of Base Cost)	$ 8,475	$ 15,850
Total Associated Capital Costs (e.g., Engineering, Land, etc.)	**$ 8,475**	**$ 15,850**
Total Facility Cost	**$ 42,375**	**$ 79,250**

Assumption: Suggested garden size assumes 7% of effective drainage area.

Table 14. Net Present Value

Year	Discount Factor	Capital & Assoc. Costs	Regular Maint. Costs	Corrective Maint.	Total Costs	Present Value of Costs	Cumulative Costs		
							Cash	Present Value	Discounted Cost per Year
Cash Sum ($)					$ 224,168	$ 154,457			
0	1.000	$ 53,218			$ 53,218	$ 53,218	$ 53,218	$ 53,218	$ 154,457
1	0.948	$ -	$ 7,380	$ 205	$ 7,585	$ 7,190	$ 60,803	$ 60,408	$ 101,239
2	0.898	$ -	$ 7,380	$ 205	$ 7,585	$ 6,815	$ 68,388	$ 67,222	$ 94,050
3	0.852	$ -	$ 7,380	$ 205	$ 7,585	$ 6,459	$ 75,973	$ 73,682	$ 87,235
4	0.807	$ -	$ 7,380	$ 4,055	$ 11,435	$ 9,231	$ 87,408	$ 82,912	$ 80,775
5	0.765	$ -	$ 7,380	$ 205	$ 7,585	$ 5,804	$ 94,993	$ 88,716	$ 71,545
6	0.725	$ -	$ 7,380	$ 205	$ 7,585	$ 5,501	$ 102,578	$ 94,217	$ 65,741
7	0.687	$ -	$ 7,380	$ 205	$ 7,585	$ 5,214	$ 110,163	$ 99,431	$ 60,240
8	0.652	$ -	$ 7,380	$ 4,055	$ 11,435	$ 7,451	$ 121,598	$ 106,882	$ 55,026
9	0.618	$ -	$ 7,380	$ 205	$ 7,585	$ 4,685	$ 129,183	$ 111,567	$ 47,575
10	0.585	$ -	$ 7,380	$ 205	$ 7,585	$ 4,440	$ 136,768	$ 116,007	$ 42,890
11	0.555	$ -	$ 7,380	$ 205	$ 7,585	$ 4,209	$ 144,353	$ 120,216	$ 38,450
12	0.526	$ -	$ 7,380	$ 4,055	$ 11,435	$ 6,015	$ 155,788	$ 126,231	$ 34,241
13	0.499	$ -	$ 7,380	$ 205	$ 7,585	$ 3,782	$ 163,373	$ 130,013	$ 28,226
14	0.473	$ -	$ 7,380	$ 205	$ 7,585	$ 3,584	$ 170,958	$ 133,597	$ 24,445
15	0.448	$ -	$ 7,380	$ 205	$ 7,585	$ 3,398	$ 178,543	$ 136,995	$ 20,860
16	0.425	$ -	$ 7,380	$ 4,055	$ 11,435	$ 4,855	$ 189,978	$ 141,850	$ 17,463
17	0.402	$ -	$ 7,380	$ 205	$ 7,585	$ 3,053	$ 197,563	$ 144,902	$ 12,608
18	0.381	$ -	$ 7,380	$ 205	$ 7,585	$ 2,893	$ 205,148	$ 147,796	$ 9,555
19	0.362	$ -	$ 7,380	$ 205	$ 7,585	$ 2,743	$ 212,733	$ 150,538	$ 6,662
20	0.343	$ -	$ 7,380	$ 4,055	$ 11,435	$ 3,919	$ 224,168	$ 154,457	$ 3,919

Assumption: 20 year facility lifetime.

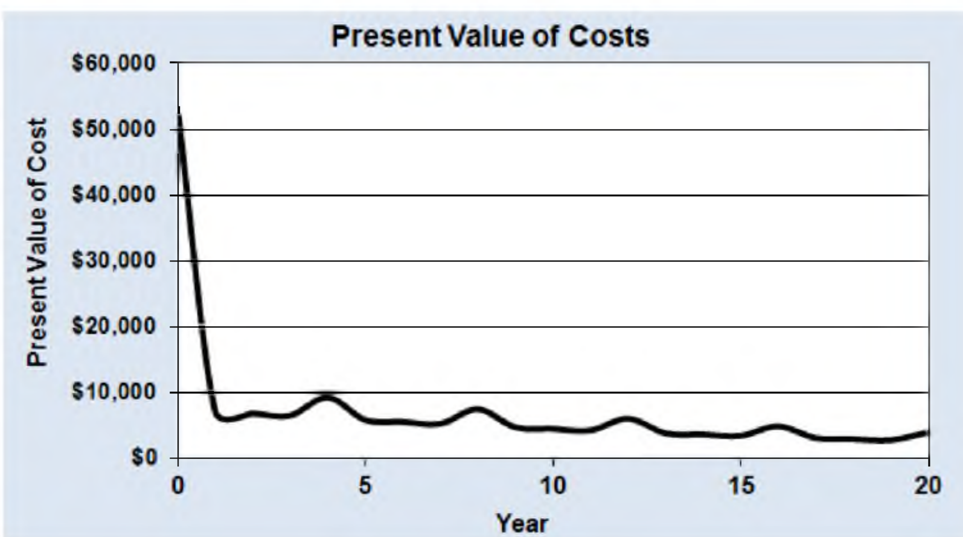


Figure 52. Net Present Value (20 Year Facility Lifetime)

A net present value of $54,948 for the facility with a 20 year lifetime was calculated as shown in Table 15. These results provide stakeholders with an example of expected whole life costs of bioretention in semiarid climates without research expenditures. The results indicate that the WERF spreadsheet's simplified costing method (A) may overestimate facility base costs based on effective drainage area.

Overall, the results are competitive with costs of traditional infrastructure. Similar findings were reported by the U.S. EPA for seventeen case studies across the United States (U.S. Environmental Protection Agency, 2007; U.S. Environmental Protection Agency New England, 2009). Of the seventeen case studies, twelve employed bioretention. Those twelve cases showed a range of 15% to 80% reduction in

Table 15. Net Present Value, Excluding Research Costs

Year	Discount Factor	Capital & Assoc. Costs	Regular Maint. Costs	Corrective Maint.	Total Costs	Present Value of Costs	Cumulative Costs		
							Cash	Present Value	Discounted Cost per Year
Cash Sum ($)					$ 72,497	$ 54,948			
0	1.000	$ 31,147			$ 31,147	$ 31,147	$ 31,147	$ 31,147	$ 54,948
1	0.948	$ -	$ 900	$ 205	$ 1,105	$ 1,047	$ 32,252	$ 32,195	$ 23,801
2	0.898	$ -	$ 900	$ 205	$ 1,105	$ 993	$ 33,357	$ 33,187	$ 22,753
3	0.852	$ -	$ 900	$ 205	$ 1,105	$ 941	$ 34,462	$ 34,128	$ 21,761
4	0.807	$ -	$ 900	$ 4,055	$ 4,955	$ 4,000	$ 39,417	$ 38,128	$ 20,820
5	0.765	$ -	$ 900	$ 205	$ 1,105	$ 845	$ 40,522	$ 38,974	$ 16,820
6	0.725	$ -	$ 900	$ 205	$ 1,105	$ 801	$ 41,627	$ 39,775	$ 15,974
7	0.687	$ -	$ 900	$ 205	$ 1,105	$ 760	$ 42,732	$ 40,535	$ 15,173
8	0.652	$ -	$ 900	$ 4,055	$ 4,955	$ 3,229	$ 47,687	$ 43,763	$ 14,413
9	0.618	$ -	$ 900	$ 205	$ 1,105	$ 682	$ 48,792	$ 44,446	$ 11,185
10	0.585	$ -	$ 900	$ 205	$ 1,105	$ 647	$ 49,897	$ 45,093	$ 10,502
11	0.555	$ -	$ 900	$ 205	$ 1,105	$ 613	$ 51,002	$ 45,706	$ 9,855
12	0.526	$ -	$ 900	$ 4,055	$ 4,955	$ 2,606	$ 55,957	$ 48,312	$ 9,242
13	0.499	$ -	$ 900	$ 205	$ 1,105	$ 551	$ 57,062	$ 48,863	$ 6,636
14	0.473	$ -	$ 900	$ 205	$ 1,105	$ 522	$ 58,167	$ 49,385	$ 6,085
15	0.448	$ -	$ 900	$ 205	$ 1,105	$ 495	$ 59,272	$ 49,880	$ 5,563
16	0.425	$ -	$ 900	$ 4,055	$ 4,955	$ 2,104	$ 64,227	$ 51,984	$ 5,068
17	0.402	$ -	$ 900	$ 205	$ 1,105	$ 445	$ 65,332	$ 52,429	$ 2,964
18	0.381	$ -	$ 900	$ 205	$ 1,105	$ 422	$ 66,437	$ 52,850	$ 2,519
19	0.362	$ -	$ 900	$ 205	$ 1,105	$ 400	$ 67,542	$ 53,250	$ 2,098
20	0.343	$ -	$ 900	$ 4,055	$ 4,955	$ 1,698	$ 72,497	$ 54,948	$ 1,698

Assumption: 20 year facility lifetime.

development costs when compared to conventional stormwater management and design approaches (U.S. Environmental Protection Agency, 2007). It should be noted that these savings were representative of all LID methods employed in each case study area; the savings associated specifically with bioretention were not reported. The case studies generally showed higher LID costs for items such as landscaping and in some cases site preparation, but indicated substantially lower costs for site grading, stormwater infrastructure, and site paving (U.S. Environmental Protection Agency, 2007). It has also been shown that LID cost savings can be associated with reduced usage of asphalt, piping, detention basins, and other stormwater infrastructure in addition to increased amounts of developable land area that would have otherwise not been available if traditional stormwater infrastructure had been used (U.S. Environmental Protection Agency New England, 2009).

Field Site #2: Mountview Park, Cottonwood Heights Utah

The project budget is outlined in Table 16.

Budget justification. Excavation costs were determined from standard hourly equipment and operator rates charged by the contracted construction company. Labor and personnel cost estimates were determined based on design engineering, graduate student, and faculty labor rates and estimated hourly contributions to the project. Well drilling cost estimates were based on a quote from Earthprobe Inc. Utelite aggregate, topsoil, and vegetation costs were justified with supplier quotes; estimates were used for the costs of plants which were not readily available. Instrumentation costs were based on supplier quotes with estimated miscellaneous costs. Facilities and administration costs were based on standard University of Utah rates for funded research.

Table 16. Mountview Park Bioretention Budget

Cost Item	Unit Cost	Unit	Quantity	Cost
Excavation				
Operator & Equipment	$150.00	Hr.	80	$12,000.00
		Excavation Total:		**$12,000.00**
Personnel & Labor				
Cottonwood Heights Engineering	$150.00	Hr.	40	$6,000.00
Grad Student Salary	$2,000.00	Mo.	4	$8,000.00
Grad Student Fringe Benefits (14%)				$1,120.00
Faculty Salary	$9,000.00	Mo.	0.25	$2,250.00
Faculty Fringe Benefits (37%)				$832.50
		Labor Total:		**$18,202.50**
Well Drilling (Contec)				
Mob/Demob - Track Mounted DPT Drill Rig	$150.00	Hr.	2	$300.00
DPT Drilling	$165.00	Hr.	8	$1,320.00
2"x10', Sch. 40 PVC Well Screen	$49.50	Ea.	10	$495.00
2" Threaded Bottom Cap	$12.50	Ea.	10	$125.00
2" Slip Cap	$5.00	Ea.	10	$50.00
Expendable Drive Point	$45.00	Ea.	10	$450.00
Standby	$150.00	Hr.	0	$0.00
		Well Drilling Total:		**$2,740.00**
Storage Layer				
Utelite 3/8" Medium Grade Aggregate	$50.00	Cy.	734	$36,700.00
		Storage Layer Total:		**$36,700.00**
Top Soil				
Topsoil (Delivered)	$30.00	Cy.	278	$8,340.00
		Top Soil Total:		**$8,340.00**
Vegetation				
CERCOCARPUS LEDIFOLIUS curleaf mountain mahogany	$17.00	Ea.	3	$51.00
CERCOCARPUS MONTANUS beechleaf mountain mahogany	$16.00	Ea.	3	$48.00
SCHIZACHYRIUM SCOPARIUM little bluestem grass	$18.00	Ea.	3	$54.00
BOUTELOUA GRACILIS blue gramma grass	$5.25	Ea.	3	$15.75
SORGHASTRUM NUTANS indian grass	$5.25	Ea.	3	$15.75
ARTEMISIA TRIDENTATA big sagebrush	$9.50	Ea.	3	$28.50
CHRYSOTHAMNUS NAUSEOSUS rubber rabbitbrush	$4.75	Ea.	3	$14.25
CHRYSOTHAMNUS VISCIDFLORUS rabbitbrush	$4.75	Ea.	3	$14.25
ATRIPLEX CANESCENCE saltbush	$17.00	Ea.	3	$51.00

Table 16 continued.

Cost Item	Unit Cost	Unit	Quantity	Cost
ACHNATHERUM LEMMONII lemmon's needlegrass	$17.00	Ea.	3	$51.00
AGASTACHE URTICIFOLIA nettleleaf giant hyssop	$4.70	Ea.	3	$14.10
AGOSERIS AURANTIACA orange agoseris	$5.80	Ea.	9	$52.20
ALLIUM BISCEPTRUM twincrest onion	$17.00	Ea.	9	$153.00
POA FENDLERIANA mutton bluegrass	$17.00	Ea.	9	$153.00
MONARDELLA ODORATISSIMA mountain beebalm	$4.70	Ea.	3	$14.10
PENSTEMON EATONII firecracker penstemon	$4.70	Ea.	3	$14.10
STANLEYA PINNATA prince's plume	$17.00	Ea.	3	$51.00
FREIGHT-SL VALLEY delivery charges	$50.00	Ea.	1	$50.00
		Vegetation Total:		**$845.00**
Instrumentation				
W-SMC, HOBOnode	$213.00	Ea.	20	$4,260.00
W-RCVR-USB, HOBOnode Receiver	$220.00	Ea.	1	$220.00
Misc.	$300.00	Ea.	1	$300.00
FREIGHT, Onset	$60.00	Ea.	1	$60.00
Model 3001 LT Levelogger Junior	$373.45	Ea.	10	$3,734.50
Misc. (i.e. Tethers, Hardware, etc)	$200.00	Ea.	1	$200.00
FREIGHT, Equipco (Solinst)	$60.00	Ea.	1	$60.00
WL700 Ultrasonic Water Level Sensor	$800.00	Ea.	2	$1,600.00
Rain Gage plus Logger	$1,000.00	Ea.	1	$1,000.00
Materials & Supplies				$400.00
		Instrumentation Total:		**$11,834.50**
		DIRECT COSTS		**$90,662.00**
Facilities & Administration (49.5%)				$11,898.32
		TOTAL COSTS:		**$102,560.32**

APPENDIX C

PHOTOS

Field Site #1: University of Utah Campus, Salt Lake City Utah

Figure 53. Photo of Well Drilling

Figure 54. Photo of Completed SCIF 4 Bioretention Cell

Field Site #2: Mountview Park, Cottonwood Heights Utah

Figure 55. Photo of Construction at Mountview Park

Figure 56. Photo of Completed Mountview Park Bioretention Cell

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