Sand River Headwaters
Green Infrastructure Project

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The preferred alternative as presented had an estimated remediation cost of $16 million. This significant remediation cost prompted the stakeholders to refocus on the root causes of stormwater erosion and to consider green infrastructure alternatives as the best first solution to address the downtown stormwater problem. This reprioritization was fully supported by the stakeholders, and the Clemson team was asked to further investigate and refine green infrastructure options.

In 2009, the City of Aiken submitted a shovel-ready green infrastructure proposal through the State Revolving Fund (SRF) to the South Carolina Department of Health & Environmental Control for consideration for EPA managed American Recovery and Reinvestment Act (ARRA) funding allocated for green infrastructure. The City was awarded $3.34 Million for use in funding the design, construction, and post-construction monitoring for green infrastructure concepts proposed in the SREMP. The Center was awarded two City-funded research grants to assist in finalizing green infrastructure concepts, establishing an innovative real-time monitoring program, and to conduct a research program on the effectiveness of the project to capture, store, infiltrate, and treat downtown stormwater.

This report summarizes research associated with the Sand River Headwaters Green Infrastructure project, conducted in partnership with the City and Woolpert Inc. The project incorporated sustainable development practices to capture and treat stormwater within downtown watersheds, including the use of bioswales and bioretention, multiple applications of pervious pavement, and a cistern.

Project objectives are outlined in Section 3 with results, summaries, conclusions and dissemination of findings presented in Section 4. From January 2010 to January 2012, there were 132 monitored storm events greater than 0.1 inches. Of these events, 131 were analyzed from the 10-foot pipe outfall into Hitchcock Woods, 119 were analyzed from the Hoods Lane monitoring station, and 104 were analyzed from the Sumter Street monitoring station. By April 31, 2011, all bioretention cell (BRC) construction was completed, and storms subsequent to this date are referred to as “post-construction”. Key findings are highlighted below:

• Results show that although there was a consistent reduction in the calculated runoff coefficient means, there was no statistically significant reduction in the mean runoff coefficients for the entire Sand River watershed as measured at the 10-foot pipe outfall. This result is most likely due to the fact that the total BRC surface area was very small compared to the total area of the watershed, approximately 0.4%. In addition, several monitored BRC locations never registered discharge under any storm conditions, suggesting infiltration was being achieved at the site scale.

• Storms analyzed individually prior to the installation of bioretention and porous paving materials generated less runoff than those events after installation at the smaller watershed scale (Hoods Lane versus Sumter Street), thus not demonstrating evidence of reduced stormwater volumes. At the Sand River Headwaters 10-ft. pipe, some stormwater reduction was evident at the larger watershed scale. Furthermore, on an average runoff coefficient basis over all storms, stormwater volumes were reduced after practice installation.

• Independently conducted soil borings during construction indicated native soils within the study area have high infiltration rates suggesting there is high potential for using Low Impact Development (LID) techniques to lessen the impact of rain events. This is supported with rapid infiltration rates associated with pervious pavement installations. However, a novel data intensive analysis technique detected a possible reduction in the porosity of the custom soil media in the bioretention cells over the 1-year study period.
by analyzing data from soil moisture sensors within the cells. This may be attributed to post-construction settling and further monitoring is necessary to determine if there are any long-term trends in changes to media composition.

- Permeable pavements were constructed throughout the retrofit area with three different types of permeable paving materials installed: permeable asphalt, pervious concrete, and permeable interlocking concrete pavers. All permeable pavements throughout the retrofit were designed to be 12-in. systems to provide for stormwater storage as well as structural support. Results indicate that the average infiltration rates across all pervious pavements were more than adequate for stormwater management purposes.

- Cyberinfrastructure support for the Sand River Headwaters Green Infrastructure project represented a landscape-scale observation instrument comprising a heterogeneous fabric of in-situ sensors covering an expansive geographic area. The instrument design was successful and enabled end-users—researchers, educators, policy makers, and private citizens—to collect, share, and utilize a broad spectrum of in-situ data at ultra-dense temporal and spatial scales. The Aiken deployment focused primarily on the collection of weather conditions and soil parameters—temperature, conductivity, and volumetric water content—at depths of 6 inches, 12 inches, and 18 inches. Observation data collected from these sensors, when coupled with meteorological information (e.g., rainfall), provided fine-grained views into stormwater infiltration throughout the parkways.

- Vegetation and site conditions were coupled with plant characteristics to inform design, with the plant palette based on species resilient to frequent inundation and drying periods. The design was naturalistic, capable of enhancing aesthetics, improving infiltration, cleansing runoff, requiring minimal maintenance, and satisfying objectives associated with green infrastructure. With few exceptions, vegetation thrived in most cells. The few complaints about site design related to the use of tall grasses in several BRC locations and lack of pedestrian access to walk through several medians. Attractive bridges were installed to provide access in three medians with excellent response.

- A fundamental goal of the Clemson team was to disseminate findings to the general public, as well as regional design engineers, site developers, municipal and county stormwater staff, state environmental agencies, landscape architecture academics and professionals, planning agencies, and peer-reviewed journals. During active data collection, a project website supported real-time access to recent data for the Aiken project. In addition, the project website provided background information about green infrastructure and the stormwater problem in Aiken, featured video and photographs of the construction process, and captured media coverage. From the website’s creation in early 2010, over 5,000 visitors have accessed the site, not only from our state and region, but across the country and the world. On June 26, 2012 the Center for Watershed Excellence, the Clemson Cooperative Extension Service, and the City of Aiken conducted the Aiken Green Infrastructure Design and Implementation Technical Workshop targeted at design engineers, stormwater managers, and regulatory agency personnel. The workshop was organized to address site design techniques and implementation practices in support of green infrastructure. On June 27, 2012 the Aiken Green Infrastructure Educational Field Day was held immediately subsequent to the technical workshop to provide citizens, the business community, and local media an opportunity to learn more about the project.

Some uncertainties in stormwater runoff analyses at the watershed scale were identified in this report. These uncertainties were attributed primarily to monitoring stations only representing a very small drainage area compared to the larger Sand River Headwaters watershed and to unknowns associated with the complex urban drainage area as well as the routing of stormwater in the subsurface pipe network, including catch basin and drop inlet connectivity and stormwater pipe alignment and grade within the system. Other complicating issues include variable storm duration and intensity between events over the course of the study, seasonal variability in antecedent wet and dry conditions prior to each storm event, and parkway irrigation contributions to stormwater discharge. The Center investigators are submitting a proposal to the City of Aiken to define sources of stormwater to the Sand River Headwaters discharge through an intensive trunk line continuous level/flow monitoring program at nine key manholes within the downtown watersheds. These efforts would result in a GIS-based map of the stormwater system contributing to Sand River Headwater flows and allow for prioritization of future strategic green infrastructure installations in downtown Aiken watersheds.
GLOSSARY OF TERMS AND ABBREVIATIONS


BMP, Best Management Practices  Structural and non-structural controls designed to prevent or reduce the release of pollutants into the environment.

bioretention  A natural water treatment system that utilizes landscaping and soils to treat stormwater by collecting it in shallow depressions and then filtering it through a planting soil media. Bioretention slows the flow of stormwater and allows it time to soak into soil while pollutants adhere, degrade, evaporate or are taken up by plants. Rain gardens and bioswales are types of bioretention areas.

bioretention area  Bioretention areas, or rain gardens, are shallow landscape features adapted to provide on-site treatment of stormwater runoff.

bioswale  A bioswale is an engineered landscape feature used to convey stormwater in order to enhance infiltration and reduce surface runoff volume.

CAD, Computer Aided Design  The use of computing technology for digitally processing architectural and engineering design documentation.

charrette  An intensive planning session wherein participants from different disciplines explore and present ideas to collaborate on a vision for a project.

CWE, Center for Watershed Excellence, Clemson University  The Center for Watershed Excellence has been established to work with local communities to identify watershed issues, develop site-based solutions toward economic and environmental sustainability, procure funding sources and provide “one-stop-shop” watershed planning and management support within South Carolina. The Center is part of Clemson University’s Institute of Applied Ecology.

cyberinfrastructure  Research environments that support advanced data acquisition, data storage, data management, data integration, data mining, data visualization and other computing and information processing services distributed over the Internet.

DHEC, Department of Health and Environmental Control  The South Carolina Department of Health and Environmental Control (DHEC) is the state agency charged with protecting public health, coastal resources, and the state’s land, air and water quality as authorized under multiple state and federal laws.

GIS, Geographic Information Systems  Computer programs to assist in analysis and visualization of geographically referenced data.

green infrastructure  Strategically planned and managed networks of natural lands, working landscapes and other open spaces that conserve ecosystem values and functions and provide associated benefits to human populations.

hydrology  A science dealing with the properties, distribution, and circulation of water on and below the earth’s surface and in the atmosphere.
IAE, Institute of Applied Ecology, Clemson University  The Institute focuses on the application of novel and emerging technologies, innovative management strategies, and multi-scale outreach programs to solve major natural resources problems (www.clemson.edu/appliedecology).

infiltration  Infiltration allows stormwater to be naturally filtered by vegetation and soils to reduce or remove pollutants while restoring groundwater supplies.

IR, Intelligent River®  The Intelligent River® is developing and operating hydrological observation systems to support research and provide real-time monitoring, analysis and management of water resources in South Carolina. These observation networks vary in purpose, scale and density of observation platforms and sensor types, but have a common need to be managed in real time with a well developed software and hardware architecture that is intended to provide 24/7 access to data and visualization products (www.intelligentriver.org).

MoteStack  A battery operated computer with the technology to allow an unprecedented number of sensors to be deployed across a large area and operate as a highly efficient network.

permeable paving  Permeable pavement, also known as pervious or porous pavement is a paving surface designed to allow stormwater to infiltrate or seep through the pavement surface into the underlying structure and/or soils.

rain gardens  Rain gardens, or bioretention areas, are shallow landscape features adapted to provide on-site treatment of stormwater runoff.

SmartState Program®  The South Carolina SmartState Program® was established by the South Carolina General Assembly in 2002, funded through South Carolina Education Lottery proceeds. The legislation authorizes the state’s three public research institutions, Medical University of South Carolina, Clemson University and the University of South Carolina, to use state funds to create Centers of Economic Excellence in research areas that will advance South Carolina’s economy (www.sccoee.org)

South Carolina Center of Economic Excellence in Urban Ecology and Restoration  The Urban Ecology and Restoration Center at the Clemson University Restoration Institute supports the growth of the state’s environmental industry and attracts world-renowned faculty in restoration development. This Center is unique for its interdisciplinary, integrative approach to the restoration of historic, ecological, and urban infrastructure resources through the integration of basic science, engineering, and urban planning.

South Carolina Center of Economic Excellence in Sustainable Development  Established in 2010, the Center’s mission is to advance sustainable development through technological innovation. This includes the development of new technologies, from optically-based chemical sensors to wireless networking platforms, as well as the development of new environmental and ecological models designed to support real-time monitoring and management of natural and built environments.

watershed  An area of land where all of the water that drains off goes into the same river, lake or other water body.
PROJECT PARTNERS

The City of Aiken
U.S. Environmental Protection Agency, Region 4

Hitchcock Woods Foundation
S.C. Department of Health & Environmental Control

SmartState® Center of Economic Excellence in Urban Ecology & Restoration
SmartState® Center of Economic Excellence in Sustainable Development
1. INTRODUCTION

Sand River Restoration Engagement
The Sand River is an urban headwater stream derived from stormwater flows and groundwater seeps originating in downtown watersheds of the City of Aiken (City), SC. The headwater stream discharges into Hitchcock Woods through a 10ft diameter pipe into a gabion lined channel. The riverbed then winds through the botanically diverse and culturally rich landscape of the 2,100 acre Hitchcock Woods urban forest, located a few blocks from historic downtown Aiken. Over the past 15 years, a deep canyon has been eroded that has transported sand downstream, seriously impacting forested wetlands and creating a physically unstable and highly braided streambed. The photograph below (Figure 1.1) illustrates extensive erosive nature and flashy nature of higher flow events.

In January 2008, Clemson University’s Center for Watershed Excellence (Center) received a grant from the City to facilitate the development of the Sand River Ecological Restoration Master Plan (SRERMP). The Center initiated the planning process with a series of charrettes and working meetings among key stakeholders, local, state and federal agencies to identify ecological stressors, review existing data, identify data needs, evaluate alternatives, and formulate strategies for moving the restoration program forward. Background information, including presentation materials, can be found on the SRERMP website: http://www.clemson.edu/restoration/focus_areas/restoration_ecology/projects/sand_river/.

Tasks included review of historic information related to Sand River, compilation of existing scientific and engineering reports, and development of specific restoration goals and objectives. This year-long planning process employed a holistic approach to balancing stormwater management with habitat preservation and restoration and evaluated innovative solutions to address the root cause.

Sand River Ecological Restoration Master Plan (SRERMP)
The Sand River Ecological Restoration Master Plan incorporated remediation plans and outlined necessary agreements among stakeholders. In addition to the vision and specific goals, the plan outlined overall success criteria that incorporated engineering, hydrology, vegetation, and biotic components; nutrient cycling; timeframes and regulatory requirements. The restoration plan included hard engineering and ecological engineering elements supported by natural processes, incorporating sufficient time to allow natural processes to reestablish the natural structural and functional elements of the vision. The final plan also incorporated a public awareness element so the greater community will recognize and understand the need and importance of the restoration program and the economic costs and ecological impacts associated with stormwater. Public awareness is important for acceptance of new technologies that will reduce the stormwater volume into Hitchcock Woods through innovative use of green infrastructure. The final plan is available at: http://www.clemson.edu/restoration/focus_areas/restoration_ecology/projects/sand_river/downloads/sroct08_masterplan.pdf.
Project Location
The Sand River Ecological Restoration project focused on downtown City watersheds contributing stormwater and groundwater to the headwaters discharge, as illustrated in Figure 1.2 below. The majority of stormwater originates in three downtown drainage areas identified as South Boundary, CSX Railroad, and Red Cross West with flow estimates noted.

Options Discussion
At the third of three charrette / working meetings, restoration options were outlined for stakeholders in the form of a decision tree (Figure 1.4). Numerous options were evaluated, with pros and cons for each decision discussed. At the conclusion of the third meeting, the Clemson research team was asked by members of City Council to develop a preferred alternative for the project and present that option to stakeholders for consideration. As requested, the preferred alternative explored root causes and addressed the remediation of the canyon and routing of downtown Sand River watershed flows through a hybrid design from multiple past engineering studies. During the options presentation, the use of green infrastructure was presented as a key element.
The general outline of the preferred alternative focused on Sand River proper is outlined below and presented in schematic form in Figure 1.6.

1. Focus primarily on remediation of Sand River proper by extending the existing 10ft. aluminum pipe approximately 7500 ft;

2. Incorporate dual pipe placement within the deeper sections of the canyon to provide temporary storage and possibly a detention basin behind the old Red Cross Building adjacent to the railroad;

3. Re-create “Sand River” surface flow on top of the proposed pipeline in a manner that functions similar to the historic drainage of Sand River, allowing tributary flow and overland flows to enter the river before reconnecting in a junction box approximately 1000 feet above historic Barton’s Pond;

4. At the confluence of surface flow and piped downtown stormwater, provide a well-engineered headwall and plunge pool followed by adequate energy dissipation, and a sediment forebay. Flow coming from the forebay will provide sediment-reduced flows into Barton’s Pond Wetland. The wetland will remain a forested wetland and serve as a temporary storage basin during high flows and allow base flow to be staged into Cathedral Aisle Wetlands;

5. Create an earthen dam with an emergency spillway near Barton’s Pond Bridge and incorporate up to three flow control structures within Barton’s Pond Wetland that regulate discharge at base flow conditions in addition to the 2-and 5-year rain events. Flows exceeding the 5-year event will spill over the concrete emergency flow structure within the dam. Discharge piping will be well configured within the concrete portions of the dam;

6. Incorporate green infrastructure where appropriate to address the root cause of the flashy storm events.

Figure 1.4 - Sand River restoration decision tree
Components of the preferred alternative are shown in Figure 1.5, with headwaters noted in the downtown areas and connection to Hitchcock Woods illustrated in the map. A rendering of the preferred alternative is shown in Figure 1.6.

**Preferred Alternative of Sand River: Components**

1. Stormwater entering the Woods from downtown watersheds will be transported and stored within large pipes buried deep in the restored canyon. 2) At the point of “day lighting”, the water will flow through an engineered energy dissipation channel and then on to 3) Barton’s Pond Wetland where it will slowly discharge to Cathedral Aisle Wetlands.

**Figure 1.5 - Preferred alternative components**

**Figure 1.6 - Rendering preferred alternative components**
At the final presentation, an estimated cost by element for the preferred alternative was presented as $16 million. This significant cost prompted the stakeholders to reprioritize options and focus on the opportunity discussed during the workshops to consider green infrastructure alternatives as the best first solution to address the root cause of the downtown stormwater problem. This reprioritization of the potential role of green infrastructure was fully supported by the stakeholders and the Clemson team was asked to further investigate green infrastructure options. An illustration of green infrastructure examples presented during the charrettes are shown in Figure 1.7.

American Recovery and Reinvestment Act (ARRA) / US EPA
In 2009, the City of Aiken submitted a shovel-ready green infrastructure proposal to South Carolina Department of Health & Environmental Control for consideration for EPA managed ARRA funding specifically for green infrastructure. The City was awarded $3.34 Million under the American Recovery and Reinvestment Act (ARRA) for use in funding the design, construction, and post-construction monitoring for the green infrastructure concepts developed as part of the Sand River restoration master plan. The City awarded Clemson University’s Center for Watershed Excellence two City-funded research grants to assist in finalizing green infrastructure concepts, establishing an innovative real-time monitoring program, and to conduct an extensive research program on the effectiveness of the project to capture, store, infiltrate, and treat downtown stormwater through a suite of green infrastructure elements.

Center for Watershed Excellence / Institute of Applied Ecology
The Center for Watershed Excellence (CWE) is part of the Institute of Applied Ecology (IAE). IAE focuses on the application of novel and emerging technologies, innovative management strategies, and multi-scale outreach programs to solve major natural resources problems. The institute designation formalizes the efforts of the entrepreneurial faculty who are driving transformative science and technology in the areas of watershed ecology, green infrastructure, cyberinfrastructure, ecological restoration, and sustainable natural resources. The CWE and IAE collaborate with the SmartState® Centers of Economic Excellence in Urban Ecology and Sustainable Development which advance the state’s knowledge-based economy and create economic opportunities through their research.
2. PROJECT TEAM

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3. PROJECT OVERVIEW

Until recently, standard site development practices included conveying untreated stormwater runoff into an engineered underground and piped drainage network, increasing the intensity and volume of peak discharges and potentially affecting local water quality. Green infrastructure is a treatment approach that municipalities can utilize to maintain healthy waters, provide multiple environmental benefits, and support sustainable communities. Unlike single-purpose stormwater infrastructure, which uses pipes to dispose of rainwater, green infrastructure uses vegetation and soil to manage rainwater where it falls.

In 2009, the Clemson University Center for Watershed Excellence in partnership with the City of Aiken and Woolpert Inc. began an ambitious project to design, implement and quantify natural treatment systems to enhance stormwater infiltration in urbanized areas. The Sand River Headwaters Green Infrastructure Project in Aiken incorporates sustainable development practices to capture and treat stormwater within downtown watersheds. Bioswales and bioretention, underground cisterns and permeable pavement provide smart green solutions for urban stormwater management. These Best Management Practices (BMPs) enhance nature’s capacity to absorb stormwater, and provide both economic and environmentally sound approaches to reduce stormwater flows that are impacting the Sand River, Hitchcock Woods and other impaired waters downstream (Figure 3.1.1).

Primary Components
The Sand River Headwaters Green Infrastructure Project is divided into three primary components:

1. Stormwater Monitoring System and Infiltration Optimization;
2. Intelligent River® Integration; and
3. Landscape Architecture Design.

Project Objectives
1. Quantify hydrologic flows, pollutant concentration and loading of representative best management practices in response to storm events.
3. Optimize site-level remote data acquisition capabilities and integrate associated collection, transmission, display and archival facilities into the Intelligent River® network.
4. Evaluate stormwater management associated with the green infrastructure project.
5. Disseminate results to the general public, as well as regional design engineers, site developers, municipal and county stormwater staff, state environmental agencies, landscape architecture academics and professionals, planning agencies and peer-reviewed journals.
4. RESEARCH ELEMENTS

(4.1) Rainfall, Hydrology and Water Quality

Objectives
In order to determine the hydrologic and hydraulic effectiveness of the green infrastructure practices installed in the City of Aiken, the objectives of this component of the project were to:

1. Characterize the Sand River watershed by:
   - Analyzing peak flow and volume data at selected locations for all storm events greater than 0.1 inches.
   - Developing runoff coefficients for the Sand River headwaters watershed, Hoods Lane (treatment) subwatershed, and Sumter Street (reference) subwatershed before and after Bioretention Cell (BRC) installation.
2. Define, analyze, and quantify the impact, if any, of the BRC construction on the volume of stormwater being discharged from the City of Aiken,
3. Characterize the unit functions occurring within the BRCs and permeable asphalt sites and develop a water budget for these systems in order to better understand the small scale effectiveness of these practices,
4. Build, calibrate, and validate a model representing BRC hydraulics and water budgets using available design parameters from the as-built BRCs as well as hydrologic monitoring data, and
5. Assess the water quality benefits of the BRCs via sampling and laboratory analyses.

The results from this work quantify the impact of the green infrastructure retrofits on peak flow and volume reduction of stormwater and the hydrologic enhancement of an urbanized watershed. Quantification of the impacts of these practices will aid in the future design and construction of green infrastructure practices in the City of Aiken and beyond as they become more widely accepted and as design criteria and standards are refined.

Methods

Weather Parameters
Meteorological parameters were monitored within the contributing Sand River Headwaters watershed. Weather data were collected in the center of the downtown area (33.561°N, -81.719°W) with an additional rain gage located near the stormwater outfall (33.555°N, -81.722°W). A Campbell Scientific® weather station was located in a parkway on Chesterfield St. between Park Ave. and Richland Ave. The data logger was configured to collect measurements on 1-minute intervals except for a brief period from April 2012 – June 2012 when the sampling frequency was temporarily changed to 10-minute intervals. Table 4.1.1 summarizes the components of the data logger and sensor equipment for measuring meteorological parameters.

<table>
<thead>
<tr>
<th>Description</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Reporting Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Logger</td>
<td>Campbell Scientific® (Logan, UT)</td>
<td>CR800</td>
<td>-</td>
</tr>
<tr>
<td>Power Supply</td>
<td>Campbell Scientific® (Logan, UT)</td>
<td>PS100-SW</td>
<td>-</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>BP® (London, UK)</td>
<td>SP10</td>
<td>-</td>
</tr>
<tr>
<td>Barometer</td>
<td>Setra® (Boxborough, MA)</td>
<td>CS100</td>
<td>kPa</td>
</tr>
<tr>
<td>Anemometer</td>
<td>RM Young® (Traverse City, MI)</td>
<td>03002-L13</td>
<td>m/s</td>
</tr>
<tr>
<td>Rain Bucket</td>
<td>Texas Electronics® (Lubbock, TX)</td>
<td>TES25-L13</td>
<td>mm</td>
</tr>
<tr>
<td>Temp/RH Sensor</td>
<td>Campbell Scientific® (Logan, UT)</td>
<td>CS215-L13</td>
<td>°C/%</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Li-Cor® (Lincoln, NE)</td>
<td>LI200X-L13</td>
<td>W/m²</td>
</tr>
<tr>
<td>PAR sensor</td>
<td>Li-Cor® (Lincoln, NE)</td>
<td>LI190SB-L13</td>
<td>mmol/m²</td>
</tr>
</tbody>
</table>

A second ISCO® tipping bucket rain gage in addition to the downtown station was deployed at the outfall of the 10 ft. pipe adjacent to Hitchcock Woods and logged with an ISCO® 6712 automated sampler.

Watershed Flow Monitoring
Stormwater flow was monitored in order to calculate the volume of stormwater contributed by two of the subwatersheds, as well as to determine the total volume of stormwater leaving the entire watershed (HUC 030601060203) for a given
storm event. The stormwater flow as overall watershed and also subcatchment discharge was monitored in three different locations (Figure 4.1.1): the Sand River headwaters (1220 acres) at the 10-foot pipe outfall in Hitchcock Woods (33.555°N, -81.722°W), the treatment catchment at Hoods Lane (47 acres) draining Newberry St. from Park Ave. (33.557°N, -81.722°W), and the control or reference catchment (340 acres) at the intersection of South Boundary Street and Sumter Street (33.552°N, -81.715°W).

For the Sand River Headwaters watershed, the ISCO® 6712 automated sampler (same as for rainfall above) equipped with an ISCO® 730 Bubbler Flow Module was deployed to measure water level in the 10-pipe at a manhole access upstream of final discharge. At the Hoods Lane and Sumter Street monitoring locations, ISCO® 2150 Area/Velocity units were used to monitor flows in stormwater pipe trunklines with available manhole access. The data collected from the ISCO® units were exported into Microsoft Excel® for further analyses, including the calculation of flow (cfs) based on the stormwater level and pipe characteristics using Manning’s equation, the volume of stormwater per storm (cf) by integration of each flow hydrograph, and then finally as the equivalent depth (in.) of outflow volume based on watershed area. The runoff coefficient was then determined with equivalent outflow depth as compared to rainfall depth as a ratio (or percentage).

**BMP Hydrology Monitoring**

Multiple sensors were placed in and around the BRCs to monitor their function and effectiveness (Figure 4.1.2). The following parameters were monitored on most of the cells: inflow, outflow, soil moisture, and level. Bioretention cell inflow and outflow were measured using ISCO® 6712 sampling units equipped with ISCO® 730 bubbler modules. Both inflow and outflow were routed through a box outfitted with a combination weir that consisted of a v-notch section and rectangular section.

Within the cell, soil moisture sensors were placed in the bioretention soil media (BSM) at different locations and multiple depths. The data from the soil moisture sensors were accessed remotely from the Intelligent River® database (see Section 4.2 Bioretention Soil Moisture for more details). Soil moisture data were analyzed to determine the infiltration rate of the bioretention soil media. This analysis was accomplished by comparing the time at the peak volumetric water content to the distance between the sensors.
In the cells located at Chesterfield Street between Richland Avenue and Park Avenue (CRP) and Park Avenue between Chesterfield Street and Newberry Street (PCN), Solinst® level loggers were installed to measure surface water stage and thus storage within the cells. The level data were analyzed to determine the maximum amount of storage achieved by any given cell based on free water height within the cell. By determining this characteristic volume at different elevations within the cell, a stage-storage relationship was developed. Based on this relationship, the level data were converted to stormwater volume in storage. Infiltration rates were also calculated from these level data. As the cell fills up with stormwater, the level quickly increased to a peak value, then declined at a steady rate until the cell no longer held any surface water. The rate of decline of the level in the cell was calculated as an infiltration rate.

**BMP Water Budget Modeling**

The Bioretention Cells (BRC) were modeled in STELLA® (ISEE Systems, Inc., 2007). This software program allows the user to create a water budget, control the physical parameters of the cell, and produce outputs that may be used to analyze BRC performance and function. The water budget included the following input information: precipitation, surface runoff, and inlet flow, evapotranspiration, exfiltration, and outlet flow, to be able to predict cell storage (Figure 4.1.3).

A BRC is different from common retention areas in that part of the designed storage volume is contained within the soil media, and is referred to as the internal water storage zone (IWS). The volume of water stored in this zone is a design parameter and is a function of the media depth and porosity.

In the development of the STELLA® model, the input data were collected from previously described devices in or near the BRC being monitored, specifically the weather station (Table 4.1.1) and the ISCO® inlet and outlet flow monitoring equipment. Potential evapotranspiration (PET) was calculated using the Turc method, which requires temperature, solar radiation, and relative humidity data. The model was designed to predict stormwater storage volume in the BRC and then compared to observed stormwater storage level based on stage data from the Solinst® level logger.
Table 4.1.2 provides a summary of the input data for the model simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>P</td>
<td>in/hr</td>
<td>Measured</td>
</tr>
<tr>
<td>Potential Evapotranspiration</td>
<td>PET</td>
<td>mm/day</td>
<td>Calculated from meteorological data</td>
</tr>
<tr>
<td>Inlet Flow</td>
<td>Q_in</td>
<td>ft³/hr</td>
<td>Calculated from inlet level data</td>
</tr>
<tr>
<td>Outlet Flow</td>
<td>Q_out</td>
<td>ft³/hr</td>
<td>Calculated from outlet level data</td>
</tr>
<tr>
<td>Infiltration Rate</td>
<td>i</td>
<td>in/hr</td>
<td>Calculated from BRC level data</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>RH</td>
<td>%</td>
<td>Measured</td>
</tr>
<tr>
<td>Temperature</td>
<td>T</td>
<td>°C</td>
<td>Measured</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td>SR</td>
<td>cal/cm²</td>
<td>Measured</td>
</tr>
<tr>
<td>Cell Area</td>
<td>A</td>
<td>ft²</td>
<td>Measured</td>
</tr>
<tr>
<td>BSM Depth</td>
<td>d</td>
<td>ft</td>
<td>Measured</td>
</tr>
<tr>
<td>Porosity</td>
<td>n</td>
<td>-</td>
<td>Measured</td>
</tr>
</tbody>
</table>

Another required physical parameter for simulations includes the stage-storage relationship pertaining to the specific BRC. Simulations were performed using an hourly time step over the duration of an individual storm event. The general schematic for the model is shown in Figure 4.1.4. Simulations were performed specifically for the cell on Park between Chesterfield and Newberry (PCN) and the cell on Chesterfield between Richland and Park southernmost cell (CRP-S) because these sites had the most complete and best quality monitoring data with which to populate the model. Nash-Sutcliffe coefficients were used to evaluate model performance between predicted and observed data.

Equation 1 provides the overall storage relationship for the BRC based on the model input data.

$$BRC(t) = BRC(t - dt) + (\text{Stormwater_Inlet} + \text{direct_rainfall} - \text{PET_loss} - \text{Infiltration} - \text{Outlet}) \times dt$$

Where,

- $BRC$ = Storage within the BRC [ft³]
- $t$ = time [hr]
- $\text{Stormwater_Inlet}$ = inflow [ft³/hr]
- $\text{direct_rainfall}$ = rainfall falling directly on the cell and the surrounding impervious surfaces [ft³/hr]
- $\text{PET_loss}$ = loss due to potential evapotranspiration [ft³/hr]
- $\text{Exfiltration}$ = loss from water within the cell leaving the soil media and infiltrating back into the native subsoil [ft³/hr]
- $\text{Outlet}$ = outflow [ft³/hr]
Figure 4.1.4 - STELLA® model configuration
BMP Water Quality

Influent and effluent water qualities were automatically sampled and monitored. The ISCO 6712® sampling units were programmed to collect water flowing in the inlet and outlet to each cell if there was a sufficient volume of water passing through the cell. Sample collection took place after a programmed volume of stormwater had flowed into the system. The automated sampling protocol had two components: (1) the first flush of stormwater and (2) a composited sample from the entire sampling event. This two-part sampling protocol was conducted to discriminate between any fluctuations in inlet concentrations over the duration of the sampling event. After a qualifying storm event, samples were collected from the ISCO® 6712 sampling unit, stored on ice, and transported to a certified lab for analyses, including total suspended solids (TSS), nitrate, ammonia, potassium, zinc, copper, phosphorus, and oil and grease (O/G) as DRO in water (Table 4.1.3).

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Method</th>
<th>Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>SM 2540-D</td>
<td>10 mg/L</td>
</tr>
<tr>
<td>Nitrate</td>
<td>SM 4500NO3-E</td>
<td>0.02 mg-N/L</td>
</tr>
<tr>
<td>Ammonia</td>
<td>EPA 350.1</td>
<td>0.1 mg-N/L</td>
</tr>
<tr>
<td>Total Phosphorous</td>
<td>EPA 365.4</td>
<td>0.1 mg-P/L</td>
</tr>
<tr>
<td>Copper</td>
<td>EPA 200.7</td>
<td>0.02 mg/L</td>
</tr>
<tr>
<td>Zinc</td>
<td>EPA 200.7</td>
<td>0.02 mg/L</td>
</tr>
<tr>
<td>Nitrite</td>
<td>SM 4500NO2-B</td>
<td>0.01 mg-N/L</td>
</tr>
<tr>
<td>DRO in Water</td>
<td>SW846 SM 3510C/8015B</td>
<td>0.469 mg/L</td>
</tr>
</tbody>
</table>

The concentration from the composited sample was considered to be the Event Mean Concentration (EMC) for a given storm because the composite sample represented a consistent sample volume taken at intervals each time a known volume of stormwater flowed into the system. The mass load of constituent (g or kg) entering a cell was calculated by multiplying the EMC and the total stormwater inflow volume. Water quality sampling was focused on the cell on Park between Chesterfield and Newberry (PCN) because it had the most significant inflow for measured storm events. There was no outflow for the PCN cell, so all mass load entering the cell was assumed to be removed from the overall stormwater system and managed solely by the BRC. None of the other bioretention cells in downtown Aiken had measurable inflows or outflows, so these were not sampled.

Results and Discussion

Watershed Hydrology

From January 2010 to January 2012, there were 132 monitored storms greater than 0.1 inches. Due to various technical problems, there were 131 storms analyzed at the 10-foot pipe outfall, 119 storms analyzed at the Hoods Lane monitoring station, and 104 storms were analyzed at the Sumter Street monitoring station. On April 31, 2011, all BRC construction was completed, and storms after this date are referred to as “post-construction”.

Figure 4.1.5 - Cumulative rainfall (right axis) and runoff (left axis) from the entire watershed (Storms larger than 0.1 in., n = 131). Note that these data provide an underestimate of runoff that was actually discharged, using only storm-based volume calculations and not including baseflow, which may be significant at this station.
Figures 4.1.5, 4.1.6, and 4.1.7 show the cumulative rainfall and the stormwater runoff volume for the entire Sand River watershed and the two subwatersheds, respectively.

Figures 4.1.8, 4.1.9, and 4.1.10 show the rainfall and runoff volume relationship for the 10-ft pipe, Hoods Lane, and Sumter Street, respectively, and with separate trends each for pre- and post-stormwater green infrastructure practice installation.
For the 10-foot pipe and Sumter Street watersheds, the post construction trend line has a smaller slope than the pre-construction trend line. These results imply that there may have been less runoff volume from these watersheds after the construction of the BRCs. Data from the Hoods Lane watershed show an opposite trend - there was more runoff after the construction of the BRCs. However, the confidence intervals (not shown but available upon request) for the pre-construction and post-construction trendlines overlap, and therefore, solely fitting trend lines to the data is insufficient evidence to show that the BRC construction significantly impacted the volume of water being discharged from the watershed.

Table 4.1.4 shows a summary of the average runoff coefficients for the entire Sand River Headwaters watershed, Hoods Lane watershed, and Sumter Street watershed. A higher runoff coefficient is indicative of a larger volume of stormwater leaving an area per unit volume of precipitation.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Pre-Construction</th>
<th>Post-Construction</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>10’ Pipe</td>
<td>0.545</td>
<td>0.497</td>
<td>131</td>
</tr>
<tr>
<td>Hoods Ln.</td>
<td>0.322</td>
<td>0.314</td>
<td>119</td>
</tr>
<tr>
<td>Sumter St.</td>
<td>0.134</td>
<td>0.0895</td>
<td>104</td>
</tr>
</tbody>
</table>

To summarize, when the storms are analyzed individually based on rainfall and runoff (Figures 4.1.9 and 4.1.10), the events prior to the installation of bioretention and permeable paving materials generated less runoff than those events after installation at the smaller watershed scale (Hoods Lane versus Sumter Street), thus not demonstrating evidence of reduced stormwater. However, at the Sand River Headwaters watershed (10-ft. pipe) (Figure 4.1.8), some stormwater reduction was evident at the larger watershed scale. Furthermore, on an average runoff coefficient basis over all storms, stormwater volumes were reduced after practice installation (Table 4.1.4). This discrepancy can be attributed to several factors: (1) the Hoods Lane monitoring station only represented a very small drainage area compared to the larger urban watershed that was retrofitted with stormwater controls; (2) a lack of monitoring that represented the larger urban watershed; (3) a lack of a full understanding of the complex urban drainage area and the routing of stormwater in the subsurface pipe network; (4) rainfall distribution over the larger urban watershed was not considered with only one rain gage located within the watershed; (5) variable storm intensity between events over the course of the study; (6) seasonal variability in antecedent wet and dry conditions prior to each storm event, and (7) the possibility of irrigation contributions to the stormwater discharge within the downtown Aiken urban watershed.
BMP Hydrology Monitoring

Each of the BRCs was designed to reduce peak flow and capture a specific volume of stormwater. Table 4.1.5 summarizes the design peak inflows and captured volumes for a 2-year storm, as well as the maximum recorded inflows and capture volumes during the time data was collected for storms of at least a 2-year return period.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Design (2-year)</th>
<th>As-built (greater than 2-year storms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Inflow (cfs)</td>
<td>Capture Volume (cf)</td>
</tr>
<tr>
<td>PUF</td>
<td>2.02</td>
<td>1196</td>
</tr>
<tr>
<td>PCN</td>
<td>11.55</td>
<td>11398</td>
</tr>
<tr>
<td>CRP-N2</td>
<td>2.76</td>
<td>2722</td>
</tr>
<tr>
<td>CRP-S3</td>
<td>1.62</td>
<td>1597</td>
</tr>
<tr>
<td>PNL</td>
<td>10.19</td>
<td>10055</td>
</tr>
</tbody>
</table>

Table 4.1.5 - Bioretention Cell Peak Flow and Capture Volume Summary

As Table 4.1.5 shows, each of the monitored cells except CRP-S appears to be over-designed in terms of peak inflow and maximum capture volume. The design of any retention structure is dependent on variables such as drainage area, land use, and rainfall. While land use and design rainfall can be determined based on assumptions, the drainage area contributing runoff to each cell is more difficult to ascertain. The design documents use varying drainage areas for each cell and they range from 0.34 acres to 3.14 acres. These drainage areas were determined by topographical maps and available stormwater pipe infrastructure diagrams. While many assumptions must be applied as design criteria for direct rainfall and surface runoff to each cell, it is more difficult to determine the appropriate drainage area when an existing storm sewer pipe is routed into the cell. Additional flow routed from the existing stormwater infrastructure is likely what accounted for the disparity between the design and as-built peak flows within the cells. Peak flows into PCN and PNL were only a fraction of what was designed and as a result, the cells are functioning at less capacity than they were designed. However, this “over-design” of the BRCs is typically more desirable than an under-sized system, which could result in flooding, short-circuiting, and/or poor hydraulic and treatment performance.

The monitored inlet into the PCN cell was not the only route that stormwater could enter the cell. Table 4.1.6 shows the measured and calculated contributing sources of stormwater for the PCN cell based on measured inflow and level data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall (in)</th>
<th>Inlet Volume (ft³)</th>
<th>Direct Rainfall (ft³)</th>
<th>Surface Runoff (ft)</th>
<th>Total Storage (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/13/12</td>
<td>0.19</td>
<td>667</td>
<td>483</td>
<td>1029</td>
<td>2178</td>
</tr>
<tr>
<td>3/16/12</td>
<td>0.15</td>
<td>655</td>
<td>381</td>
<td>1202</td>
<td>2238</td>
</tr>
<tr>
<td>3/23/12</td>
<td>0.27</td>
<td>519</td>
<td>686</td>
<td>961</td>
<td>2166</td>
</tr>
<tr>
<td>3/31/12</td>
<td>0.55</td>
<td>1818</td>
<td>1398</td>
<td>487</td>
<td>3702</td>
</tr>
<tr>
<td>4/1/12</td>
<td>0.2</td>
<td>763</td>
<td>508</td>
<td>1567</td>
<td>2838</td>
</tr>
<tr>
<td>4/2/12</td>
<td>0.66</td>
<td>433</td>
<td>1677</td>
<td>96</td>
<td>2206</td>
</tr>
</tbody>
</table>

Total: 4854 ft³, 5133 ft³, 5341 ft³, 15328 ft³

Measured inlet flow accounts for approximately one-third of the stormwater entering the cell, with calculated direct rainfall accounting for another third. Surface runoff is calculated by subtracting the volumes entering via the inlet structure and falling directly on the cell from the total volume of storage measured within the cell. With the installation of the level logger, the contributing volume of surface runoff can be calculated. However, the peak flow from the surface runoff is almost impossible to accurately quantify because flow routing of surface runoff across the permeable asphalt cells and through the numerous curb cuts. However, the relative volume of surface runoff entering the cell through...
the curb cuts could present a valid explanation for the small measured flows summarized in Tables 4.1.5 and 4.1.6. Thus the cells may be functioning closer to their designed capacity for peak flow reduction than based on measurements only at the inlet.

Infiltration rates for the BSM as designed, as-built, and as tested one year post-construction are detailed in Table 4.1.7.

Table 4.1.7 - Bioretention Soil Media Infiltration Rates

<table>
<thead>
<tr>
<th>Cell</th>
<th>Design (in/hr)</th>
<th>Native Soil (in/hr)</th>
<th>After 1 year (in/hr)</th>
<th>BSM (S-M sensors) (in/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUF</td>
<td>10</td>
<td>10.8</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>PCN</td>
<td>10</td>
<td>ND</td>
<td>35.8</td>
<td>ND</td>
</tr>
<tr>
<td>CRP-N</td>
<td>10</td>
<td>16.8</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>CRP-S</td>
<td>10</td>
<td>ND</td>
<td>30.7</td>
<td>2.3</td>
</tr>
<tr>
<td>PNL</td>
<td>10</td>
<td>21.6</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

(ND = not determined)

The tested BSM displayed infiltration rates in excess of the specified infiltration rates. The native soil also had infiltration rates larger than the design values. High infiltration rates in both the BSM and the native subsoil may explain why the maximum measured capture volume is much less than the designed capture volume. If the stormwater is infiltrating into the BSM and exfiltrating into the native subsoil at a rate higher than the design rate, there would be significantly less ponding measured on the surface of the BRC.

**BMP Hydrology Modeling**

Using data from March - June 2012, the level of captured stormwater in the PCN BRC was simulated with a 1-hour time step and compared to the observed level data measured on a 10-minute time step during the same time period. A four-month period was simulated using the Runge-Kutta method for solving differential equations. During the modeled period there were 15 storm events of varying duration and intensity. Predicted versus observed results are provided in Figures 4.1.11 and 4.1.12 for PCN and CRP-S, respectively.

Modeled level peaks coincide with the measured level peaks for larger storms, and for one storm, occurring on 5/9/12, the model over-predicted the level in the PCN cell.
Nash-Sutcliffe coefficients were calculated from the measured and modeled data from each cell to determine the effectiveness of the model, and this information is summarized in Table 4.1.8.

<table>
<thead>
<tr>
<th></th>
<th>PCN</th>
<th>CRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2NS</td>
<td>-0.70</td>
<td>0.68</td>
</tr>
</tbody>
</table>

The average and median rainfall for a storm during the modeled time period was 0.71 in. and 0.53 in., respectively. An analysis of the Nash-Sutcliffe coefficients suggests that the model is more effective at predicting the level in the CRP BRC than using only the mean of the measured data, but not as effective at predicting the level in the PCN BRC (Nash-Sutcliffe coefficients range from -1 to +1 with the larger number being a better correlation). This disparity could be due to several reasons including the time step of the model and the input data used to model the PCN cell. The model tended to under-predict storms with rainfall less than 0.25 in. Since the model had a time step of one hour, it is possible that small storms with short durations could be missed. Level data would be more sensitive because the sampling frequency was 10 minutes. Due to the larger time step used in the model and the relatively high infiltration rates of the bioretention soil media and the native subsoil, the smaller storms may have occurred and infiltrated within the one hour period. Using a smaller time step within the model may correct the problem for smaller storms, but it will cause the modeled time span to be much shorter due to the internal restrictions present in the program. Also, using a smaller time step may require more modification of the input data to ensure proper functioning within the program. Larger storms tended to result in over-prediction of the level in the cell.

**BMP Water Quality**

The effectiveness of the PCN BRC in improving water quality was quantified by examining the influent and effluent event mean concentrations (EMCs) of several common pollutants. By comparing the EMC for the influent and effluent flows, the net capture or export of pollutants was determined. As previously mentioned, the PCN cell frequently experienced backflow conditions, which made the precise calculation of EMCs very difficult. Four storms (11/29/11, 12/28/11, 1/21/12, and 2/24/12) had a backflow occur, which led to an over-estimation in the EMC for the inlet. As a result, it was assumed that the BRC likely received a maximum inflow of 7800 cubic feet (58,500 gallons). This value was calculated using the level and flow data from similar sized storms occurring after the installation of the level logger.
Sampling events, rainfall, storage volume, and constituent mass collect in PCN are detailed in Table 4.1.9. The primary pollutants were Total Suspended Solids (TSS), Nitrate, Ammonia, and Zinc.

Table 4.1.9 - Sampling Event EMC Summary for Selected Pollutants in the PCN Cell

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Rainfall (in)</th>
<th>Storage (gal)</th>
<th>TSS (kg)</th>
<th>Nitrate (g)</th>
<th>Ammonia (g)</th>
<th>Tot. P (g)</th>
<th>Cu (g)</th>
<th>Zn(g)</th>
<th>Nitrite (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/19/2011</td>
<td>0.26</td>
<td>39085</td>
<td>2.5</td>
<td>12.3</td>
<td>17.0</td>
<td>-</td>
<td>-</td>
<td>8.6</td>
<td>-</td>
</tr>
<tr>
<td>11/16/2011</td>
<td>0.52</td>
<td>43440</td>
<td>2.9</td>
<td>6.9</td>
<td>20.2</td>
<td>-</td>
<td>1.1</td>
<td>11.4</td>
<td>-</td>
</tr>
<tr>
<td>11/29/2011*</td>
<td>0.78</td>
<td>58531</td>
<td>1.4</td>
<td>32.4</td>
<td>37.2</td>
<td>27.3</td>
<td>1.9</td>
<td>17.7</td>
<td>-</td>
</tr>
<tr>
<td>12/28/2011*</td>
<td>0.87</td>
<td>58531</td>
<td>9.8</td>
<td>66.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>21.6</td>
<td>-</td>
</tr>
<tr>
<td>1/12/2012</td>
<td>0.26</td>
<td>30365</td>
<td>2.1</td>
<td>15.6</td>
<td>16.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1/18/2012</td>
<td>0.22</td>
<td>8262</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>NT</td>
<td>3.4</td>
<td>NT</td>
</tr>
<tr>
<td>1/21/2012*</td>
<td>1.01</td>
<td>58531</td>
<td>5.1</td>
<td>32.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>54.7</td>
<td>-</td>
</tr>
<tr>
<td>2/24/2012*</td>
<td>0.81</td>
<td>58531</td>
<td>4.3</td>
<td>36.6</td>
<td>-</td>
<td>-</td>
<td>4.8</td>
<td>14.6</td>
<td>-</td>
</tr>
<tr>
<td>3/3/2012</td>
<td>0.56</td>
<td>102396</td>
<td>0.1</td>
<td>1.0</td>
<td>2.1</td>
<td>-</td>
<td>0.1</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>3/31/2012</td>
<td>0.55</td>
<td>27691</td>
<td>2.4</td>
<td>12.5</td>
<td>42.0</td>
<td>-</td>
<td>-</td>
<td>6.9</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>5.84</strong></td>
<td><strong>485363</strong></td>
<td><strong>30.6</strong></td>
<td><strong>216.5</strong></td>
<td><strong>134.8</strong></td>
<td><strong>27.3</strong></td>
<td><strong>7.9</strong></td>
<td><strong>140.9</strong></td>
<td><strong>1.4</strong></td>
</tr>
</tbody>
</table>

- Below Detectable Limit
* Backflow conditions
NT = Not Tested
Next Steps

Expanded Subcatchment Monitoring

One of the major challenges associated with the urban watershed monitoring and subsequent collection of information about green infrastructure effectiveness for stormwater management in Aiken has been the lack of understanding of true watershed boundaries and stormwater infrastructure routing. Some uncertainties in stormwater runoff analyses at the watershed scale were identified in this report, and these were attributed to several factors: (1) the Hoods Lane monitoring station only represented a very small drainage area compared to the larger urban watershed that was retrofitted with stormwater management practices; (2) a lack of monitoring that represented the larger urban watershed; (3) a lack of a full understanding of the complex urban drainage area as well as the routing of stormwater in the subsurface pipe network, including catch basin and drop inlet connectivity and stormwater pipe alignment and grade within the system; (4) rainfall distribution over the larger urban watershed was not considered with only one rain gage located within the watershed (with a second gage on the boundary at the Sand River Headwaters discharge point); (5) variable storm duration and intensity between events over the course of the study; (6) seasonal variability in antecedent wet and dry conditions prior to each storm event; and (7) the possibility of irrigation contribution to the stormwater discharge within the downtown Aiken urban watershed.

Investigators have a working proposal submitted to the City of Aiken to undertake efforts to better understand the urban watershed delineations and sources of stormwater to the Sand River Headwaters watershed discharge. These efforts would allow for prioritization of future strategic green infrastructure installations in the downtown Aiken area and also within the larger watershed. Proposed efforts include:

1. Quantification of Volume and Routing for Sand River Headwaters Watershed (including all known flow sources that contribute to the “10-ft pipe” network)

2. Integration with Intelligent River® network: As a first step, a new wireless infrastructure will be installed to extend the wireless mesh in Aiken. The infrastructure would be based on the new hardware that was put in place a few months back, but would leverage new radios that will offer better obstacle penetration. The next step is the installation of the mote devices. Depending on the project timeline, we may opt to install version 1.0 devices and could then go in and do an upgrade at a later point. Current efforts include a full system overhaul, including a new web front-end. This represents a significant software development cost reduction for the city.
3. **Optimize Location for Future GI Installation:**
- Hydrologic Analysis based on #1 above
- Cost-Benefit Analysis
- Development of Decision Matrix
- Existing Infrastructure
- Drainage Area Contribution to Stormflow and Watershed Discharge
- Water Volume Available
- Proximity

**Continued BMP Investigations – Water Quantity and Quality**
The results of completed work provided in this report confirms the need for continued monitoring of both water quantity and quality to better understand the performance of green infrastructure installations for effective stormwater peak flow and volume reduction. The continued work using existing monitoring equipment, sampling and analyses, and data interpretation as described in this report would be beneficial toward accomplishing this goal.

**Watershed Scale Modeling**
One of the remaining major tasks is to integrate the stormwater control measures, whether existing or future practices or both, into larger watershed scale models to effectively examine the overall performance of stormwater management using green infrastructure technologies. This integration of practice and watershed scale information would be beneficial not only to the City of Aiken but also to similar urban areas that are experiencing stormwater volume and flow control issues and reduction needs. The City of Aiken has been a pioneer in implementing green infrastructure in their urban setting, and the associated past and future research efforts related to this project have led and will lead to a better understanding these innovative technologies.
4. RESEARCH ELEMENTS

(4.2) Bioretention Soil Moisture Monitoring, Modeling and Visualization

Introduction
The hydrology of urban areas is influenced by high percentages of impervious cover and alterations to soil and vegetation (Arnold et al. 1996; Stankowski 1972; Pitt et al. 2000). These factors lead to increased frequency and magnitude of stormwater production, degradation of water quality, and alterations to ground water recharge (US EPA 2007). Management decisions can reduce the negative impacts of stormwater at the local and watershed scale. Stormwater management has traditionally focused on conveyance of stormwater away from urban centers as quickly as possible (Niemczynowicz 1999; Arnold et al. 1996). Recently, Low Impact Development (LID) design practices have shown promise as an alternative to traditional stormwater control structures. Bioinfiltration technologies are among the most widely applied LID management techniques in urban watersheds. The benefits of bioinfiltration systems include reductions in peak flows, increases in ground water recharge, decreases in runoff volumes, pollutant filtering.

Bioinfiltration systems are a relatively recent LID practice and there has been little research evaluating their long-term performance and maintenance requirements (Davis et al. 2009). Studies investigating trends in multi-year performance of bioinfiltration sites have produced varying results. Lindsey et al. (1992) found that 27% of infiltration basin BMPs surveyed functioned as designed after four years, with 46% of these failures attributable to excessive sediment washing into the BMP and becoming trapped in the void spaces of the surface layer. However, Jenkins et al. (2010) found that sediment deposits were not an issue after eight years. Similarly, Emerson and Traver (2009) did not find any systematic reductions in performance over a four-year period. Besides sedimentation, mechanical compaction, raindrop impact, repeated ponding influence long-term performance of infiltration BMPs (Brown and Hunt 2010; Davis et al. 2009; Pitt et al. 2000).

The uncertainty associated with the design and lifecycle of bioinfiltration BMPs makes monitoring and maintenance a crucial component of their success. Continuous monitoring using automated methods may yield information not otherwise available through standard methods (e.g., infiltration rate testing and drawdown testing) that require site visits. Common continuous measurement parameters for bioinfiltration systems include inflow and outflow measurements, ponding level, local precipitation, and soil water content. Wireless sensor network (WSN) technology, which is able to stream data to remotely located data consumers, is appropriate for continuous monitoring of soil water content at higher resolutions or greater spatiotemporal scales (Bogena et al. 2010). Streaming data can be processed and validated using automated techniques which simplifies data management and avoids the “information overload” potential that exists with high levels of sensor readings. Other advantages include the ability to automatically identify faults and notify responsible parties when failures occur (Eidson et al. 2010).

The optimal design of bioinfiltration systems is complicated by the challenges associated with characterizing surface hydrology in urban areas. These challenges stem from alteration to topography, additions of impervious surfaces, and routing of stormwater flows to underground conveyance systems. Urban surface hydrology modeling methods may be soil physical theory based (e.g., Richard’s equation, Green-Ampt equation) or empirically based (e.g., SCS Curve Number, Rational Method). Parameterization and calibration of infiltration models requires detailed precipitation, topography, and soil property information. Geographic Information Systems (GIS) can aid in data management, data preparation, and analysis of model results. Grid modeling approaches, based on cell-based raster data, can perform prediction at a within-catchment spatial scale. Within-catchment scales describe a model that discretizes space into elements smaller than a hydrologic catchment. This scale is necessary to capture the localized hydrological processes that govern bioinfiltration performance and cannot be adequately described by point or lumped approaches.
Numerous studies have shown that soil infiltration rates exhibit limited spatial dependency, even at local scales (Beven 2012; Greminger et al. 1985; Sobieraj et al. 2004). At catchment or regional scales, soil map unit and series may adequately describe spatial heterogeneity of infiltration. However, at local scales biological processes such as tree roots, earthworm burrows (Lee 1985) or ant nests (Eldridge 1994) may dominant. Estimation of soil properties in urban areas presents an additional challenge, as urban soils are subject to anthropogenic disturbance, e.g., compaction (Pitt et al. 2000). Uncertainty associated with soil property estimation has implications for bioinfiltration system design. Variations in soil properties greatly influence the infiltration rates of soil and media (Kale 2011). Grid-based infiltration models can describe and illustrate infiltration processes at within catchment spatial scales. This spatial scale is important when modeling bioinfiltration systems that may only drain contributing areas encompassing a few city blocks. Grid-based approaches are also conducive to visualization, which opens up the decision making process to a non-engineering audience.

This chapter evaluates bioinfiltration systems installed as part of a green infrastructure initiative in the City of Aiken. Monitoring data is used to evaluate the efficacy of LID practices and identify temporal trends in media properties. This research focuses on within-catchment scales, using soil, topography, and hydrologic data encoded as cell-based raster data. Analysis and modeling is performed within a GIS framework and illustrated using 3D visualization techniques. The objectives of this research were: 1) summarize the physical and hydraulic properties of soil within the City of Aiken, SC; 2) evaluate the spatial structure of saturated hydraulic conductivity within the study area to help parameterize the model discussed subsequently; 3) examine temporal trends in effective porosity using a wireless sensor network of soil moisture sensors and evaluate its potential as a bioinfiltration performance indicator; 4) implement a grid-based infiltration and rainfall excess model geared towards modeling bioinfiltration systems at within catchment scales; 5) visualize modeled bioinfiltration basin performance.

### Soil / Media Properties

**Native Soil Description**

The bioinfiltration basins under observation are located in the City of Aiken, South Carolina (33.549397, -81.720689), which is located in the Upper Coastal Plain physiographic region of the southeastern United States (Figure 4.2.1).

![Figure 4.2.1 - Map of study area, monitoring sites and bioinfiltration basins](image)

Monitoring and soil characterization is performed on a 0.62 square kilometers (0.24 sq. mi.) area of interest (AOI) located in the central commercial district (Figure 2). The AOI is predominantly Orangeburg loamy sand (OrA, 0.43 sq. km2 or 69% of AOI) soil with some Fuquay sand (FuB, 0.191 sq. km2 or 31% of AOI) soil (Figure 4.2.2 and Table 4.2.1).
Figure 4.2.2 - Map of soil sample sites and soil map unit boundaries
**Table 4.2.1 - Selected soil physical and chemical properties for Fuquay and (FuB) and Orangeburg loamy sand (OrA) for Figure 4.2.1 (Source: USDA/NRCS Soil Data Mart, 2012)**

<table>
<thead>
<tr>
<th>Horizon(s)</th>
<th>Depth (cm)</th>
<th>Soil pH</th>
<th>Organic matter (%)</th>
<th>Clay</th>
<th>Moist bulk density (g cm$^{-3}$)</th>
<th>Saturated hydraulic conductivity (mm hr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuquay sand (FuB), 2-6 % slope (loamy, kaolinitic, thermic Arenic Plinthic Kandiudults)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap</td>
<td>0-20</td>
<td>4.5-6.0</td>
<td>0.5-2.0</td>
<td>1-7</td>
<td>1.60-1.70</td>
<td>151.20 – 507.60</td>
</tr>
<tr>
<td>E</td>
<td>20-53</td>
<td>4.0-6.0</td>
<td>0.0-0.5</td>
<td>0-15</td>
<td>1.45-1.55</td>
<td>151.20 – 507.60</td>
</tr>
<tr>
<td>E</td>
<td>53-88</td>
<td>4.5-6.0</td>
<td>0.0-0.5</td>
<td>10-35</td>
<td>1.40-1.60</td>
<td>14.40 – 50.40</td>
</tr>
<tr>
<td>Bt1, Bt2, Btv1, Btv2</td>
<td>88-175</td>
<td>4.5-6.0</td>
<td>0.0-0.5</td>
<td>20-35</td>
<td>1.40-1.60</td>
<td>1.51 – 5.04</td>
</tr>
<tr>
<td>Orangeburg loamy sand (OrA), 0-2 % slope (fine-loamy, kaolinitic, thermic Typic Kandiudults)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap, BA</td>
<td>0-15</td>
<td>4.5-6.00</td>
<td>0.5-1.0</td>
<td>4-10</td>
<td>1.35-1.55</td>
<td>50.40 – 151.2</td>
</tr>
<tr>
<td>Bt1</td>
<td>15-60</td>
<td>4.5-5.5</td>
<td>0.0-0.5</td>
<td>18-35</td>
<td>1.60-1.75</td>
<td>14.0 – 50.40</td>
</tr>
<tr>
<td>Bt2</td>
<td>60-150</td>
<td>4.5-5.5</td>
<td>0.0-0.5</td>
<td>18-45</td>
<td>1.60-1.75</td>
<td>14.0 – 50.40</td>
</tr>
</tbody>
</table>

Fuquay and Orangeburg soils belong to hydrologic soil group B. Group B soils consist of moderately deep or deep, moderately well drained or well drained soils with moderately fine to moderately course texture. Group B soils have a moderate infiltration rate when thoroughly wet. The City of Aiken lies on the boundary of the Savannah (HUC 030601) and Edisto (HUC 030502) river basins, with the majority of surface water draining towards the Savannah River by way of the Sand River. The general topography of the Upper Coastal Plain is low relief. However, relatively wide ranges of elevations exist within the city boundary. LIDAR derived elevation models show an elevation range between 87.48 and 168.76 meters (287.01 – 553.68 ft.). The low minimum elevations correspond to channels of the Sand River, which has canyon-like morphology in its headwater reaches. A baseline inventory of soils was performed using the Web Soil Survey and the SSURGO dataset for the AOI. Soil survey data includes soil order, texture, and saturated hydraulic conductivity (Table 4.2.2). Native soil borings and laboratory analysis were performed prior to construction. A total of 20 test borings were collected and analyzed by an independent engineering consultant (Fairbanks and Wargo 2009). Ten of these borings were obtained from potential BRC sites. These borings were taken to a depth of approximately 1.83 meters (6 ft.) below grade using a direct push method. The remaining ten borings were drawn from areas with pavement cover to variable depths using a hollow stem auger.
Selected samples were evaluated in a laboratory for natural moisture content and gradation analysis (Table 4.2.2). Infiltration tests were performed in the ten vegetated median sites within twenty-four hours of well excavation and described in the technical report of Fairbanks and Wargo (2009). A polyvinyl chloride (PVC) casing with the lower 0.91 meters (3 ft.) screened and slotted was placed in the borehole. Boreholes were repeatedly filled with water over a twenty-four hour period to achieve saturated conditions. The infiltration test was performed by filling the casing with water and monitoring the change in water level over time. Level and time was recorded until the well completely drained or a stabilized rate of decline was observed. Measured infiltration rates vary from 194.14 to 1,270.00 mm/hr (7.64 in/hr – 50.00 in/hr) (Table 4.2.2).

**Table 4.2.2 - Selected geotechnical data for native soil samples**

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample depth (ft.)</th>
<th>Infiltration rate (mm hr⁻¹)</th>
<th>Soil classification</th>
<th>Natural moisture (%)</th>
<th>Percent passing No. 200 sieve</th>
<th>Gravel (%)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native soils in vegetative medians. Sample Date: 6/8/09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-1 (FuB)</td>
<td>0 - 6</td>
<td>426.72</td>
<td>silty fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-2 (FuB)</td>
<td>0 - 6</td>
<td>365.76</td>
<td>silty fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-3 (FuB)</td>
<td>0 - 6</td>
<td>1,270.00</td>
<td>silty clayey fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-4 (FuB)</td>
<td>0 - 6</td>
<td>579.12</td>
<td>silty clayey fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-5 (Fub)</td>
<td>2 - 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>NP</td>
<td>NP</td>
<td>NP</td>
<td>7.2</td>
<td>16.3</td>
</tr>
<tr>
<td>B-6 (OrA)</td>
<td>0 - 6</td>
<td>104.14</td>
<td>silty fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-7 (OrA)</td>
<td>0 - 6</td>
<td>274.32</td>
<td>silty clayey fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-8 (OrA)</td>
<td>0 - 6</td>
<td>426.72</td>
<td>clayey fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B-9 (OrA)</td>
<td>1 - 5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>33</td>
<td>22</td>
<td>11</td>
<td>20.2</td>
<td>47.0</td>
</tr>
<tr>
<td>B-10 (FuB)</td>
<td>0 - 6</td>
<td>213.36</td>
<td>clayey fine to medium sand</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index, NP = Non-Plastic
Engineered Media Sampling and Composition Analysis

Samples of the engineered bioinfiltration soil media (BSM) were obtained after the media had been graded into the excavated cell. Laboratory tests include soil gradation, chemical composition, soil structure, organic matter, and density. Soil gradation tests were performed according to ASTM D1140 (ASTM 2006; Table 4.2.3). Results from soil gradation analysis were tabulated using Gradistat (Blott and Pye 2001; Table 3). Media mixtures varied in volumetric proportions of gravel, sand, soil, and compost. Within these mixtures, the gravel component ranged from 0.0% to 1.3%, sand from 81.2% to 87.9%, clay from 1.2% to 4.6%, and silt from 6.6% to 17.5% (Table 4.2.3).

<table>
<thead>
<tr>
<th>Location (SLSCODE)</th>
<th>Sampling date (m)</th>
<th>Sample depth (m)</th>
<th>Saturated Hydraulic Conductivity* (mm hr⁻¹)</th>
<th>Organic matter (%)</th>
<th>Soil classification</th>
<th>Percent passing No. 200 sieve</th>
<th>Gravel (%)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Method</th>
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<td>1.4</td>
<td>Gradistat**</td>
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* Estimation based on procedure described by Saxton and Rawls, 2006
** Method described by Blott and Pye, 2001
*** Method described by ASTM, 2006
Chemical analysis of engineered media was conducted by the Clemson University Agricultural Service Laboratory using its standards approved analytical procedures and documented Quality Assurance/Quality Control procedures. Standard soil tests were conducted by the test laboratory to determine soil and buffer pH; acidity; total extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn), copper (Cu), boron (B), and sodium (Na); and cation exchange capacity (CEC). Upon receipt, test laboratory personnel logged in the samples and assigned each one a unique 7-digit identification number. The samples were then placed on drying racks with a fan blowing room temperature air across them to facilitate complete drying. After drying, the soil samples were screened through a 10-mesh (2-mm) screen, ground to reduce the particle size, and mixed uniformly before analysis. Chemical properties are summarized in Table 4.2.4.

### Table 4.2.4 - Selected chemical properties for engineered media samples

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<th>Location</th>
<th>Sampling date</th>
<th>Sample depth (m)</th>
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<th>Acidity (meq 100g⁻¹)</th>
<th>CEC (meq 100g⁻¹)</th>
<th>P</th>
<th>K</th>
<th>Na</th>
<th>Ca</th>
<th>Mg</th>
<th>Zn</th>
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<th>B</th>
<th>Fe</th>
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The pH of all soil samples was determined by equilibrating 20 g of each soil with 20 ml of deionized water for a minimum of 1 h and then measuring the pH with a calibrated AS-3000 Dual pH Analyzer. Buffer pH was determined for these same samples using the Adams-Evans buffer method (Moore and Franklin 2002) and the pH analyzer. Soil acidity (meq/100 g) was calculated by the test laboratory as 8 times the difference between pH 8 and the measured buffer pH, which accounts for the soil mass used in the buffer pH test. Mineral analyses (P, K, Ca, Mg, Na, Zn, Mn, Cu, B) were determined using a Mehlich No. 1 extraction solution and element quantification by inductively coupled plasma optical emission spectroscopy (ICP-OES) (Isaac and Donohue, 1983; Jones, 2001). Following the test laboratory’s standard procedure for soils in South Carolina, CEC was estimated from the sum of acidity plus all base cation (K, Ca, Mg, Na) concentrations in the Mehlich 1 extract expressed in meq/100 g. Note that this laboratory reported CEC value is an estimate of the actual CEC because it is calculated from the Mehlich 1 extractable cations and the calculated soil acidity (Mullins and Heckendorn 2009). For example, for high pH soils or soils with high levels of soluble salts, the CEC estimated by this procedure can be erroneously high (Mullins and Heckendorn 2009). However, for most acidic soils in the Southeast U.S., the value estimated by this procedure can be considered an effective CEC since it is the CEC at the current soil pH (Mullins and Heckendorn 2009). The test laboratory calculated total base saturation as the percent of estimated CEC occupied by all base cations measured in the Mehlich 1 extract.

**Soil Moisture Content Monitoring Procedure**

**Sensor Description**

Soil moisture measurements were taken in selected BRC sites (Figure 4.2.1). The measurement assembly consists of a vertical profile of Decagon 5TE and Decagon 5TM volumetric water content sensors. These sensors measure VWC at a resolution of 0.0008 m$^3$m$^{-3}$ below 0.50 m$^3$m$^{-3}$ and 0.009 m$^3$m$^{-3}$ above 0.65 m$^3$m$^{-3}$ (Personal Communication Douglas Cobos, Decagon Devices).

**Sensor Installation**

Sensor spacing and orientation was controlled by mounting the base of the sensor in a 25.4 mm (1 in) PVC pipe prior to installation (Figure 4.2.3).

Individual sensors were positioned to orient vertically once installed in the soil. Sensors were placed at depth intervals of 15.24 - 30.48 cm (6 - 12 in) to monitor multiple depths of engineered soil media and the basin subsurface (native soil). Monitoring locations and depths are described in Table 4.2.5. The number of sensors in the profile depended on the depth of the basin at the installation point. Sensor spacing is necessary to prevent current from one probe from being detected by a second probe. To minimize media disturbance during installation, 25.4 cm (10 in) PVC sleeves are used as a placeholder for the sensor assembly prior to media infill. Once media installation was complete, the soil moisture sensing assembly was lowered into the sleeve to a predetermined depth. The sleeve was removed and the native soil and soil media was carefully replaced. Additionally, four soil moisture sensors were placed within BRCs, but outside of the ponding area.
These sensors were located near mature trees at shallow depths to monitor root zone moisture (Table 4.2.5).

Table 4.2.5 - Soil moisture monitoring assembly configuration by site and depth

<table>
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<tr>
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<th>Site Number</th>
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<th>Soil Moisture Probe Depth (cm)</th>
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</table>

* Abbreviation for street intersection. See Figure 4.2.1
** Root zone monitoring site

Soil Moisture Data Analysis

Preliminary Observation Data Processing and Analysis

Prior to analysis, all soil moisture data underwent a calibration adjustment to transform diaelectric permittivity (ε) to Volumetric Water Content (VWC, m⁻³ m⁻³). Decagon Devices, Inc. generated an Equation (1) based on a laboratory analysis of media samples:

\[
θ = -0.000263ε^2 + 0.0257ε - 0.0695 \quad (1)
\]

Where θ is the volumetric water content with units (m³ m⁻³), and ε is the measured diaelectric permittivity returned by the probe.

Basic quality control (QC) was performed on observation data using the MATLAB analysis software. Rainfall data collected by the Campbell Scientific data logger required no removal of outliers or invalid data. Soil moisture and flow data required considerable preliminary processing before it could be incorporated into later analysis steps. This was due to the volume of data, the frequency of missing data, and the presence of erroneous values.

The first QC step involved a check to ensure all measurements fell within the manufacturers specified measurement range. Data outside of this range was discarded. Several techniques were evaluated for outlier detection, e.g., box (and whisker) plots. However, the highly positively skewed distributions made automated outlier detection difficult, even with data transformations, e.g., log transform. Methods involving time-series analysis, e.g., exponentially weighted moving averages, likewise yielded poor results. The data exhibited long periods of consistent values followed by abrupt fluctuations, a scenario that is typical of soil moisture data. Missing data points further complicated QC. Missing data resulted in sequences of observations appearing to have abrupt variations (spikes) when the true measurement values would have shown a more gradual fluctuation. Rather than risk removing valid data points; no outlier removal was performed on either the soil moisture or water depth measurements.
Soil moisture and water depth measurements were resampled to align on regular intervals to simplify later analysis. This step facilitated comparison among measurements and introduced a minimal amount of smoothing over the data. Data was aligned to five-minute intervals. In the case of soil moisture and water depth data, multiple measurements within the interval window were averaged, ignoring missing values. If no measurements were available for a given window, a value of Not-a-Number (NaN) designation was assigned. Rainfall data were aligned to the same five-minute intervals based on summing, rather than averaging.

Additional exploratory data analysis was performed to validate sensor function, identify notable rainfall events and ascertain the extent of missing data present during each rainfall event. This includes univariate statistics, histograms, and Quantile-Quantile (Q-Q) plots to evaluate untransformed and transformed data against a normal distribution.

Spatial Structure of Infiltration Properties Analysis
Infiltration rates of soils exhibit high spatial variability (Beven 2001; Greminger et al. 1985), particularly in disturbed urban soils (Pitt et al. 2000). Infiltration rate in soil is dependent, among other things, on soil water content. For consistency, this analysis uses saturated hydraulic conductivity $K_{sat}$ to describe infiltration rate at saturation. Spatial structure analysis of $K_{sat}$ is evaluated using three methods. Univariate exploratory data analysis (EDA) is used to evaluate measures of central tendency and facilitate qualitative assessment of the distribution of measured values. A spatial autocorrelation statistical test is applied to evaluate whether observed $K_{sat}$ in our AOI is spatially autocorrelated. Finally, a geostatistical approach using a semivariogram is used to evaluate the influence of scale on the spatial autocorrelation. All analysis was performed using the MATLAB data analysis and programming environment.

The spatial autocorrelation statistical test is based on a null hypothesis of Complete Spatial Randomness (CSR). Spatially structured processes, e.g., geologic, climate, determine the characteristics of soils at large-scales. This implies that spatial autocorrelation is always present in soil properties. At smaller scales, non-spatial processes may be the predominate source of variation, leading to Type II statistical errors when applying spatial autocorrelation tests. Previous studies of spatial autocorrelation of $K_{sat}$ have demonstrated this dependence on scale. Processes like topography and soil series dominate at large scales and biological processes dominate at local scales (Sobieraj et al. 2004). At the spatial scale of the AOI, biological processes or urban disturbance are expected to be more significant drivers of variation than topography or soil unit. To evaluate whether spatial structure is present in the AOI, the Moran’s $I$ statistical test for spatial autocorrelation is applied (Moran P.A.P. 1950). Moran’s $I$ is calculated as follows:

Where $n$ is the number of observations on variable $x$ at locations $i,j$. The mean of $x$ is shown by $x$. The $w_{ij}$ term is the weight matrix, with $S_0$ being the sum of all elements in weight matrix. The weighting is based on the inverse distance of features. Moran’s $I$ will vary from negative one to positive one. If no spatial autocorrelation occurs, than Moran’s $I$ will take on the expected value shown in Equation 4, which approaches zero as sample size increases. A positive Moran’s $I$ indicates positive spatial autocorrelation, while a negative value indicates negative spatial autocorrelation.
The degree of spatial autocorrelation is dependent on scale (Goodchild 1986). Sobieraj et al. (2004) found a lack of spatial structure in observed \( K_{\text{sat}} \) based on semivariogram analysis at scales of 0.25, 1, 10, and 25 meters. We evaluate the observed \( K_{\text{sat}} \) at similar scales for our AOI using a semivariogram. The semivariogram estimator \( y(h) \) is described by Goovaerts (1997) as follows:

\[
y(h) = \frac{1}{2N(h)} \sum \limits_{i=1}^{N(h)} \left[ z(x_i) - z(x_i + h) \right]^2
\]  

(5)

Where \( y(h) \) measures the average dissimilarity between data separated by vector \( h \). Vector \( h \) is the lag distance between observed value at location \( z(x_i) \). The number of pairs separated by a given lag distance is \( N(h) \). Sample site distances are less than 1 km. A lag distance of 10 meters is chosen to avoid summarization (binning) of distance pairs.

Measured saturated hydraulic conductivity (\( K_{\text{sat}} \)) for the AOI ranged from 104.14 mm/hour to 1270.00 mm hr\(^{-1}\) (Table 4.2.2). The value of 1270.00 mm hr\(^{-1}\) far exceeded both the next highest observed value (579.12 mm hr\(^{-1}\)) as well as previous published findings for similar soil textures (e.g., 210.00 mm hr\(^{-1}\) (Rawls et al. 1982). High measurement values could be due to soil macropores or local scale processes present at the sample site. Even with additional proximal samples, it is difficult to ascertain the validity of this measurement without a corresponding understanding of local-scale processes present at the sampling location. The presence of a single large value with a small sample size (\( n = 10 \)) makes estimation procedures based on the sample distribution problematic, the 1270.00 mm hr\(^{-1}\) value was excluded in these circumstances.

The small sample size and high variation of the area of interest \( K_{\text{sat}} \) measurements limited the statistical power available for analysis of spatial structure (Table 4.2.6).

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<th>Value</th>
</tr>
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<td>3rd Quartile (mm hr(^{-1}))</td>
<td>548.64</td>
<td>457.20</td>
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</tbody>
</table>
Exploratory data analysis indicates the presence of a positive skew (Figure 4.2.4) and necessitated a log transformation prior to further analysis.

Figure 4.2.4 - Histogram of measured $K_{sat}$ for native soil
(Source: measured $K_{sat}$ from Schnabel Engineering, LLC, 2009)
Transformed data approximates a normal distribution (Figure 4.2.5). The existence of spatial autocorrelation is tested using Moran’s I with the log transformed $K_{sat}$ based on inverse Euclidean distance between samples. The Moran’s I statistic indicates a lack of sufficient evidence to support the hypothesis of spatial autocorrelation in the $K_{sat}$ dataset ($I = -0.0018, p = 0.7019$).

Figure 4.2.5 - Log normal QQ-Plot of measured saturated hydraulic conductivity ($K_{sat}$) (Source: measured $K_{sat}$ from Schnabel Engineering, LLC, 2009)
Visual inspection of a semivariogram plot (Figure 4.2.6) supports the findings of the Moran’s I test, indicating little to no spatial structure at the scales observed in this study. While the small sample size limited the ability of this analysis to distinguish spatial structure from noise, previous findings with larger sample sizes have produced similar results (Sobieraj et al. 2004).

*Figure 4.2.6 - Log transformed semivariogram for saturated hydraulic conductivity $K_{sat}$ in native soils (Source: measured $K_{sat}$ from Schnabel Engineering, LLC, 2009)*
The lack of spatial structure has implications for the parameter estimates of $K_{sat}$ required by local-scale infiltration models. It suggests that estimations based on nearby $K_{sat}$ measurements or geostatistical interpolation will not adequately capture the true variability of $K_{sat}$ at the local or point scale. In this case, it is more appropriate to estimate $K_{sat}$ based on a back-transformed value randomly selected from a lognormal $K_{sat}$ sample distribution.

**Trend Detection in Effective Volumetric Water Content at Saturation**

Bioinfiltration systems are a relatively recent stormwater management technology with limited long-term monitoring data to evaluate how bioinfiltration systems change over time (Emerson and Traver 2009). Previous studies have identified compaction and sedimentation as two of the leading causes of degradations in performance (Lindsey et al. 1992). Soil compaction from heavy machinery traffic and excavation techniques during installation can reduce infiltration capacity (Brown and Hunt 2010). Further compaction may occur after installation due to landscaping and foot traffic, particularly if the bioinfiltration basin is covered with grass turf (Davis et al. 2009). Thompson et al. (2008) found that soil wetting lead to compaction, increased bulk density, and decreased moisture-holding capacity; and was dependent on the engineered media composition.

Emerson and Traver (2009) describe a bioinfiltration performance indicator suitable for long-term monitoring of bioinfiltration basins. This indicator is based on the receding limb of a ponding depth measurement. The measurement is taken during and following a rain event. An estimate of $K_{sat}$ is made based on the slope of the recession limb versus time, subject to a correction for media porosity. Emerson and Traver (2009) use this approach to identify a strong seasonal signal in infiltration performance due to temperature-induced viscosity changes in water, i.e. summer increasing $K_{sat}$, winter decreasing $K_{sat}$. The performance indicator does not account for matric-suction early-time infiltration or the effects of air entrapment (Emerson and Traver 2009). Additionally, no accommodation is made for sustained rainfall events, where continuing rainfall input may decrease the ponding depth recession rate. Thus, sustained rainfall scenarios may influence the receding limb approach. This may partially account for the seasonality findings. Shorter duration, higher intensity rainfalls occur more frequently in the summer, whereas longer sustained rainfall are more likely in the winter. The use of ponding depth limits this approach to bioinfiltration basins that experience measureable ponding. Sites with high infiltration rates or under drain systems may not generate enough data to produce performance measurements.

An alternative method of monitoring performance is presented based on the relationship between the saturation limit of volumetric water content ($VWC_{sat}$) and the effective soil porosity of the media. A declining trend in effective soil porosity corresponds with degradation of bioinfiltration performance. Trends in effective porosity can be evaluated based on ($VWC_{sat}$) measurements over time. The relationship between porosity and observed ($VWC_{sat}$) can be obscured by dynamic factors, e.g., hysteresis effects. The presence of air bubbles trapped in the media or the presence of clay, which may swell upon wetting (ASCE 1996). Rainfall intensity and magnitude influence observed ($VWC_{sat}$) as faster ponding or greater ponding depths affect air entrapment within the media. Another limitation of the ($VWC_{sat}$) approach is the assumption that saturation will occur under heavy or prolonged rainfall. In media with high hydraulic conductivity, the saturation point may not necessarily be reached.

Saturated volumetric water content was measured using the Decagon 5TE/TM sensors. Identification of saturating conditions was performed by first evaluating a twenty-four hour window of $VWC$ measurements following a rainfall event. Rainfall events were identified based on rainfall thresholds. Low thresholds were used to avoid ruling out saturation conditions caused by low magnitude rainfalls occurring during periods of high antecedent moisture. Rainfall events within 3 days of another event were considered as a single event, with the greater of the rainfall magnitudes being chosen as the representative value. A local maximum was identified during the rainfall event period. Local maximums were evaluated visually and by comparison with water depth measurements obtained within the basin outflow structure. This analysis step resulted in an identification of saturating rainfall events and corresponding ($VWC_{sat}$) maximums for every soil moisture sensor.
Statistical analysis was performed to identify whether (VWC\textsubscript{sat}) measurements exhibited a detectable trend over time. Exploratory data analysis was performed to evaluate the distribution of measured values and the validity of normality assumptions. A linear model was fit to the measured (VWC\textsubscript{sat}) response as a function of time. Homogeneity was validated based on visual inspection of residuals versus fitted value plots. The slope of the trend line was evaluated using a t-statistic. The linear model provides an easily interpretable result, but is subject to limitations. The linear model is not able to isolate the influence of depth, site, or native soil vs. engineered media factors on the VWC response. Furthermore, the use of repeated measurements on the same experimental units (soil region surrounding sensor), introduces a violation of the independence of observation assumption. An alternate approach based on a linear mixed effects model was applied to evaluate the influence of fixed effects and the importance of the independence assumption. Time, depth, and native soil versus engineered media are treated as fixed effects while site is treated as a random effect. The model was fit using REML. Unlike repeated measures ANOVA approaches, mixed effects models support missing and unbalanced data. Combinations of effects and interactions were evaluated to find the optimal model configuration. Normality and homogeneity were checked by visual inspection of Q-Q and residual plots. All analysis was performed using the R statistical analysis software (R Core Development Team 2012) and the R package ‘nlme’ (Pinheiro et al. 2012).

The study period included observations between June 1, 2011 and May 16, 2012. Precipitation data was available for the entire study period. The distributions of VWC measurement for each sensor site tended to be positively skewed (Table 4.2.7 and Figure 4.2.7).

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Figure 4.2.7 - Histogram for measured volumetric water content at all sites and depths between June 2011 and May 2012.
Variations among the distribution varied both site-to-site (*Figure 4.2.8 and 4.2.9*) and depth-to-depth at the same site (*Figure 4.2.9 and 4.2.10*). As anticipated, VWC measurements over the study period show a strong positive correlation with rainfall measurements.

*Figure 4.2.8* - Histogram for measured volumetric water content at site CRPS site 1, depth 12” between June 2011 and May 2012

*Figure 4.2.9* - Histogram for measured volumetric water content at site CRPS site 7, depth 12” between June 2011 and May 2012

*Figure 4.2.10* - Histogram for measured volumetric water content at site CRPS site 7, depth 18” between June 2011 and May 2012
Figure 4.2.11 shows VWC at multiple depths versus time for the study period with a hyetograph overlay. The monitoring site is located in the bioinfiltration basin located at the intersection of Chesterfield, Richland, and Park Streets. Figure 4.2.12 shows the same plot for an individual storm event, illustrating the rapid response of VWC measurement to rainfall events. This response supports the use of high frequency sampling rates. VWC responses can reach saturation from antecedent conditions within a five-minute sampling interval. Higher frequency monitoring allows a more accurate description of VWC responses over time. This information is useful for tracking the movement of a wetting front through a soil column.
Figure 4.2.12 - Precipitation and soil water content for CRPS site 4 at multiple depths between September 21, 2011 and September 24, 2011
Exploratory data analysis indicated a slight positive skew in the distribution of saturated volumetric water content ($VWC_{sat}$) observations (Figure 4.2.13), but not enough to warrant a data transformation. The relationship between observed ($VWC_{sat}$) and time (days) was visually evaluated for each site and depth (Figure 4.2.14). A negative trend is evident in several of the sensor sites.
The 95% confidence interval plot (Figure 4.2.15) indicates non-zero slope terms at individual sensor sites, further supporting the presence of an identifiable trend.

A linear model was fit to the entire data set with \((VWC_{sat})\) as the dependent variable and time (days since beginning of monitoring) as the independent variable.
The resulting linear model shows a statistically significant slope with $b = -0.0004238$, $t(226) = -4.54$, $p < 0.0001$ (Figure 4.2.16).
Visual inspection of residuals vs. fitted values (Figure 4.2.17) indicates that no violation of homoscedasticity.

*Figure 4.2.17 - Residuals plot for effective soil porosity ($K_{sat}$) versus time*
A normal probability plot of fitted residuals indicates that the assumption of normality is valid (Figure 4.2.18).

Figure 4.2.18 - Normal probability plot for residuals of effective soil porosity ($K_{sat}$) versus time linear model

A linear mixed effects model is applied to the $VWC_{sat}$ dataset to evaluate the influence of time, site, media, and depth on observed values. The initial model incorporated the fixed effects of time, media, depth, and the random effect of site. Iterative removal of effects and examination of model results indicate that media did not significantly improve the model. Subsequently, the final model included only time and depth as fixed effects and site as a random effect. The exclusion of the media effect from the model may have resulted from redundancy between the depth and media effects. The sensor sites observing native soil were located at depths of 20.32 cm (8 in) and 45.72 cm (18 in), while the sensor sites observing engineered media were located at depths of 15.24 cm (6 in) or 30.48 cm (12 in).

As with the linear model, the time effect was found to be significant with $F(1, 216) = 14.00, p = 0.0002$. The depth effect was significant with $F(1.216) = 4.47, p = 0.0356$. No significant interaction between effects was detected at a 95% significance level. The fixed effects model was compared with a model containing only random effects using a likelihood ratio test with $p < 0.0001$, indicating that the mixed effects approach offered an improvement over a null model. The mixed effects model produced a negative coefficient estimate for the depth effect ($b = -0.0037$), indicating that $VWC_{sat}$ observations at deeper depths experience a greater decline in moisture holding capacity over time.

Results from this analysis indicate a negative trend in $VWC_{sat}$ over time at the sensor sites in Aiken, SC. A declining trend in effective porosity has implications for the performance of bioinfiltration basins. The basin located near the intersection of Park, Union and Fairfield Street (PUF) is used to illustrate the impact of trends in effective porosity. The engineered media located within the PUF basin occupies a volume of 198.87 m$^3$. Assuming an effective porosity of 0.42 m$^3$m$^{-3}$ at the start of the study, the engineered media located in PUF would have the capacity to store 82.93 m$^3$ of water fully saturated. Application of the linear model produces an estimated porosity of 0.32 m$^3$m$^{-3}$ yielding a storage capacity of 64.24 m$^3$, a reduction of 18.70 m$^3$. A reduction in effective porosity decreases the time to ponding, thus lowering the total stormwater handling capacity during a given time period. The decline trend in observed $VWC_{sat}$ during the study period may have resulted from factors other than a decline in effective porosity. There is an underlying assumption in this analysis that the observed $VWC_{sat}$ was obtained under truly saturating conditions. A closer investigation of the first and second rainfall events indicates a potential violation of this assumption. The two rainfall events occurred just 24 days apart with the second event resulting in significantly higher observed $VWC_{sat}$; one tailed paired $t(20) = -5.12, p < 0.0001$. This contradicts the overall findings and indicates that other factors are influencing observed $VWC_{sat}$. One explanation is a variation in rainfall intensity and magnitude between the events. The first event was a short duration storm with 1.6 cm (0.63 in) of rainfall. The second event occurred over the course of 24 hours with 11.30 cm (4.45 cm) of rainfall and resulted in a greater ponding depth and duration. The prolonged saturation of the media may have produced higher valued $VWC_{sat}$ observations. While consistency in ponding depth and duration is unlikely to occur in an observational study, a direct ponding depth measurement would have aided an assessment of the relationship between ponding depth and duration on observed $VWC_{sat}$. The only depth measurements
available in this study were taken inside of basin outflow structures and proved to be a poor indicator of ponding depth due to the introduction of water into the structure from sources besides the basin and the high threshold required for water to “overflow” into the structure. In addition to ponding depth measurements, future studies would benefit from the inclusion of an antecedent condition effect into the model, perhaps by introducing a soil moisture deficit term \((VWC_{\text{sat}} - VWC_{\text{residual}})\).

Runoff and Infiltration Production and Routing Model

**Development**

Two methods are used to model infiltration and runoff excess for the study area. The first approach employs the Green-Ampt (GA) equation to calculate infiltration and runoff production for each raster cell of the bioinfiltration basin and the surrounding pervious area (BRC). The GA component operates within a GIS framework and supports spatially varying soil/media properties, unsteady rainfall inputs, and runoff excess flow routing. The flow routing component implements the D-infinity multiple flow direction algorithm (Tarboton 1997). A second infiltration modeling approach is used to calculate rainfall excess originating from regions of impervious cover directly connected to the bioinfiltration basin. This method uses the empirically derived Curve Number (CN) methodology to generate a unit hydrograph for each connected impervious area (US SCS 1972). A ponding component is incorporated into the model to allow the redistribution of rainfall excess volume across a basin depression at each model time step.

First described in 1911, the GA equation is widely used to model one-dimensional vertical movement of water into unsaturated soils (Green and Ampt 1911; Browne et al. 2008; Dussaillant et al. 2004; Heasom et al. 2006). It offers a simplified solution to Richard’s equation. Richard’s equation describes water movement through unsaturated soils. However, it does not have an analytical solution under most circumstances. The GA simplification is based on assumptions about the physical processes of infiltration. Notably, the GA equation assumes a sharply defined wetting front that divides the unsaturated and saturated zones of a column of soil. The unsaturated zone is defined by constant initial volumetric water content, while the saturated zone is assumed to have volumetric water content equal to its effective porosity. The GA infiltration rate and infiltration depth is calculated by:

\[
\begin{align*}
F_t &= F_t(1 + \frac{1}{\psi}) \left( \frac{VWC_{\text{sat}} - VWC_{\text{residual}}}{F_t} \right) \quad t \leq t_p \\
F_{t+\Delta t} &= F_t + \min(R, F_t) \\
F_t &= \text{infiltration rate} \left( L \ T^{-1} \right) \\
R_t &= \text{rainfall} \ (L) \\
\psi &= \text{wetting front saturation} \ (L) \\
VWC_{\text{sat}} &= \text{effective soil porosity} \ (L \ L^{-1}) \\
VWC_{\text{residual}} &= \text{initial soil water content} \ (L \ L^{-1}) \\
t_p &= \text{time to surface ponding}
\end{align*}
\]

Where:
- \(K_t\) = hydraulic conductivity at saturation
- \(\psi\) = wetting front saturation
- \(VWC_{\text{sat}}\) = effective soil porosity
- \(VWC_{\text{residual}}\) = initial soil water content
- \(F_t\) = infiltration depth
- \(t_p\) = time to surface ponding

Parameters are based on soil properties. These properties may be directly observed or obtained through estimation techniques (e.g., pedotransfer functions [Rawls and Brakensiek 1982]). Skaggs and Khalel (1982) performed a sensitivity analysis of the GA equation and found infiltration rate to be most sensitive to the porosity and hydraulic conductivity. Parameter estimates for this model are based on measured soil properties and estimation techniques described in the literature.

Data preparation steps are performed using ESRI’s ArcGIS® Desktop software (www.esri.com). This step included estimation of soil property surfaces and delineation of BRC and directly connected impervious areas. GA and CN infiltration, rainfall excess, and runoff routing algorithms were developed using Python, the ESRI ArcPy library, and the NumPy scientific data analysis software package (Jones et al. 2012). The gray boxes indicated the four main components of the model, plus the model output component. The model solves the infiltration, routing, and surface depression storage components of the model at each time step for every grid cell of the input parameters. The model output
component deserializes model results into the NetCDF (http://www.unidata.ucar.edu/software/netcdf/) file format. NetCDF provides a standardized data model and format for multidimensional scientific data, supporting spatial and time dimensions. NetCDF files are compatible with a variety of software visualization tools including ESRI’s ArcGIS® Desktop and ArcScene.

Data preparation steps involve a series of sub-models developed using ArcGIS® Model Builder. The infiltration depth ($F_t$) and rainfall excess parameters are continuously updated during model execution. Generally, these parameters are set to zero at the start of model execution. Effective porosity ($VWC_{sat}$) is obtained from the section of this study on trend detection in effective soil porosity. Initial soil water content ($VWC_{initial}$) is obtained from measured values at the beginning of the modeled rainfall event or, in the case of simulations, estimated based on historical record. Saturated Hydraulic Conductivity $K_{sat}$ is based on the spatial structure of saturated hydraulic conductivity section of this study. Wetting front suction ($\psi$) is estimated based on the procedure described by Rawls and Brakensiek (1982). The D-infinity flow direction grid is obtained using the TauDEM software (http://hydrology.usu.edu/taudem/taudem5.0/index.html). The digital elevation model parameter for the study region was derived from LIDAR elevation data from the U.S. Geological Survey and from Woolpert, Inc. survey drawings. Grid cell resolution is chosen to approximate flow velocity based on bioinfiltration cell cover type and average slope. For example, using the U.S. Department of Agriculture’s upland method (US SCS 1972), the overland flow velocity for forest cover and 2% slope is 0.107 m/s. If a model time step of one second is used, overland flow velocity dictates that the model cell size should be approximately 0.10m.

The Green-Ampt method captures heterogeneity across spatially varying parameters, e.g., $K_{sat}$, ($\psi$), and $VWC_{sat}$. The Curve Number methodology takes an alternate approach based on empirically derived relationship between surface cover and runoff. The relationship has no direct basis in physical measurements of the soil. For this component of the model, impervious regions directly connected to bioinfiltration basins are assumed to have homogenous infiltration rates and higher surface velocities than the turf and vegetative cover types found within the basins. The impervious areas are lumped and described by a hydrograph according to the TR-55 method described by Chronshey (1986). The directly connected impervious regions are identified and delineated using the Watershed tool, which is part of the Hydrology toolkit of the ArcGIS® Spatial Analyst extension.

Validation

In order to evaluate the bioinfiltration model, a sample rain event from the monitoring period was chosen. During the study period, five bioinfiltration basins underwent data collection between 2010 and 2012. For this analysis, the CRPS basin (Figure 4.2.1) was chosen as a representative bioinfiltration basin. This basin is located near the intersection of Chesterfield, Richland, and Park streets. It contains four soil moisture-monitoring assemblies at depths described in Table 4.2.5. CRPS has three curb cuts directly connected to impervious regions including roadways and parking areas. Rainfall excess originating from the northeastern curb cut was significant enough to cause rill erosion between the curb cut and the bioinfiltration basin. A rainfall event producing 6.375 cm (2.51 in) of rainfall occurred on September 21, 2011. Event rainfall and initial soil water content ($VWC_{sat}$) from prior to the start time was used to parameterize the model. The remaining parameters were selected based on the steps described in the methods section of this study. A cell size of 0.10 meter was used for all raster inputs. The time step was set to one second, with model output serialized every fifteen seconds.
Results from the model for the September 21, 2011 rainfall for an individual grid cell located at CRPS Site #4 are shown in Figure 4.2.19.

The infiltration rate is equivalent to the rainfall rate until $t_p$ is reached. The time to ponding cannot be directly calculated for unsteady rainfall, but can be approximated by the infiltration rate curve. Because the rainfall rate was below the mean infiltration rate for (Table 4.2.8), significant surface runoff from the soil media and surrounding native soil did not occur.

The performance of the bioinfiltration model is evaluated by comparing the time for the wetting front to reach the depth of the soil water content sensors between the model and the measured response. This approach is limited by the assumptions implicit in the Green-Ampt equations, namely that a sharp wetting front exists and full saturation occurs. Saturation ($VWC_{sat}$) is based on the point where ($VWC_{sat}$) measurements cease to increase in a saturating rain event. However, this validation step requires an accurate saturation time. The accuracy of the observed saturation time is limited by the five-minute sampling interval. This process can be evaluated at each site and depth where information is available. For the CRPS cell, a single rain event was simulated and compared against observed measurements. The modeled time to wetting front were found to follow the observed times at depths for locations CRPS Site 1, 2 and 4 (Site 3 was offline during rainfall event). The Nash-Sutcliffe Efficiency (NSE) results indicate a model performance of 0.94 ($n = 7$). A value of 1 indicates a perfect correspondence to the observations. A value of zero indicates the predications are as accurate as the mean of observed values. The small number of observed versus simulated data points weakens the strength of this NSE metric. More rain events would strengthen this model performance measure. A number of model factors contribute to this model efficiency. The uncertainty associated with the estimation of the soil parameters, particularly saturated hydraulic conductivity, result in discrepancies between observed and simulated results. The contribution of directly connected impervious area is also subject to uncertainty related to area estimations. Runoff in urban areas is difficult to accurately quantify and flow contribution area may change due to any of a number of dynamic factors including vehicle traffic and storm sewer failures in other parts of the watershed. This study did not incorporate surface ponding level measurements, which would benefit future validation tests of this model. Future revisions of the model might incorporate vegetation interception, evaporation, and transpiration components to better capture the effective inputs of rainfall on the basin and surrounding areas. Additionally, this model assumes a constant overland flow velocity for sheet and shallow concentrated flow. The small spatial extent of the watersheds used for this study make a constant flow velocity assumption reasonable. Over larger areas, greater flow channelization is expected, leading to a wider range of possible velocities. In these cases, a kinematic wave solution for overland flow would provide a more realistic description of flow velocity by incorporating parameters of flow depth, Manning’s roughness and slope.

### Table 4.2.8 - Saturated hydraulic conductivity ($K_{sat}$) univariate analysis for native soil

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Minimum (mm hr$^{-1}$)</td>
<td>104.14</td>
<td>104.14</td>
</tr>
<tr>
<td>Maximum (mm hr$^{-1}$)</td>
<td>1270.00</td>
<td>579.12</td>
</tr>
<tr>
<td>Mean (mm hr$^{-1}$)</td>
<td>451.87</td>
<td>360.96</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>321.98</td>
<td>153.85</td>
</tr>
<tr>
<td>Skewness</td>
<td>1.70</td>
<td>-0.12</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>5.37</td>
<td>2.11</td>
</tr>
<tr>
<td>1st Quartile (mm hr$^{-1}$)</td>
<td>274.32</td>
<td>259.08</td>
</tr>
<tr>
<td>Median (mm hr$^{-1}$)</td>
<td>396.24</td>
<td>365.76</td>
</tr>
<tr>
<td>3rd Quartile (mm hr$^{-1}$)</td>
<td>548.64</td>
<td>457.20</td>
</tr>
</tbody>
</table>
Visualization

Model visualization is performed with the ESRI’s ArcScene® 3D visualization application. Elevation models for the native and media soils were generated based on contour datasets from surveyed drawings provided by Woolpert, Inc. Raster surfaces were converted to triangulated irregular networks (TIN) and extruded into multi-patch volumes using the ESRI 3D Analyst toolkit. Cross sections were converted into 3D volumes using ESRI 3D Analyst. NetCDF model output is loaded into ArcScene using the ESRI Multi-dimension Toolkit. The ‘Animation Manager’ is used to step through and record the model results.

Model visualization is performed on the CRPS cell described above. A simulated rainfall event is used in order to cause greater ponding depths to occur within the basin depression. The U.S. National Weather Service Precipitation Frequency Data Server (PFDS) at [http://www.nws.noaa.gov/oh/hdsc/index.html](http://www.nws.noaa.gov/oh/hdsc/index.html) was used to determine a 50-year precipitation frequency estimate for Aiken. A rainfall event of 63.00 mm (2.48 in) for a duration of 30 minutes was used for the model simulation. Rainfall was allocated so that a 50-year, 5-minute rainfall occurred beginning at a time of ten minutes. Initial volumetric water content was chosen to be 0.22 m$^3$ m$^{-3}$. A grid cell size of 0.1 m was used with a time step of one second. Model output was written at fifteen-second intervals.

A two dimensional view of surface excess and basin ponding at three different time steps is shown in Figure 4.2.20, with a heat map indicating rainfall excess depth. The lighter blue areas denote areas where surface excess is occurring, and hotter colors indicate areas where water is channelizing (e.g., from curb cuts) or is accumulating in basin depressions.

Figure 4.2.21 shows a cross sectional view of saturation depth in addition to surface excess. Figure 4.2.21 shows the same cross sectional view using an adjusted effective porosity measurement. The impact of the adjustment is visible between Figure 4.2.20 and 4.2.21. The visualizations show that media and native soils with high infiltration rates can support large volume of stormwater storage. Based on these simulations it appears that the basins in the City of Aiken study region could support higher volumes of stormwater inflow, perhaps through additional storm sewer pipe connections to the basin.

Figure 4.2.20 - Bioinfiltration excess simulation - CRPS 50 year, 30 minute rainfall simulation

Figure 4.2.21 - Rainfall excess simulation - CRPS 50 year, 30 minute rainfall simulation
Summary of Study Results
Soils in this study area have high infiltration rates which show there is high potential for using LID techniques to lessen the impact of rain events. A novel analysis technique detected a possible reduction in the porosity of the media in the bioretention cells within the over the 1-year study period by analyzing data from soil moisture sensors in the cells. This may be attributed to post-construction settling and further monitoring is necessary to determine if there are any long-term trends in changes to media composition. Additionally, the error associated with this infiltration rate monitoring method has not yet been quantified. Low sediment levels have been detected in on-site water quality samples, so sediment fouling of bioretention media pores is not expected and this is one of the key mechanisms for long-term performance reduction (Lindsey et al. 1992). A spatial model was developed to predict soil moisture and cell ponding during rain events. The model is implemented in a Geographic Information System (GIS) framework and is appropriate for the fine-scales necessary to evaluate bioretention cells. Model results were successfully compared to soil moisture sensor values and were illustrated using 3D visualization techniques.

Conclusions

Monitoring to Enable Long Term BMP Evaluations
LID design philosophies are increasingly guiding stormwater BMPs, with bioinfiltration systems playing a key role in these management techniques. The benefits of bioinfiltration systems are many, with research documenting reductions in peak flows, increases in ground water recharge, decreases in runoff volumes, and pollutant filtering. An improved understanding of the processes that govern the efficacy of bioinfiltration BMPs will encourage wider adoption of LID approaches. This research incorporated GIS technology to characterize and model bioinfiltration systems at scales capable of capturing the complex biological, pedological, and hydrological processes that govern their performance.

A soil chemical and physical property analysis found that native soils in the region identified by this study were characterized by high infiltration rates, allowing naturally high rates of stormwater infiltration. This illustrates the benefit of adopting pervious cover types within the City of Aiken, allowing natural processes to lessen stormwater volumes. The high standard deviation of infiltration rates suggests that local scale processes (e.g., biological activity) play a significant influence on the hydraulic properties of soil. Analysis of the spatial structure of infiltration measurements in the study region reinforces existing findings that soils exhibit limited spatial dependency at the scales influencing urban stormwater BMPs. The lack of spatial structure has implications for hydrologic modeling applications that depend on soil property estimation.
Modeling is an important component of stormwater BMP design. Conventional urban stormwater design tools focus on point-scale or catchment scale processes. As a local or in-situ control measure, bioinfiltration systems occupy a problem space that is not encompassed by these scales. A grid-based within catchment scale model is described that operates at scales fine enough to capture the spatial heterogeneity of processes affecting bioinfiltration operation. The model is suited to evaluating the significance of variations in soil hydraulic properties, including those resulting from temporal trends. In addition to quantitative results, the model is conducive to qualitative interpretation through 3D visualization. Hypothetical bioinfiltration system performance was simulated using a 50-year rainfall event.

**Recommendations for Future Monitoring**

Long term monitoring of bioinfiltration systems is important to refining engineering design practices and creating recommendations for maintenance strategies. This research demonstrated the utility of wireless sensor technology as a means to implement continuous monitoring. Long-term data can identify temporal trends in infiltration performance. This investigation found that observed effective soil porosity for the monitored bioinfiltration basins experienced gradual decline over time. This finding suggests that bioinfiltration systems may lose subsurface storm-water storage capacity over time. The use of effective soil porosity as a bioinfiltration performance indicator may help guide future decisions regarding engineered media composition. Future installations of bioinfiltration systems should include wireless sensor technology to evaluate installations and provide real-world data to refine these important techniques.

**References**


4. RESEARCH ELEMENTS

(4.3) Vegetation and Planting Schemes

Bioretention areas were located in roadway medians in downtown Aiken. These sites are located in an urban area comprised of commercial uses such as retail, banking and professional offices, with limited residential use. This area has pedestrian and vehicular traffic bordering the Bioretention cells (BRC). BRCs are depressional areas that collect and cleanse stormwater runoff by encouraging infiltration and evapotranspiration through vegetation (Sawyer et al, 2012). These areas were designed to engage the public’s attention through aesthetically pleasing combinations of showy, indigenous plant species (Figure 4.3.1).

Site conditions were coupled with plant characteristics to inform design. The plant palette (Figure 4.3.3) and selection was based on species resilient to frequent inundation and drying periods that satisfied aesthetic conventions such as texture, color, and bloom times, as well as wildlife habitat potential, particularly for pollinators. The design allows for visual access across the medians in this urban setting and creates a pleasing experience for both pedestrians and motorists (Figure 4.3.2). Although the design is naturalistic, it fulfills the intended function of serving as an inviting demonstration project to encourage others to consider implementing rain gardens capable of enhancing aesthetics, improving infiltration, cleansing runoff and satisfying objectives associated with green infrastructure.

Green infrastructure objectives encourage the use of ecosystem services to improve environmental quality. These objectives encourage the use of natural systems to filter, sequester, and convert constituents or pollutants into less harmful forms. Although these objectives may be difficult to integrate into an urban fabric, Aiken has many opportunities because of the existing, landscaped medians in the downtown core that total over 100 acres. Many of these medians have mature vegetation that offers shade and habitat to enrich the aesthetic quality. As a result, careful consideration of existing vegetation, underground and overhead utilities and the urban character helped define the bioretention design.
Figure 4.3.3 - The plant palette for the Aiken Green Infrastructure Project
The existing vegetation is composed of numerous canopy and sub-canopy trees and a variety of shrubs. Turf areas are also present. Much of the vegetation is planted in a park, or arboretum, setting that has evolved over the years (Figure 4.3.4). Except for a row of Southern Magnolias, there are very few plantings of trees in rows. The naturalistic plantings lend themselves well to organic forms, which complement the gridded street network.

Designing bioretention areas in the urban setting requires careful attention to the context of the site to maximize stormwater treatment while creating an inviting and interesting aesthetic experience. The context of the site was evaluated by inventorying social and environmental characteristics. Social aspects included viewsheds and interaction of people with the medians. The viewsheds of the medians needed to appeal to pedestrians, and to a lesser extent, people in vehicles. Although very few pedestrians crossed the medians, visual access across and into the medians is critical to the design and perception of safety (Figure 4.3.5).

Sight triangles for motorists were kept relatively clear unless an area benefited from traffic calming. The downtown location and low speed limit of the site does not lend itself to much nuisance noise from vehicles, but plantings assisted with attenuating vehicular noise.

The environmental inventory included climate, soils, aspect, exposure and hydrologic regimes. The climate in this area is categorized as USDA Hardiness Zone 8a and is located in the sandhills. However, the soils within the medians ranged from clay (fill) to sandy soils with little loam or clay content. Sandy soils infiltrate runoff faster than clayey soils and are a good choice for bioretention areas. Due to the variance in soil conditions, amended soils were uniformly placed and under-drained. On-site testing ensured soils had a low phosphorous content and a suitable organic component for plant nutrition, but minimized leaching of nutrients into the shallow groundwater. The aspect of the sites was uniform because of the flat topography and medians were oriented approximately north-south or nearly east-west. The exposure of each bioretention area was mapped based on tree canopy (Figure 4.3.6). Assessments were recorded ranging from full sun to mostly shady.
Lastly, the hydrologic regimes of the median consisted of very little contribution of water from off site as most medians were surrounded by curb and gutter. These were breached as part of the design so that more off site runoff could be diverted to the medians along with under-drains from the on-street parking areas retrofitted with permeable paving. The bioretention landforms were designed and sculpted to allow full draw down not to exceed several days. Initially, the draw down of the bioretention areas occurred within a matter of hours. Because of the environmental conditions, irrigation was installed to help establish plant material. These conditions were considered in the site and planting design of each bioretention area.

The site and planting design (Figure 4.3.7) addressed the urban context through the use of low and intermediate height indigenous plant materials placed in intertwining groupings within the bioretention areas. The perimeters of the bioretention areas were blended into existing mulch planting beds or turf areas and in a few instances, only turf was placed in the bioretention area. The design of these areas follows a suggestion of providing “cues to care” that include a more manicured edge of turf grass in the foreground (Nassauer 1995) to increase public acceptance. The planting design includes a variety of species placed in the best environmental condition, such as placing soft rush or iris in the low areas of the bioretention because of their ability to tolerate saturated conditions. Plants were also placed where texture and color contrasts helped define the perceived depth of these areas. Combined, these components contribute to an aesthetically rich experience with the understanding that people will steward landscapes they enjoy. Also, the maintenance of the planting areas is limited mostly to removing trash and yearly pruning of grasses and shrubs.

Plant selection is critical in planting design and for maintenance. Many of the plants were indigenous or indigenous cultivars. Plant species were originally selected based on inundation/drought characteristics, sun/shade tolerance, habit, showy characteristics, origin, remediation and habitat potential criteria on the USDA’s plants website (plants.usda.gov). Results from the web query were further screened based on professional judgment and local availability. Although hundreds of plants meet some of these criteria, the plant list was reduced to several dozen for conceptual design purposes. These designs were field-truthed and refined into planting plans by Ryan Younce as a service-learning project under the direction of Dr. Vikki Chanse (Figure 4.3.8).
Figure 4.3.7 - Representative design and schedule for bioretention planting on Park Road, between Laurens and Newberry Streets
Figure 4.3.8 - A detailed planting schematic for a bioretention cell
After the bioretention areas were shaped and stabilized, plants were installed and irrigated. Several growing seasons have passed and anecdotal post occupancy evaluations reveal several items for consideration as others replicate this successful project (Calabria et al, 2012). First, some of the tree protection fencing was smaller than specified and was portable, which allowed contractors to operate on top of root systems and impact the health of existing trees. Secondly, field changes were not always updated in the planting plans. Existing trees were removed and the planting plans were not changed to reflect the new environmental conditions. As a result, species intended for shady areas were placed in full sun. Also, several areas were planted too densely when field changes were not updated in the planting plan. The contract was originally proposed on a unit cost basis to allow for inevitable field changes, but then was converted to lump sum contract based on plant list quantities that were not altered. This resulted in the overcrowding of some species, while others responded well, such as Virginia Sweetspire. Lastly, River Oats, an indigenous grass that can tolerate partial shade, outcompeted other planted species. Lessons learned from this project can benefit others who install rain gardens.

References


4. RESEARCH ELEMENTS

(4.4) Permeable Paving

Permeable pavements were included within the project because of the needs of the City to maintain adequate parking facilities for the public and the desire to take advantage of the stormwater management benefits of permeable pavements. When deciding on suitable locations for permeable pavements in the retrofit, several factors were considered. The pavements needed to be located where traffic loads would not be too high. Due to the high void content in permeable pavements (permeable concrete and permeable asphalt), they cannot withstand high volumes of heavy truck traffic. Therefore, it was decided to limit the use of permeable pavements to parking areas, which would see minimal truck traffic. Secondly, to maximize the benefits of permeable pavements, they should be located where they will intercept stormwater runoff from adjacent locations. By receiving this runoff, the permeable pavement will divert the water from the storm sewer. Finally, permeable pavements should be located where their functionality (infiltration) will remain for long periods of time. One of the most common causes of permeable pavement failure is when the surface becomes clogged with sediment. When it becomes clogged, then the pavement is rendered impermeable and behaves as a normal impervious pavement. Therefore, it was important to select locations where excessive quantities of sediment would not be deposited on the permeable pavement surface.

Permeable pavements were constructed throughout the retrofit area as indicated in Figure 4.4.1. Three different types of permeable paving materials were used: (1) permeable asphalt, (2) pervious concrete, and (3) permeable interlocking concrete pavers. Permeable asphalt was used in the parallel and diagonal parking spaces along Park Ave. from Laurens St. to Union St. as well as on Fairfield Ave (Figure 4.4.2).

Figure 4.4.1 - Location of permeable pavements in the Aiken green infrastructure retrofit

Figure 4.4.2 - Photos of permeable asphalt on (a) Park Ave. and (b) Fairfield Ave.
Pervious concrete was used to reconstruct the parking lot off of Richland Ave (Figure 4.4.3). In this location, pervious concrete was utilized for the drive lane as well as the parking spaces.

Additionally, pervious concrete was utilized in the reconstruction of the diagonal parking spaces behind the Department of Public Safety building (Figure 4.4.4).

Finally, permeable pavers were used to reconstruct the parking spaces on Newberry St. along the sidewalk. Permeable pavers were selected for this location to match the aesthetic of the current pavers in the parking areas in the middle of Newberry St. (Figure 4.4.5).

Pavement Designs and Materials
All of the permeable pavements throughout the retrofit were designed to be 12-in. systems. This means that the high porosity structure of the pavement was to be approximately 12-in. thick to provide for storage of stormwater as well as structural support. For the permeable asphalt pavements (Figure 4.4.6), the reservoir course consisted of a crushed No. 57 stone having a thickness of approximately 9-in., which was surfaced with a 3-in. layer of permeable asphalt. For the pervious concrete pavements (Figure 4.4.7), the base course consisted of 6-in. of No. 57 stone that was surfaced with a 6-in. layer of pervious concrete. Finally, the permeable paver sections consisted of 10-in. of No. 57 stone that was covered with a 2-in. layer of No. 8 stone that acted as a choker/bedding course (Figure 4.4.8). This bedding course provided a smooth platform to place the concrete pavers. The joints between the pavers were then filled with No. 8 stone to promote interlock while maintaining permeability. All of the pavement designs included a geotextile that provided separation between the fine subgrade and larger stone used for the reservoir course. This separation will prevent mixing of the subgrade and the base course and prolong the life of the pavement.
Each pavement type consisted of two main layers: surface course and reservoir course. The reservoir course was constructed using a crushed granite aggregate having the AASHTO designation of No. 57 and the gradation in Table 4.4.1. The surface course was the major difference for each pavement. The permeable asphalt was produced in accordance with the specifications for an open graded friction course (OGFC) outlined by the South Carolina Department of Transportation (SCDOT).

Table 4.4.1 - Gradation specifications for the No. 57 stone used for the permeable pavement reservoir course

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Passing, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ½-in.</td>
<td>100</td>
</tr>
<tr>
<td>1-in.</td>
<td>95 – 100</td>
</tr>
<tr>
<td>½-in.</td>
<td>25 – 60</td>
</tr>
<tr>
<td>No. 4</td>
<td>0 – 10</td>
</tr>
<tr>
<td>No. 8</td>
<td>0 – 5</td>
</tr>
</tbody>
</table>
The job mix formula (JMF) for the permeable asphalt mix is presented in Table 4.4.2. The aggregate was mixed with a styrene-butadiene-styrene (SBS) modified binder (6.0% binder by mix weight) meeting the specifications of a PG 76-22 binder. Cellulose fibers were also incorporated in the mix at a rate of 0.3% by mix weight as a stabilizing additive to prevent binder draindown during production and in the long-term. Finally, hydrated lime was added as an anti-stripping additive at a rate of 1% by weight of aggregate.

The pervious concrete mix design is summarized in Table 4.4.3. Finally, the permeable pavers used on the project were Eco-Prioria permeable pavers manufactured by Pavestone.

### Table 4.4.2 - Job mix formula and specifications for the permeable asphalt mixture

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Passing, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job Mix Formula</td>
<td>Specification</td>
</tr>
<tr>
<td>¾-in.</td>
<td>100</td>
</tr>
<tr>
<td>½-in.</td>
<td>94</td>
</tr>
<tr>
<td>⅜-in.</td>
<td>70</td>
</tr>
<tr>
<td>No. 4</td>
<td>20</td>
</tr>
<tr>
<td>No. 8</td>
<td>7</td>
</tr>
<tr>
<td>No. 200</td>
<td>2</td>
</tr>
<tr>
<td>Optimum binder content, %</td>
<td>6.0</td>
</tr>
</tbody>
</table>

### Table 4.4.3 - Mix design for the pervious concrete mixture

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Passing, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>¼-in.</td>
<td>100</td>
</tr>
<tr>
<td>⅜-in.</td>
<td>85 – 100</td>
</tr>
<tr>
<td>No. 4</td>
<td>10 – 30</td>
</tr>
<tr>
<td>No. 8</td>
<td>0 – 10</td>
</tr>
<tr>
<td>No. 16</td>
<td>0 – 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity per yd³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I/II cement</td>
<td>600 lbs.</td>
</tr>
<tr>
<td>No. 8 stone</td>
<td>2418 lbs.</td>
</tr>
<tr>
<td>Water</td>
<td>25 gal.</td>
</tr>
<tr>
<td>Air</td>
<td>21.9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Admixture</th>
<th>Quantity per 100 lbs. of cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-range water reducer</td>
<td>2.0 fl oz.</td>
</tr>
<tr>
<td>Retarder</td>
<td>0.5 fl oz.</td>
</tr>
<tr>
<td>Hydration stabilizer</td>
<td>3.0 fl oz.</td>
</tr>
</tbody>
</table>
Construction

The construction of the permeable pavements began in January 2010. The first demolition took place on Fairfield Ave. The same construction process was followed for all of the permeable pavements with the exception of the placement of the surface course. This process began with the removal of the existing asphalt pavement. This was accomplished by saw cutting the boundary of the area and removing the material using an excavator (Figure 4.4.9). The material to be disposed of was delivered to a facility where it would be processed and used for other applications (Figure 4.4.9).

The subgrade was then excavated to the planned depth (Figure 4.4.10).

Once the area was cleared, a 9-in. wide concrete header curb was placed along the perimeter of the permeable pavement cell (Figure 4.4.11). This header served two purposes. First, it provided a solid support for the edge of the new permeable pavement. Secondly, it created a barrier to prevent the water stored in the permeable pavement from saturating the foundation of the adjacent asphalt pavement, which could potentially lead to the undermining of the foundation and potential failure of the existing impervious pavement.

After the concrete header cured sufficiently, the subgrade of the cell was leveled and gently compacted before being covered with a geotextile separation fabric (Figure 4.4.12).
With the geotextile in place, the cell was filled with No. 57 stone, which was then compacted with a steel wheel roller (Figure 4.4.13). Once the stone reservoir course was in place, the surface course was then added to complete the installation. The permeable asphalt pavement was installed in a similar manner to a typical asphalt pavement. The permeable asphalt mix was delivered to the paving site using a typical haul truck with the load tarped. The mix was deposited into a material transfer vehicle (MTV), which ensured uniform mixing and temperature of the mix prior to transferring it to the paver. Using the MTV also minimized the amount of traffic on the stone reservoir course as heavy traffic would create ruts in the stone that would have to be reworked prior to paving. The MTV travelled on the adjacent pavement lane and travelled parallel to the direction of the paver (Figure 4.4.14). The permeable asphalt was placed by the paver so as to have a finished thickness of 3-in. after compaction. The asphalt mat was compacted with a steel wheel roller once the mix cooled to a temperature of approximately 200°F where the roller could be supported by the mat without causing excessive deformation. It was important not to over-compact the mat because it could reduce the porosity of pavement and, therefore, the functionality. After the mix cooled, a lightweight roller was used to roll out any roller marks left from the initial compaction. The pavement was then closed to traffic for a minimum of 3 days to allow the mix to cool sufficiently to support traffic. In some instances, water was applied (by rain or water truck) to reduce the duration for which the pavement was closed to traffic due to the hot temperatures experienced in July and August when the permeable asphalt was placed.

The placement of the pervious concrete was conducted using a method that was somewhat different than typical concrete flatwork and pavements. The pervious concrete mix was delivered to the site in ready mix concrete trucks having a capacity of 11 yd³. Each truck was loaded with approximately 8 yd³ of mix. When the truck arrived at the paving site, it drove on the stone reservoir course to the discharge location. As the mix was discharged in an arc from the chute at the front of the truck, the truck travelled in reverse. The mix was discharged as close to its final position as possible, but some movement of the mix was required to be done by the workers. In addition, some of the ruts formed in the stone base by the truck were smoothed by the workers during placement. The mix was screeded to its final elevation using a hydraulic roller screed that spanned the entire width of the pavement and rested on the edge forms (or curbs or adjacent pavement) (Figure 4.4.15).
After the screed passed over the mix, the pavement was sprayed with bean oil to aid in curing and cross rolled with a 3-ft. wide roller to smooth the pavement (Figure 4.4.16). Transverse joints (1¾-in. depth) were then formed every 12 to 15-ft. with a joint roller (Figure 4.4.17). The pavement was covered with construction plastic for at least 7 days while the concrete cured (Figure 4.4.18). After curing, the plastic was removed and traffic was allowed on the pavement.

The permeable interlocking concrete pavement sections required the addition of a layer of smaller aggregate (No. 8 stone) on top of the reservoir course. This layer served as a bedding (or choker) course that filled the larger voids in the coarser No. 57 stone, which provided a smoother bed of material to place the pavers (Figure 4.4.19).

Once the bedding course was placed and compacted with a vibratory plate compactor, the pavers were placed by hand in a herringbone pattern (Figure 4.4.20). As the pavers were placed, they were seated in the bedding course using a vibratory plate compactor. After this initial compaction, No. 8 stone was placed on the pavers and worked into the joints using a broom. This joint material creates interlock between the pavers while maintaining a high porosity promoting infiltration of stormwater though the joints.
Pavement Performance

The performance of each of the permeable pavement sections was evaluated within one month after completion to assess the functional, structural, and surface performance. The functional performance was evaluated by measuring the infiltration rate through the pavement surface (Figure 4.4.21). Infiltration tests were conducted in accordance with ASTM C 1701 Standard Test Method for Infiltration Rate of In Place Pervious Concrete. This procedure was used on both pervious concrete and permeable asphalt pavements. A stratified random sampling approach was used to test each pavement section. Each pavement section was divided into sublots and test locations were randomly selected within each sublot. The infiltration rate of the permeable interlocking concrete pavement (PICP) on Newberry St. was not evaluated due to the difficulty of conducting such a test on the pavers.

The results of the infiltration tests for the pervious concrete and permeable asphalt pavements in Aiken are summarized in Table 4.4.4. The results indicate that the average infiltration rates for all of the pavements were more than adequate for stormwater management purposes. The pervious concrete pavements yielded the highest infiltration values followed by the permeable asphalt. This discrepancy is likely due to the difference in aggregate gradation of the two materials as the pervious concrete used a more uniform aggregate gradation than the permeable asphalt.

It was also found that the infiltration rate of the permeable asphalt was more consistent than the pervious concrete as indicated by the coefficient of variation (ratio of standard deviation to the average). The permeable asphalt had a coefficient of variation of 44% and the two pervious concrete sections had values of 75% and 70%. This could potentially be due to variability of each load of pervious concrete mix delivered to the site. At times, the water content of the pervious concrete appeared to be higher than others. When this occurs, the paste surrounding the aggregate in the mix has a tendency to clog the voids at the surface when the concrete is finished, thus limiting the infiltration of the pavement (Figure 4.4.22).

<table>
<thead>
<tr>
<th>Material</th>
<th>Department of Public Safety</th>
<th>Public Parking Lot</th>
<th>Park Ave. &amp; Fairfield Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration, in/hr.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>986</td>
<td>1499</td>
<td>677</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>736</td>
<td>1052</td>
<td>300</td>
</tr>
<tr>
<td>Maximum</td>
<td>1973</td>
<td>3721</td>
<td>1414</td>
</tr>
<tr>
<td>Minimum</td>
<td>37</td>
<td>0</td>
<td>317</td>
</tr>
</tbody>
</table>

Table 4.4.4 - Permeable pavement infiltration test results

Figure 4.4.21 - Conducting an infiltration test

Figure 4.4.22 - Sealing of the surface voids with cement paste
It should be noted, however, that the infiltration tests were conducted at random locations and low values occurred in isolated areas that were surrounded by areas that had higher infiltration rates. Void sealing, as shown in Figure 4.4.22, was not common throughout the pavement, but when it did occur, the areas were surrounded by areas of higher infiltration that would accommodate the runoff from the sealed location.

The structural and surface performance of the permeable pavements was evaluated by means of visual survey of the pavement condition. The pavement condition was evaluated within a month of opening to traffic and periodically afterwards. The structural performance was based on the presence of cracking in the pavement as the primary indicator of the structural issues. None of the permeable pavements have experienced any cracking to date. This was expected because of the lighter traffic loads and also due to the relatively short evaluation period of less than three years so far. It should be noted that a dumpster truck routinely empties a dumpster in the Public Parking Lot and the pervious concrete has not experienced any cracking under these loads (Figure 4.4.23).

Safety exhibited localized areas of minor raveling (Figure 4.4.24), which were likely the result of a dry pervious concrete mix (low water content) at the time of placement. There were also a few localized areas of moderate raveling in the pervious concrete at the Public Parking Lot, which can also be attributed to dry pervious concrete mix. The permeable asphalt has also experienced small areas of minor raveling along Park Ave., which have resulted from abrasion due to the turning of wheels of parked cars.

The surface performance of the permeable pavements was primarily evaluated based on the degree of raveling of the pavement surface. Raveling is identified as loose pavement material that has debonded from the pavement structure and is the primary distress found in permeable asphalt and pervious concrete pavements. After construction, the pervious concrete at the Department of Public Safety exhibited localized areas of minor raveling (Figure 4.4.24), which were likely the result of a dry pervious concrete mix (low water content) at the time of placement. There were also a few localized areas of moderate raveling in the pervious concrete at the Public Parking Lot, which can also be attributed to dry pervious concrete mix. The permeable asphalt has also experienced small areas of minor raveling along Park Ave., which have resulted from abrasion due to the turning of wheels of parked cars.

Permeable Pavement Monitoring
The functionality of the permeable pavements in infiltrating stormwater was evaluated by monitoring the depth of the water in the reservoir course beneath the pavement. To accomplish this, monitoring boxes were placed in the various permeable pavements around Aiken. The boxes used for monitoring were fiberglass polymer concrete pull boxes typically used for utilities located beneath pavements and sidewalks as seen in Figure 4.4.25.

Figure 4.4.23 - Dumpster located on the pervious concrete in the public parking lot

Figure 4.4.24 - Minor raveling at the Dept. of Public Safety

Figure 4.4.25 - Photo of a pavement monitoring box prior to installation
The boxes were 12-in. by 12-in. wide and 12-in. tall with an open bottom. Prior to installation, holes were drilled near the bottom flange of the box and a geotextile filter fabric was wrapped around the exterior of the box. The holes allowed water to enter the box, so the water level in the reservoir course could be measured. The geotextile was used to keep aggregates from migrating into the box. In some cases, the boxes were installed during construction (Figure 4.4.26), while in others, the boxes were placed in the pavement after construction (Figure 4.4.27).

Figure 4.4.26 - Installation of a pavement monitoring box during pervious concrete pavement construction

Figure 4.4.27 - Installation of a monitoring box in a permeable asphalt pavement after construction
To measure the depth of water in the permeable pavement structure (reservoir course) during a rain event, water level loggers were placed in the monitoring boxes. The loggers that were used for the data collection were Model WL-16 water level loggers supplied by Global Water (www.globalw.com) (Figure 4.4.28). This model is a datalogger and submersible pressure transducer combination that is ideal for shallow water with depths ranging from 0 to 3 ft. Because the loggers were to be installed beneath the surface of the roadway and susceptible to submerged conditions, it was not possible at the time to utilize wireless sensors that could be tied into the wireless sensor network utilized for the other monitoring efforts on the project. Therefore, these sensors were selected as an alternative.

Prior to installation, the data logger portion of the sensor was sealed in a water tight PVC housing to prevent moisture from fouling the logger if it were to become submerged. Then, any aggregate was removed from inside the box to expose the geotextile on top of the subgrade (the bottom of the reservoir course). The pressure transducers was placed on its side on top of the geotextile and held in place with a large staple covered with a rubber sleeve (Figure 4.4.29). This staple kept the sensor in place. The encased data logger was then positioned vertically as close to the top of the box as possible to minimize the chances of water entering the atmospheric vent at the top of the assembly. Four sensors were installed in monitoring boxes located in the permeable asphalt pavement along Park Ave. These were all installed in the parking areas along the medians in both directions of traffic. Sensors were installed on Park Ave. between Newberry St. and Laurens St. on the North side (PNL-N) and South side (PNL-S) of the median. This is the section of Park Ave. directly in front of the Municipal Building. Two other sensors were located on Park Ave. between Union St. and Fairfield St. on the North side (PUF-N) and South side (PUF-S) of the median.

Data collected from the pavement water level sensors were processed for each rain event in which the depth of the water in the reservoir course was as least 0.5-in. Figure 4.4.30 provides a visual explanation of the results. In Figure 4.4.30, stormwater infiltrated the permeable pavement and was stored in the reservoir course before it naturally infiltrated the subgrade soil below. In this particular event, high intensity rainfall resulted in an immediate accumulation of water in the reservoir to a depth of approximately 3.5-in. As the rainfall subsided, the depth gradually decreased as the stored water infiltrated the subgrade over a period of approximately five hours.

Figures 4.4.31 through 4.4.53 present the data for 24-hour periods when water was present in the reservoir course as the result of a rainfall event in Aiken, SC during the period from June 16, 2011 to March 14, 2012. This data is further summarized in Table 4.4.5. The data indicates that water is infiltrating the surface of the pavements as intended and that there is some degree of storage that occurs depending on the amount of rainfall and the rainfall intensity of a given storm. The data also show that a greater amount of storage occurs in the PNL-N section of pavement compared to PNL-S, but the water level never exceeds the 12-in. depth of the pavement indicating that the storage volume is adequate if not over designed for the conditions. The section of PUF-N did had some storage for some of the storms, but was generally lower than the other sections. This is likely due to the presence of a functioning underdrain in this pavement section.
## Table 4.4.5 - Summary of maximum water level in permeable asphalt pavements during rain events from June 16, 2011 to March 14, 2012

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum Water Depth in the Porous Pavement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PNL-N</td>
</tr>
<tr>
<td>Jun. 18-19, 2011</td>
<td>3.420</td>
</tr>
<tr>
<td>Jun. 22-23, 2011</td>
<td>0.516</td>
</tr>
<tr>
<td>Jul. 25-26, 2011</td>
<td>6.072</td>
</tr>
<tr>
<td>Aug. 6-7, 2011</td>
<td>3.108</td>
</tr>
<tr>
<td>Aug. 8-9, 2011</td>
<td>3.720</td>
</tr>
<tr>
<td>Aug. 11, 2011</td>
<td>0.684</td>
</tr>
<tr>
<td>Aug. 29-30, 2011</td>
<td>3.264</td>
</tr>
<tr>
<td>Sep. 5-6, 2011</td>
<td>1.176</td>
</tr>
<tr>
<td>Sep. 23, 2011</td>
<td>3.780</td>
</tr>
<tr>
<td>Sep. 24, 2011</td>
<td>2.244</td>
</tr>
<tr>
<td>Sep. 26, 2011</td>
<td>1.152</td>
</tr>
<tr>
<td>Sep. 27-28, 2011</td>
<td>3.996</td>
</tr>
<tr>
<td>Oct. 11-12, 2011</td>
<td>0.984</td>
</tr>
<tr>
<td>Oct. 18-19, 2011</td>
<td>1.104</td>
</tr>
<tr>
<td>Nov. 16-17, 2011</td>
<td>0.612</td>
</tr>
<tr>
<td>Nov. 29-30, 2011</td>
<td>0.744</td>
</tr>
<tr>
<td>Dec. 27, 2011</td>
<td>2.040</td>
</tr>
<tr>
<td>Feb. 19, 2012</td>
<td>2.376</td>
</tr>
<tr>
<td>Feb. 24, 2012</td>
<td>2.484</td>
</tr>
<tr>
<td>Feb. 29-Mar. 1, 2012</td>
<td>1.068</td>
</tr>
<tr>
<td>Mar. 4, 2012</td>
<td>0.648</td>
</tr>
</tbody>
</table>

* Water level was less than 0.1 in.
** A vehicle was parked over the monitoring box, so the data could not be downloaded for this period
*** The sensor ceased to collect data
Figure 4.4.31 - Water level data from June 18, 2011 to June 19, 2011

Figure 4.4.32 - Water level data from June 22, 2011 to June 23, 2011

Figure 4.4.33 - Water level data from July 25, 2011 to July 26, 2011

Figure 4.4.34 - Water level data from July 26, 2011 to July 27, 2011.
Figure 4.4.35 - Water level data from August 6, 2011 to August 7, 2011

Figure 4.4.36 - Water level data from August 8, 2011 to August 9, 2011

Figure 4.4.37 - Water level data from August 11, 2011

Figure 4.4.38 - Water level data from August 29, 2011 to August 30, 2011
Figure 4.4.39 - Water level data from September 5, 2011 to September 6, 2011

Figure 4.4.40 - Water level data from September 21, 2011 to September 22, 2011

Figure 4.4.41 - Water level data from September 23, 2011

Figure 4.4.42 - Water level data from September 24, 2011
Figure 4.4.43 - Water level data from September 26, 2011

Figure 4.4.44 - Water level data from September 27, 2011 to September 28, 2011

Figure 4.4.45 - Water level data from October 11, 2011 to October 12, 2011

Figure 4.4.46 - Water level data from October 18, 2011 to October 19, 2011
Figure 4.4.47 - Water level data from November 16, 2011 to November 17, 2011

Figure 4.4.48 - Water level data from November 29, 2011 to November 30, 2011

Figure 4.4.49 - Water level data from December 27, 2011

Figure 4.4.50 - Water level data from February 19, 2012
Figure 4.4.51 - Water level data from February 24, 2012

Figure 4.4.52 - Water level data from February 29, 2012 to March 1, 2012

Figure 4.4.53 - Water level data from March 4, 2012
4. RESEARCH ELEMENTS

(4.5) Cyberinfrastructure

Intelligent River® Overview
The cyberinfrastructure support for the Aiken Green Infrastructure (AGI) project leverages a technology development program that began in 2007 and has remained in continuous operation since that time. The program is focused on the development of an environmental macroscope, a landscape-scale observation instrument comprising a heterogeneous fabric of in situ sensors that cover an expansive geographic area. The instrument design enables end-users – researchers, educators, policymakers, and private citizens – to collect, share, and utilize a broad spectrum of in situ data at ultra-dense temporal and spatial scales. In contrast to existing earth instrumentation systems, Clemson’s macroscope is an end-to-end toolset comprising new telemetry platforms, wireless transmission technology, data processing and storage systems, visualization tools, and presentation facilities.

The architecture of the macroscope installed in Aiken is illustrated in Figure 4.5.1; it consists of four tiers. The first tier implements a wireless sensing fabric comprising terrestrial sensing platforms. The Aiken deployment is focused primarily on the collection of soil parameters – temperature, conductivity, and volumetric water content – at depths of 6 inches, 12 inches, and 18 inches. Observation data collected from these sensors, when coupled with meteorological information (e.g., rainfall), provides fine-grained views into stormwater infiltration throughout the parkways. The second tier of the Intelligent River® instrument provides a transit and uplink system for relaying observation data from the sensing fabric to Clemson’s high performance computing backbone.

On the backbone, the third tier provides observation management middleware for automating the validation, storage, and dissemination of observation data from multiple data publishers to multiple data subscribers. Finally, the fourth tier provides presentation services for presenting that data to end-users.

Sensing Fabric
The sensing fabric serves as the instrument lens, comprising multiple wireless sensor networks. The design desiderata include (1) broad support for common interconnect standards, (2) high-fidelity sensing, (3) scalable temporal and spatial coverage, (4) rapid and reliable deployment, and (5) network longevity.

While commercial providers like Campbell Scientific and National Instruments offer a range of data acquisition systems, these systems do not satisfy the observation goals in Aiken – long-lived, at-scale, “transparent” sensing. Commercial systems are too large, require too much energy, offer limited customization capacity, and retail at a price point that prohibits large-scale deployment. To suit the needs of AGI and other deployments, the team has designed a new sensing platform based on a stackable, componentized architecture with integrated power gating across all device peripherals – the MoteStack. (The device has been submitted for patent protection; the patent

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1 This terminology is consistent with H.T. Odum’s use of the term “macroscope” to emphasize the importance of holistic consideration of ecological systems (Odum 1971, Hagen 1992) – precisely what the Intelligent River® toolset enables.
is pending.) The MoteStack will operate for over one year on a 9-volt battery when sampling digital and analog sensors every fifteen minutes, at a price point that is significantly less than commercial offerings in the same capability class.

**Transit and Uplink System**
The transit and uplink system is responsible for relaying observation data from the instrument lens to a high performance computing backbone. The design desiderata for this tier include (i) adaptability to diverse environments, (ii) coverage scalability, (iii) fault-tolerant data transport, and (iv) minimal operating expense.

In general, the networks that form the sensing fabric must span a range of environments that vary not only in terms of their geography (e.g., open fields, hilly terrain, dense forests), but also in terms of the communication options they allow (e.g., Wi-Fi, cellular, network-isolated). The transit and uplink system accommodates this diversity through adaptation. Site engineers tailor their technology selections based on sensing requirements (e.g., coverage, sampling rate), technology characteristics (e.g., coverage, bandwidth, foliage penetration), and estimated operating expense (e.g., cellular or satellite fees). At each site, adaptation occurs within a two-tier architecture consisting of a regional network (e.g., Zigbee, Wi-Fi mesh) and a long-range network (e.g., cellular, satellite).

**Observation Management Middleware**
The observation management middleware is a distributed software system that executes within Clemson’s high-performance computing center. The system receives raw observation data from in situ field installations and is responsible for transforming this data into standard formats, ensuring the validity of the data, and routing the data to an extensible set of consumers. The design desiderata for this tier include (i) massive data handling scalability, (ii) near real-time performance, and (iii) fault-tolerant, secure messaging.

To satisfy the need to support an unlimited number of data producers and data consumers, the current implementation relies on an internet-scale publish/subscribe substrate. The implementation is structured as a loosely-coupled set of publish/subscribe applications organized in consecutive levels. The first receives raw data from the backhaul links, adds observation metadata, converts the aggregate to a standard format, and publishes the result to a level-zero stream. Quality control procedures are implemented in subsequent levels, with each level performing more robust checks of data validity. A final set of stream processors archive this data in the desired scientific data formats before the data is streamed back out for consumption by end-user applications.

**Presentation Services**
The Intelligent River® system provides a Web 2.0 data access portal that provides a geospatial interface based on the Google Maps API for exploring instrumentation sites, the installed platforms, and the data they produce. The portal aggregates content from the sensing fabric and third-party providers, including the U.S. Geological Survey and U.S. Army Corps of Engineers. The site provides access to raw observation data, instrument performance statistics (e.g., middleware traffic, platform status), and quality control results (see [www.intelligentriver.org](http://www.intelligentriver.org)). This interface served as the primary public face of the AGI data collection effort, enabling end-users to interactively explore the efficacy of the BMP installations – via a desktop system, or alternatively, via a smartphone or tablet, while touring the field sites in person.

**Transit and Uplink Installation**
The transit and uplink system provides a wireless backbone used to route observation data collected from in situ field sensors to Clemson’s high performance computing cluster. The installation in Aiken was guided by a long-term vision of providing full coverage to the city center. To enable this type of expansion, the engineering team chose a mesh networking solution. This type of network comprises distributed wireless access points that route network traffic over a series of “hops” leading to an Internet gateway. This type of multi-hop solution provides a number of advantages, including scalability, fault tolerance, and high performance.

2 Note that while the website remains operational, the real-time feeds from Aiken are no longer being displayed. These feeds are being transitioned to a new website implementation, scheduled to be released in 2013.
The Aiken installation consists of two layers. The first is composed of 7 mesh networking devices provided by Anaptyx, LLC. These devices provide 2.4Ghz connectivity to client devices and rely on either a 2.4Ghz or a 5.4Ghz back-channel for mesh support (i.e., multi-hop routing). Figure 4.5.2 shows one of the Anaptyx routers and illustrates their placement in Aiken. The large circle denotes the end-point router, which links to the city’s Internet gateway. The soft green highlights between the circles denote the available network routing paths.

The wireless sensors deployed in Aiken rely on 900Mhz XBee radios. While these radios offer low power consumption and long lifetimes, they cannot directly communicate with traditional wireless networks. To bridge these 900Mhz devices to the 2.4Ghz Anaptyx network, the second layer of the Aiken installation relies on “base station” devices comprising a 900Mhz receiver and a 2.4Ghz transmitter. These devices receive observation data, process that data (e.g., to include observation metadata, diagnostic information), and then transmit the resulting payload to the mesh network. This payload is routed through the mesh network to the Internet gateway, and is finally delivered to Clemson’s high performance computing cluster.

In the original Aiken installation, the second layer of the network was implemented using Digi ConnectPort devices, each running a proprietary operating system. In the summer of 2012, these devices were replaced with embedded Linux devices running a custom configuration developed by the Clemson team. These devices eliminate the team’s dependence on a proprietary operating system, provide significantly better diagnostic capabilities, and enable simplified remote management. It is now possible, for instance, to upgrade the application services running in Aiken from an administrative center within Clemson.

The network upgrade additionally includes support for cellular fail-over: should the city’s Internet gateway ever be disconnected, the Intelligent River® network will automatically fail over to a cellular Internet gateway. While the performance of the system will be degraded, key services will remain functional during the city’s network outage.

Sensing Fabric Installation

All of the sensors integrated with the Intelligent River® infrastructure rely on the MoteStack sensing platform. In Aiken, each platform is configured with 4 layers, providing computation, wireless transmission, SDI-12 support, and basic human interaction (i.e., LEDs, tactile switches), respectively. Each is housed in a small weatherproof enclosure, which includes the platform, a supporting antenna, and a 12-volt power supply. Sensor connections are routed downward along the enclosure’s support post. Representative images from the Aiken installation are shown in Figures 4.5.3 and 4.5.4. The first image shows the inner chamber of a deployed enclosure. The second provides an image of a deployed enclosure in the context of a broader BMP installation.
To avoid the technical burden and attendant risks of using multiple sensor standards, the Aiken installation adopts the SDI-12 protocol throughout. This protocol, developed by a consortium of leading sensor manufacturers, describes a standard mechanism for communicating with digital sensors. Perhaps the most significant advantage offered by the protocol is the ability to chain many digital sensors to a single device. In Aiken, this capability is leveraged by linking up to 6 multi-parameter soil sensors to a single MoteStack, thereby further reducing network complexity and cost.

A summary of the instrumentation deployed in Aiken to support the Green Infrastructure project is shown in Figure 4.5.5. The blue and green triangles represent weather stations and Isco samplers, respectively. Each orange triangle represents three multi-parameter soil sensors deployed at depths of 6 inches, 12 inches, and/or 18 inches, respectively. These devices provide soil temperature, conductivity, and volumetric water content over the SDI-12 protocol. Each is linked to a MoteStack for data collection and transmission.

Throughout the soil moisture network, observations are collected at 5-minute intervals. These samples are ultimately transmitted to Clemson’s middleware system via the transit and uplink system to support data reporting and presentation.
4. RESEARCH ELEMENTS

(4.6) Data Reporting and Presentation

Real-time Quality Assurance (QA) is a critical component to ensure the accuracy of data collection that benefits both data producers and data consumers. These processes run in real-time and are validating and flagging potentially erroneous data prior to data archival. The Intelligent River® Quality Assurance / Quality Control (QA/QC) services are implemented as internal subscribers that receive and validate observation data of the published data streams. These processes identify such errors as timestamp anomalies and whether data fall within expected ranges. This real-time QA/QC application is performed as a series of steps termed that identify and flag potentially problematic data. The flags for each check are appended together and are archived along with the data values as permanent records describing the quality of the record.

For the Aiken data, Level 0 is the data state prior to QA. Level 0 data are parsed and examined for range checks, duplicate timestamp anomalies, and a variability or step check. As each observation is processed by the QA functions, a two-character code for each observation indicating either a pass or failure for each check, results in a six-character string that is attached to the observation.

The six-character descriptor is as follows:

<table>
<thead>
<tr>
<th>Range Check</th>
<th>Dupe Check</th>
<th>Step Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R) or O</td>
<td>(H or L) or K</td>
<td>D or O</td>
</tr>
<tr>
<td></td>
<td>O or K</td>
<td>S or O</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(H or L) or K</td>
</tr>
</tbody>
</table>

The Range Check Descriptor bit can be:
RH – Exceeded the maximum range limit
RL – Exceeded the minimum range limit
OK – Range Check Passed

The Dupe Check Descriptor bit can be:
DO – Duplicate Observation
OK – Dupe Check Passed

The Step Check Descriptor bit can be:
SH – Exceeded the maximum variability limit
SL – Exceeded the minimum variability limit
OK – Step Check Passed

For example, a temperature observation value that exceeded the expected range will generate the following flag:

R H O K O K

Following initial data flagging, the Level 2 process addresses duplicate timestamp values and other anomalies. Overall, the primary QA efforts focused on range checks and duplicate timestamps was not a concern. The step check was not of particular use for Aiken data due to the fact that the Intelligent River® team did not have a history of data collection with which to determine expected variability of the parameters under observation.

Data threads are generated based on the QA processing level (Figure 4.6.1). This provides a high level of flexibility to consume data for various purposes depending on the data and information management goals. The Intelligent River® framework also supported a diversity of end points for data storage including web tools, simple text files and relational databases.
Figure 4.6.1 - Schematic showing QA/QC processing steps and data archival

Data Visualization and Analytics
The flexibility of the Intelligent River® middleware and repository systems supported multiple types of online and desktop applications. During active data collection, the Intelligent River® website supported real-time access to the most recent data (Figure 4.6.2). All reporting systems could be accessed from a project page for Aiken and the data of interest could be selected for data visualization. Through this interface a user could access the most recent data from any given platform and could launch Flash-based graphs that supported up to a time period of up two weeks.
Additional services supported mobile access (Figure 4.6.3) to data to enable data visualization and sensor and network error reports as well as standard online map-based solutions. Network and sensor outage notification systems were loosely designed around the Open Geospatial Consortium Sensor Web Enablement (White et. al. 2010). A desktop Adobe Air product that currently supports long-term data visualization tool and data export (Figure 4.6.4).

Long-Term Data Archival and Access
A PostgreSQL database is the current long-term archive for Aiken data that is administered by Clemson Computing and Information Technology (CCIT) and Intelligent River®. Although there are currently no online tools for accessing these data, the Adobe Air tool can access and download data with efforts underway to move the tool online. Future efforts will include the update and upgrade of database software and hardware and the creation of ISO 19115-2 metadata record to support federal metadata requirements.
In 2009, the American Association of State Colleges and Universities determined “the publicly engaged academic institution is fully committed to direct, two-way interaction with communities and other external constituencies through development, exchange, and application of knowledge, information, and expertise for mutual benefit.” To those ends, a fundamental goal of the project team was to disseminate findings to the general public, as well as regional design engineers, site developers, municipal and county stormwater staff, state environmental agencies, landscape architecture academics and professionals, planning agencies and peer-reviewed journals. The outreach component will remain active as long as participating faculty continue to engage in refining and publicizing relevant results. A summary of trainings, presentations, website work, media coverage and publications that covered the project is provided below.

Training

On June 26, 2012, the Center for Watershed Excellence, the Clemson Cooperative Extension Service and the City of Aiken conducted the Aiken Green Infrastructure Design and Implementation Technical Workshop targeted at design engineers, stormwater managers, and regulatory agency personnel. The workshop was organized to address site design techniques and implementation practices in support of green infrastructure. The workshop provided 6 CEU (Continuing Education Units) for professional engineers and surveyors, authorized by the SC Department of Labor, Licensing and Regulation. Other professionals may appeal to their respective boards to obtain professional education credits. We will provide a certificate of attendance at the conclusion of the workshop.

This workshop offers 6 PDH (Professional Development Hours) for professional engineers and surveyors, authorized by the SC Department of Labor, Licensing and Regulation. Other professionals may appeal to their respective boards to obtain professional education credits. We will provide a certificate of attendance at the conclusion of the workshop.

Figure 4.7.1 – Aiken Green Infrastructure Technical Training Workshop announcement and agenda

Figure 4.7.2 – Photographs from the workshop

AGENDA

9:00AM – 12:00PM

Welcome

Richard Peake, City Manager, City of Aiken

Project Overview

Gene Eidson, Ph.D., Institute of Applied Ecology

Cal Sawyer, Ph.D., Center for Watershed Excellence

9:00AM – 12:00PM

Introduction

• Vegetation

Jon Calabria, Ph.D., University of Georgia

Chris Post, Ph.D., Clemson University

Project Overview

Gene Eidson, Ph.D., Institute of Applied Ecology

Cal Sawyer, Ph.D., Center for Watershed Excellence

12:00PM – 1:00PM

Lunch

1:00PM – 3:00PM

Field Demonstration

Intelligent River® Integration

Brad Potman, Ph.D., Clemson University

Permeable Pavement

Brad Potman, Ph.D., Clemson University

Bioretention

Richard Peake, City Manager, City of Aiken

Municipal Auditorium, Aiken City Hall

Tuesday, June 26, 2012

9:00AM – 3:00PM
Outreach

Professional presentations given to date are listed below in **Table 4.7.1**.

<table>
<thead>
<tr>
<th>Date</th>
<th>Presentation Title</th>
<th>Event</th>
<th>Presenter(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 28, 2010</td>
<td>Sand River Headwaters Green Infrastructure Project</td>
<td>CSRA Geological Society Meeting</td>
<td>Gene Eidson, Ph.D.</td>
</tr>
<tr>
<td></td>
<td>to Implementing Green Infrastructure Practices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct 13, 2010</td>
<td>Real-Time Quality Control (QC) Processing, Notification, and Visualization Services</td>
<td>2010 SC Water Resources Conference</td>
<td>David White, Ph.D.</td>
</tr>
<tr>
<td></td>
<td>Supporting Data Management of the Intelligent River®</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov 17, 2010</td>
<td>Aiken Green Infrastructure Retrofit</td>
<td>T&amp;DI / ASCE Green Streets and Highways Conference - Denver, CO</td>
<td>Brad Putman, Ph.D.</td>
</tr>
<tr>
<td>Sep 16, 2011</td>
<td>Sand River Headwaters Green Infrastructure Projects</td>
<td>The Rotary Club of Aiken</td>
<td>Gene Eidson, Ph.D.</td>
</tr>
<tr>
<td>Sep 16, 2011</td>
<td>Using Green Infrastructure to Improve Urban Watershed Hydrology</td>
<td>USDA Southern Region Water Conference</td>
<td>Dan Hitchcock, Ph.D., P.E.</td>
</tr>
<tr>
<td>Mar 14, 2012</td>
<td>Green Infrastructure in Aiken, SC</td>
<td>Catawba Watershed Sustainable Growth Speaker Series</td>
<td>Cal Sawyer, Ph.D.</td>
</tr>
<tr>
<td>Apr 23, 2012</td>
<td>Innovative Stormwater Management in Aiken, SC</td>
<td>Sumter County Low Impact Development Planning Workshop</td>
<td>Cal Sawyer, Ph.D.</td>
</tr>
<tr>
<td>Aug 16, 2012</td>
<td>Examining the Effectiveness of Bioretention Cells and Porous Asphalt in Aiken, SC</td>
<td>Thesis Defense, Clemson University</td>
<td>Casey Johnson</td>
</tr>
<tr>
<td>Sep 10, 2012</td>
<td>Green Infrastructure Monitoring and Research in Aiken, SC</td>
<td>Hitchcock Woods Foundation Board of Trustees</td>
<td>Gene Eidson, Ph.D., Cal Sawyer, Ph.D.</td>
</tr>
<tr>
<td>Nov 1, 2012</td>
<td>Green Infrastructure in Aiken, SC</td>
<td>SC Association of Stormwater Managers</td>
<td>Larry Morris, P.E., Cal Sawyer, Ph.D.</td>
</tr>
</tbody>
</table>

**Dissemination of Findings - RESEARCH ELEMENTS (4.7)**
On June 27, 2012 the Aiken Green Infrastructure Educational Field Day was held immediately subsequent to the technical workshop. Clemson University distributed a news release the week before the event. The Aiken Standard published an announcement for the event and ran an article afterwards written by a reporter who participated in the field day activities. The first part of the workshop focused on presentations by principal research scientists covering different project components, including bioretention and bioswales, permeable parking and essential technologies to help understand the preliminary results. The event gave citizens, the business community and local media an opportunity to learn more about affected parkways (event photos in Figure 4.7.2). Aiken mayor Fred Cavanaugh opened the program with comments reflecting the history of the City’s involvement and continuing interest in proactively addressing water quality and quantity issues affecting the Hitchcock Woods. The Field Day announcement and agenda are shown in Figure 4.7.3.

Dissemination of Findings - RESEARCH ELEMENTS (4.7)

Some of your Aiken parkways are now delivering multiple benefits! Not only do they continue offering unparalleled beauty in an historic urban setting, several parkways have been retrofitted to provide important ecological services. In 2009, the City of Aiken, Clemson University and several other partner organizations embarked on an ambitious project to use available surface area in the parkways to treat stormwater, which was causing significant and costly impairments downstream.

The first part of the workshop will focus on presentations by principal research scientists covering different project components, including bioretention and bioswales, permeable parking, and essential technologies to help understand the results. If you have questions, or have been curious about what's been going on in the affected parkways over the last two years, this is your chance to get some answers!

Come LEARN about the project that won the S.C. Municipal Association's 2011 Municipal Achievement Award; SEE the practices being used to treat water quality and water quantity concerns; TALK to the scientists, researchers and engineers who have studied and investigated the processes; EXPERIENCE the instruments and techniques utilized to collect, transmit and analyze important data regarding Aiken's valuable water resources.

9:00AM - 9:15AM Opening Remarks - Mayor Fred Cavanaugh, City of Aiken
9:15AM - 10:30AM Project Overview
Bioretention, Permeable Pavement & Intelligent River® Integration
10:45AM - 12:30PM Field Demonstrations (Informal QA at Parkway Research Sites)

Project Website
A project website was developed at www.clemson.edu/watershedcenter/aiken_green and is hosted within the Center for Watershed Excellence site to provide background information about green infrastructure and the stormwater problem in Aiken, feature video and photographs of the construction process, capture media coverage and provide additional information. From the website’s creation in early 2010, over 5,000 visitors have accessed the site, not only from our state and region, but across the country and the world (including Canada, India, Germany, the United Kingdom, France and Spain). A screen shot of the home page is provided in Figure 4.7.4.
News Media

There was one US EPA Region IV press release and four Clemson University press releases distributed, along with over two dozen stories published in newspapers, magazines and bulletins and aired on television about the project from July 2009 through 2012. The Emmy Award-winning Making it Grow! program produced by ETV and Clemson University featured the Aiken Green Infrastructure Project on their June 11, 2011 episode. Following is a timeline of news and media coverage.

June 27, 2012 - Aiken Standard
Residents hear progress of green infrastructure
*Story also published on American Planning Association website (www.planning.org - June 28, 2012)*

June 25, 2012 - Aiken Standard
Learn how green infrastructure parkway changes are benefiting city at field day

June 21, 2012 - Clemson University Newsroom Press Release
Aiken residents to get look at green infrastructure project during field day

September 28, 2011 - News Channel 6, WJBF
Aiken’s Hitchcock Woods being eroded by runoff

September 19, 2011 - Aiken Standard
Clemson professor studies Aiken stormwater

June 21, 2011 - SC ETV’s Making it Grow!
Featuring the Aiken Green Infrastructure Project

June 21, 2011 - Aiken Standard
Parkways win green award

June 21, 2011 - WJBF, News Channel 6
City of Aiken receives municipal achievement award

June 1, 2011 - City of Aiken News
Making It Grow Gardening Show Highlights Aiken’s Green Infrastructure

May 4, 2011 - Aiken Standard
TV show visits Aiken to feature parkways

April 25, 2011 - The Post and Courier
New technology = smarter rivers: Wireless sensor can supply key data immediately

March 30, 2011 - WJBF, News Channel 6
Aiken Parkway Project is Only One Step in Saving Hitchcock Woods

September 1, 2010 - Aiken Standard
Parkways to be ready for Makin’

August 18, 2010 - Aiken Standard
Parkways in progress

*Figure 4.7.4 - Sand River Headwaters Green Infrastructure project website*
Dissemination of Findings - RESEARCH ELEMENTS (4.7)

July 2010 - Greater Aiken Chamber of Commerce
Aiken’s Makin’: Pardon Our Progress (Greater Aiken Chamber of Commerce)

July 4, 2010 - Aiken Standard
Storms postpone parkway construction

June 10, 2010 - Aiken Standard
City making progress on parkways

Spring 2010 - City of Aiken News, Public Works Dept.
Progress in Aiken Parkways Should Soon Mean Peace of Mind in Hitchcock Woods
Parkways will be filled with soil mix to treat stormwater

Spring 2010 - Clemson Impacts Magazine
Building a “green infrastructure”

May 25, 2010 - Clemson University Newsroom Press Release
Clemson green project selected for national recognition
*Story also published by Anderson Independent Mail - May 27, 2010*

April 27, 2010 - Erosion Control (www.erosioncontrol.com)
Saving Hitchcock Woods

April 20, 2010 - WAGT-TV NBC Augusta
Millions used to save Hitchcock Woods

April 9, 2010 - The Times & Democrat
Federal Investments Help Clemson

February 19, 2010 - Stormwater Solutions (www.estormwater.com)
Recovery Act Funding Jumpstarts Construction Phase of Green Infrastructure Project

February 18, 2010 - WRDW News 12
City of Aiken cashing in on “Green Infrastructure”

February 18, 2010 - US EPA Region IV Press Release
Recovery Act Funding Jumpstarts Construction Phase of Green Infrastructure Project

February 18, 2010 - Clemson University Newsroom Press Release
Aiken, Clemson, EPA kick off project to make stormwater ‘green’

February 12, 2010 - Clemson University Newsroom Press Release
Clemson helps Aiken turn stormwater ‘green’

February 1, 2010 - Aiken Standard
Project to lessen erosion in Woods
*Story also carried by WaterWorld (www.waterworld.com)*

July 16, 2009 - Augusta Chronicle
Aiken median work to reduce water runoff

July 5, 2009 - Aiken Standard
City looks to reverse erosion in Sand River

Educational Videos
Several videos were created to explain green infrastructure and show the processes of different phases of the parkway and pavement construction in Aiken. These videos are available on the project website at [www.clemson.edu/watershedcenter/aiken_green](http://www.clemson.edu/watershedcenter/aiken_green). The videos are also available on the following YouTube playlist link along with several videos detailing the Intelligent River component which involves the monitoring - [http://www.youtube.com/watch?v=7RVTHOhS7Vg&feature=share&list=PLcA0HMLq3-Di3HZjY_jooZ8HR2uzvoTy](http://www.youtube.com/watch?v=7RVTHOhS7Vg&feature=share&list=PLcA0HMLq3-Di3HZjY_jooZ8HR2uzvoTy)

Newsletters and Bulletins
Sand River Headwaters Green Infrastructure Project updates were featured in several IAE / CWE program related newsletter issues including:

- Winter 2012 - Carolina Clear Newsletter (statewide audience)
- Spring / Summer 2010, Vol. 1, No. 1 Center for Watershed Excellence / Restoration Institute Newsletter
APPENDICES INDEX

APPENDIX A
Evaluation Results for the Aiken Green Infrastructure Design and Implementation Technical Workshop

  The remaining appendices (B - H) are provided in electronic file format on the accompanying flashdrive.

APPENDIX B
Bioretention Soil Mix (BSM) Tests

Analysis Literature
  * Bulk Density / PIndex

Information
  * Analysis / NC State / Waters

Results
  * Compiled Analysis Clemson / NC State / Organic Matter / Waters / Woolpert

Files for each parkway with lab reports

APPENDIX C
Geographic Information Systems (GIS)

(GIS was used to both record the location of sensor assemblies and also to model the water flow in selected bioretention basins.)

mxd / dwg files
Aiken – files made up of jp2 / sid / aux / e00
Aug – East
Elevation Conversions – Unix files
Google – kmz files
Graniteville - files made up of jp2 / sid / aux / e00
HOI Creek - files made up of jp2 / sid / aux / e00
  * Output – dir / dat / nit
New Ell
  * Output – dir / dat / nit
Nor AUG
  * Output – dir / dat / nit

APPENDIX D
Maps

Electricity Monitoring (includes kmz files)
Soils
Stormwater
Weather
WI-FI
APPENDIX E

Photographs
Project Website Construction Timelines
Bioretention Cell
  *Bioretention Media Site / Irrigation / Securebox Monitor*
Bioretention Cell Monitoring
Intelligent River® Site Photos
MoteStack
Other Monitoring Sites
  *Cistern / Hitchcock Woods / Soil Moisture / S. Boundary / Weather Station*
Pavement
People & Events
WI-FI

Parkways
Parkway Photos

Pavement
Site Photos
Surfaces and Testing

APPENDIX F

Plans & Final Punch Lists
As-Built – asc / dwf / dwg / bak files and CAD
Completion Timelines
MISC – plant list / pavement underdrain
Pre-Construction Plans – planting / pavement / landscaping
Proposal

APPENDIX G

Soil Test Reports
(The soil borings conducted prior to construction to inform about the infiltration capacity of the native or parent soils.)

APPENDIX H

Weekly Updates by Site Manager
APPENDIX A - Evaluation Results for the Aiken Green Infrastructure Design and Implementation Technical Workshop (4 screen shots total)
APPENDIX A - Evaluation Results for the Aiken Green Infrastructure Design and Implementation Technical Workshop