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Transforming Our Cities: High-Performance Green Infrastructure

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TRANSFORMING OUR CITIES: HIGH-PERFORMANCE GREEN INFRASTRUCTURE

by:

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WATER ENVIRONMENT RESEARCH FOUNDATION

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ABSTRACT AND BENEFITS

Abstract:

Traditional approaches to stormwater management include construction of large, centralized end-of-pipe or interceptor solutions that can be extraordinarily expensive and contribute to other environmental impacts such as downstream flooding. The goal of this research is to look beyond conventional approaches to stormwater infrastructure and examine the effectiveness of various decentralized controls that use natural elements to dampen stormwater surges. Specifically, the research team examined highly distributed real-time control (DRTC) technologies for green infrastructure, such as advanced rainwater harvesting systems, dynamically controlled green roofs, wet detention basins, and underdrained bioretention systems. Particularly, the objective is to demonstrate that these DRTC systems can play a critical role in transforming our nation's urban infrastructure.

Benefits:

- Demonstrates that DRTC green infrastructure can significantly reduce contributions to combined sewers and mitigate post-storm combined sewer overflows.
- Shows that DRTC green infrastructure can reduce stormwater runoff.
- Illustrates that DRTC green infrastructure can conserve water, with particular benefits in drought-inclined areas.
- Shows that DRTC green infrastructure can maximize stormwater reuse for irrigation
- Supports the hypothesis that controlled, highly-distributed green infrastructure is a cost-effective approach to urban stormwater management.

Keywords: Real-Time, stormwater, CSO, combined sewer, blue roof, green roof, active control, rainwater harvesting, porous pavement, onsite use, RTC, Internet of Things, smart water, smart cities, bioretention, field pilots.

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API	Application Programming Interface
BMPs	Best Management Practices
CDN	Content Distribution Network
CSO	Combined Sewer Overflow
CSS	Combined Sewer Systems
DCFD	District of Columbia Fire Department
DRTC	Distributed Real-Time Control
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NYCDEP	New York City Department of Environmental Protection
POP	Probability of Precipitation
QPF	Quantitative Precipitation Forecast
REST	Representational State Transfer
RTC	Real-Time Control
SOAP	Simple Object Access Protocol
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geologic Survey

EXECUTIVE SUMMARY

The objective of this project is to demonstrate that the highly distributed real-time control (DRTC) technologies for green infrastructure being developed by the research team can play a critical role in transforming our nation's urban infrastructure. These technologies include advanced rainwater harvesting systems, dynamically controlled green roofs, actively controlled detention systems, and controlled underdrained bioretention systems. The scope of work for this project includes: 1) modeling high-performance green infrastructure; 2) conducting field pilot investigations; and 3) cost analysis of implementation of DRTC technologies.

Despite significant federal investment in combined sewer overflow (CSO) control over the past few decades, CSOs remain a significant point source of pollution to receiving water bodies in the United States. The research team hypothesized that dynamically controlled green infrastructure can significantly reduce wet weather contributions to combined sewers. To investigate this, a linear optimization model of a dynamically controlled rainwater harvesting cistern was compared to a simulation model of a conventional passive cistern. These models were run under baseline historical precipitation data with varying cistern storage capacities, as well as under various precipitation time series created with a statistical weather generator. The optimized dynamic system significantly mitigated CSO discharges when compared to the simulated passive system under all tank storage capacities, and proved much more robust under a wide range of plausible precipitation scenarios resulting from climate change.

Investigations at several pilot sites were conducted to determine the validity of model results and to demonstrate the practical implementation and quantitative benefits of DRTC technologies. Pilot sites included:

- Advanced rainwater harvesting systems in New Bern, NC; Austin, TX; St. Louis, MO; Denver, CO; and Lawrenceville, GA.
- Smart detention in Seattle, WA and Saint Joseph, MO.
- Controlled green roof in Newtown Square, PA.
- Controlled porous pavement in Omaha, NE.
- Underdrained bioretention system in Lawrenceville, GA.

The obtained pilot site results support the hypotheses that DRTC technologies can greatly reduce contributions to CSOs, reduce stormwater runoff, and retain stormwater for future onsite use and that these systems are practicable.

The project has yielded useful technical results as well as examples of benefit/cost analysis for the types of systems evaluated in the pilots.

The project has demonstrated that through both targeted field pilots and planning level analysis, the integration of these innovative systems provides a new suite of tools for utility operators to optimize investments in green infrastructure and potentially solve problems that are intractable, unachievable, or not cost effective using conventional passive solutions. Cities facing a high cost of expanding stormwater infrastructure with gray or green strategies can achieve the same benefit with a lower cost by retrofitting existing systems with real-time monitoring and controls.

CHAPTER 1.0

INTRODUCTION

1.1 Project Background

Between 1970 and 2000, the federal government invested more than $122 billion in the nation's wastewater infrastructure. The U.S. EPA estimates that current combined capital investment in wastewater infrastructure from federal, state, and local governments is over $13 billion annually. Many municipalities have made significant investments in CSO control within their jurisdictions primarily utilizing grey infrastructure solutions (U.S. EPA, 2008). Although billions more will be spent in the United States over the next 30 years to attempt to resolve the overflow issues in combined sewer system (CSS) communities, few truly innovative approaches have been proposed to address the problem. As a result, future investments in CSO control systems risk being unnecessarily expensive and insufficiently effective.

New approaches and recent advances in information technology infrastructure as well as hardware systems and software solutions provide the foundation for a future of ubiquitous, digitally connected, green infrastructure. Intelligent management of such infrastructure will change the means and methods by which we understand and control our urban environments and impact natural systems. Low cost, programmable logic controller systems are available and can easily be coupled with wired and wireless internet communications, which makes onsite real-time and dynamic controls viable options for both new construction and retrofits with green infrastructure-based stormwater systems.

New designs, applications, and equipment that incorporate the most recent advances in hardware and software have the potential to address some of our most intractable urban water resources challenges. These innovative solutions have the potential to reduce the cost of major CSO mitigation processes by orders of magnitude.

The objective of this project was to demonstrate that the highly DRTC technologies for green infrastructure being developed by the research team, such as advanced rainwater harvesting systems, dynamically controlled green roofs, smart detention systems, and underdrained bioretention systems, can play a critical role in transforming our nation's urban infrastructure. The scope of work for this project includes: 1) modeling high-performance green infrastructure; 2) conducting field pilot investigations; and 3) cost analysis of implementation of DRTC technologies.

The DRTC systems that have been evaluated are based on lightweight and low cost secure IP based real-time control (RTC) hardware (i.e., ioBridge® Gamma module) as the primary gateway for enabling sensors and actuators in the field. These endpoints are coupled with a cloud based MS Windows Azure Application which provides a redundant instance architecture for data collection, storage, archiving, automated processing, post-action processing, and dashboard and internet-based delivery. This system architecture provides a generic platform for implementation of high-performance green infrastructure as well as for any potential application of water information systems real-time monitoring and control. Fundamentally, the approach allows environmental real-time monitoring and control to be reduced to an extensible enterprise data management problem. It represents a new category of field hardware and software for these types of applications. The overall approach is commonly known as the “internet-of-things”.

CHAPTER 2.0

MODELING HIGH-PERFORMANCE GREEN INFRASTRUCTURE

2.1 Modeling Approach

An optimization model was used to compare the performance of a passive and a dynamically controlled rainwater harvesting cistern at a planned Forest House Affordable Housing Development ("Forest House") in the Bronx, New York. Although this location was not part of the field pilot program, it was selected for this portion of the project due to the availability of existing detailed analysis of conventional CSO mitigation costs and the availability of commercial cost information for installation of the DTRC system outside of a research setting. The operation of the system is nearly identical to all of the pilot smart/detention and rainwater harvesting DTRC systems studied in the field pilot program. The models that were run for this project tested varied precipitation scenarios plausible under current climate change predictions.

The dynamically controlled cistern proposed at Forest House provides irrigation for a rooftop greenhouse at the onsite building and decreases the property's contribution of stormwater volume to CSOs and mitigates timing impacts of those flows. The 15,560-gallon cistern receives inflows from parking lot and roof runoff. It is fitted with a draw-down orifice, an overflow orifice, and two pumps. The outflows through the orifices enter the combined sewer, while the pumps provide water for irrigation of the rooftop greenhouse. The dynamic control system was designed to operate a control valve fit to the passive draw-down orifice, allowing the valve to open or close depending on the current stored volume in the tank and the 12-hour weather forecast. If the anticipated runoff volume from a forecast storm event exceeds the current available storage volume in the tank, the control valve will open automatically without human intervention. This drains the cistern prior to the storm event, and decreases runoff volume entering the combined sewer during the storm event.

An optimization model of the dynamically controlled cistern was created to evaluate the performance of the system with perfect foresight using past precipitation data. A simulation model of a passively operated system was also created, and the results of the two models were compared. Since the optimization model has perfect forecast foresight, it was considered the upper bound of performance for the dynamically controlled cistern. Both models were run with a historical precipitation record from 1/1/1949 to 1/31/2009 from Central Park Tower, New York, which was obtained from the National Climatic Data Center (NCDC).

The objective of the optimization model was to maximize system performance by reducing wet weather outflow to the combined sewer while also providing the maximum amount of water for irrigation. The objective function added the summations of outflows multiplied by their assigned cost or savings (Equation 2-1). Assigning the variables as either a cost or savings was dependent on whether the associated outflow was considered positive or negative to the system. Outflows to the combined sewer had a cost and outflows for irrigation had a savings. The values assigned for the costs and savings were dependent on their relative level of importance as compared to providing water for irrigation. The reduction of the cistern's contribution to CSOs was considered more important than the benefits of supplying irrigation water. Values of \$0.03/ft^3 for irrigation outflow savings, \$0.08/ft^3 for overflow outflow costs, and \$0.10/ft^3 for spill outflow costs were assigned.

$$\boldsymbol{Z = \sum_{t=1}^{T} S_I R_{h,t} + \sum_{t=1}^{T} S_I R_{g,t} - \sum_{t=1}^{T} C_O R_{O,t} - \sum_{t=1}^{T} C_S R_{S,t}}$$

Equation 2-1: Equation for Objective Function - Maximize Benefits

Where,

Z = system performance (\$)

S_I = savings of irrigation outflow = \$.03/ft^3

C_O = cost of overflow outflow = \$.08/ft^3

C_S = cost of spill = \$.10/ft^3

$R_{h,t}$ = greenhouse pump outflow at time *t* (ft^3)

$R_{O,t}$ = overflow of tank outflow at time *t* (ft^3)

$R_{S,t}$ = spilled outflow of tank at time *t* (ft^3)

$R_{g,t}$ = grass area pump outflow at time *t* (ft^3)

The optimization model of the dynamic system and the simulation model of the passive system were also run under different tank capacities, ranging from the current size of 1,500 ft^3 [11,220 gallons] to 20,000 ft^3 [149,600 gallons], in order to analyze the associated performances. It is hypothesized that a smaller tank size is possible with a dynamic system, saving costs associated with installation and space. This factor is significant in urban areas where additional land acquisition is often expensive or not possible.

The performance of the optimized dynamically controlled cistern was also assessed under plausible climate change scenarios to analyze its robustness under climate change as compared to a conventional passive system. A stochastic weather generator simulated 77 plausible scenarios of daily precipitation under climate change. Refer to Attachment A.2 for additional detailed information on the modeling effort means and methods.

2.2 Results

Over the 61-year simulation period, approximately 10,278,832 gallons (168,506 gallons/year) overflowed from the passive cistern to the combined sewer while approximately 107,465 gallons (1,765 gallons/year) overflowed from the dynamically controlled cistern to the combined sewer. The dynamically controlled system reduced volume discharged to the combined sewer during storm events by 98.9% compared to the passive cistern. The amount of outflow was significantly reduced when the tank storage capacity was changed from the current capacity of 2,080 ft^3 to 5,000 ft^3, and it became zero at 14,000 ft^3. The maximum benefits achieved by the controlled system, calculated using the objective function, were about \$100,656, while the maximum benefits achieved by the passive system were about \$-23,756. It should be noted that the costs and benefits are often not incurred and obtained respectively by the same parties. This separation of interests can be mitigated through a number of policy and market mechanisms (e.g., stormwater credit trading systems such as the recently established program in Washington, D.C.) that are beyond the subject of the current research.

The passive system required a tank capacity of approximately 134,650 gallons to achieve the maximum benefits that the controlled system achieved with a tank capacity of only 15,560 gallons. An additional analysis accounting for the cost of the cistern (approximately $5.00 per 7.48 gallons) was conducted. The benefit of the passive system over the period of the model duration is much lower than the controlled cistern, never exceeding $20,000, while the maximum benefit of the controlled system (about $90,000) is achieved by using a smaller size tank.

Since the optimized dynamically controlled cistern represents the ideal performance of the RTC cistern, a simulation model was created, which represented more realistic performance of the RTC cistern. The results indicated that a simulated RTC cistern with two different sets of control rules performed far better than the simulated passive cistern, especially at smaller tank capacities.

According to the results obtained with the stochastic weather generator, the simulated RTC cistern was much more robust than the conventional passive cistern under a range of precipitation scenarios; the simulated passive cistern's performance fluctuated much more with changing precipitation scenarios. Among these precipitation scenarios, the worst performance of the passive cistern discharged approximately twice as much water to the combined sewer during precipitation as the simulated dynamically controlled cistern under its worst performance.

The total volume of available irrigation water to the onsite rooftop greenhouse at the study site is similar among all four models under historical precipitation with increasing tank storage capacities, as well as under the current storage capacity of 2,080 ft^3 under a range of precipitation scenarios created with the weather generator. The savings obtained from rainwater reuse for greenhouse irrigation did not substantially increase with increasing tank capacity. This is significant, because it indicates that the rainwater reuse performance of the RTC cistern is not significantly compromised by the controlled outflow component of the cistern or increasing tank size.

Overall, this analysis indicates that an optimized RTC cistern performed far better, in terms of CSO control, than a simulated passive cistern under a historical precipitation record as well as under 77 precipitation scenarios created with the weather generator. The optimized RTC cistern was therefore less sensitive to different plausible sequences of precipitation. This has positive implications for small-scale stormwater management with such a system in the face of climate change.

CHAPTER 3.0

FIELD PILOT INVESTIGATIONS

A summary of sites where field pilot investigations were conducted is included in Table 3-1.

Table 3-1. Summary of Field Pilots and Available Data.

Project Location	Collaborator	Project Type	Date Start of Data Collection	Date Forecast Logic Implemented	Comments
New Bern, NC	North Carolina State University	Advanced Rainwater Harvesting	6/7/11	9/20/11	This is the most comprehensive dataset collected during the study. Full automated operation during the study period was accomplished.
Washington, DC	District Department of the Environment	Advanced Rainwater Harvesting	7/1/12	10/21/13	Full installation and operation of monitoring equipment was accomplished during the study. Full automated operation during the study period was accomplished. The system functioned as a real-time monitored conventional harvesting system for much of the study period. The DDOE site was used for the July Benefit-cost Analysis as the case study location.
Newtown Square, PA	SAP, Inc.	Green Roof	7/31/12	6/17/13	Full installation and operation of monitoring equipment was accomplished during the study. Weather forecasts are currently being monitored at the site (i.e. probability of precipitation), and logic controlling the green roof irrigation system using forecast information was implemented in the summer of 2013. The site was winterized on for 2012 and 2013 by removing the valve assembly; however, monitoring of water levels will continue throughout the winter. This system was very robust during the pilot monitoring period and an extensive dataset is available from the project.
St. Louis, MO	McCormack Baron Salazar	Advanced Rainwater Harvesting	6/21/12	10/17/2012	Internet connectivity at several sites has been somewhat unreliable and not under the control of the project team. The sites were regularly winterized. Repairs to the networks and integration of forecast data into automated controls are dependent on the site developer.
Denver, CO	Urban Drainage and	Advanced	9/7/12	6/19/13	The system has been regularly winterized and repairs needed to be

Project Location	Collaborator	Project Type	Date Start of Data Collection	Date Forecast Logic Implemented	Comments
	Flood Control District	Rainwater Harvesting			made a number of times during the data collection period. Adequate results were obtained for study of the system. Full installation and operation of monitoring equipment is complete. Full control logic of the harvesting systems using weather forecast information was implemented in late Spring 2013. Extensive data is available from these systems, however the completeness of the datasets was partially compromised by inconsistent network connectivity and onsite system management issues that are outside the scope of the WERF project. Sufficient data was collected to demonstrate likely long-term performance of the systems if maintained properly. Data collection will be complete at end of December 2013.
Seattle, WA	Seattle University	Smart Detention	2/15/13	6/6/13	Little useable data were obtained prior to late 2013 due to leaks in the University's tank.
Austin, TX	City of Austin, TX	Advanced Rainwater Harvesting	1/16/13	7/18/13	Additional modifications were made the week of April 29, 2013.
Omaha, NE	City of Omaha, NE	Permeable Pavement	5/9/13	7/12/13	In early December of 2012 level sensors and weirs were installed in two inlets of the porous pavement parking lot. During the week of May 6, 2013, controlled weir plates, ultrasonic level sensors and temperature probes were installed.
Lawrenceville, GA	Gwinnett County, GA	Advanced Rainwater Harvesting and Underdrain Bioretention	8/14/13	9/6/13	Final authorization was received on June 4, 2013.
Saint Joseph, Missouri	City of Saint Joseph	Smart Wetland Detention in CSO	Did not Commence prior to Project Completion	Did not Commence prior to Project Completion	Design was completed during the project however final installation approval was not received until January 2014. Data was not able to be collected for this report due to delays in project contracting and installation.

3.1 Overview of Pilot Projects

The original scope of the project anticipated installing three pilot systems; however additional interest from potential collaborators identified through WERF outreach resulted in expansion of the project over the course of the project. As a result of this interest from the WERF subscriber base, ten pilot sites were included in the project to demonstrate the application and performance of DRTC for green infrastructure. This section provides an overview of all the pilot project sites and systems.

3.1.1 DRTC System Description

The intent of this study is to demonstrate and evaluate the roles and performance of DRTC systems independent of the specific underlying hardware and software. The implementation of the pilot systems could have been carried out on any number of combinations of hardware and software and implemented in a variety of ways. The intent of the project is to demonstrate the underlying application of technologies as well as their current practical deployment and use.

For this project the team selected the OptiRTC DRTC system developed separately by Geosyntec Consultants. OptiRTC is a suite of cloud-based web service applications deployed on the Microsoft Azure platform that have been specially designed to ingest, store, process, analyze, act on, and deliver (via web-based dashboards) environmental systems data. OptiRTC is comprised of the following service components:

- Permission Services
  - Delegated identity providers (e.g., MS Accounts/Facebook/Google): OptiRTC connects with common social web applications and email systems to identify users via an OAuth 2.0 scheme. Outsourcing the sign-in process leverages ongoing investments by the largest internet entities in identity management, while avoiding the requirement that users manage another password for the OptiRTC system.
  - Authorization Services: OptiRTC maintains an internal record of what actions each user can perform in the system, and enforces these requirements in its HTTP APIs. An internal usage tracking system attributes authorized requests to the projects that commissioned the systems queried in each request, providing a per-request accounting of the service operation costs.
- Data Ingestion Services: OptiRTC allows administrators to configure pre-built connectors to a wide variety of networked data sources. The architecture assumes that additional connectors will be developed as new sensors emerge and new communication protocols are developed. After a connector is configured, OptiRTC will either listen for new data pushed from the source or pull data from the source on a scheduled interval without human oversight.
  - Internet-of-things hardware (e.g., ioBridge hardware used for this project): OptiRTC includes connectors to many different Internet-of-things micro controllers and other networked computing devices. Micro controllers allow for custom sensor platforms to be assembled for relatively low cost, and can operate conservatively-programmed local control systems and offline data logging autonomously in the case of network failure.
  - Web services (Simple Object Access Protocol (SOAP)/ Representational State Transfer (REST)), for example the National Oceanic and Atmospheric Administration (NOAA)

forecast data and United States Geologic Survey (USGS) stream gauge data: OptiRTC includes connectors that are pre-configured to use known document schemas to reduce setup time for popular data sources. For example, a connector for ingesting WaterML-based web services allows the instant configuration of ingestion of any valid URL for USGS instantaneous values. Another performs the same setup for National Weather Service forecast data, extracting parameters commonly used internally to predict future site conditions.

- FTP and CSV file ingestion: OptiRTC is able to connect to FTP servers to pull files from a file system directory. While more prone to failure than conventional web service-based integrations, this often provides a simple way to integrate with legacy information systems with minimal technical oversight.
- Generic format agnostic ingestion: OptiRTC includes connectors capable of reading data from any schema in a variety of formats, including many common industry formats such as CSV, XML, and JSON. By adding new connectors, OptiRTC enables the configuration of schema-agnostic connectors for new data formats. To configure a connector, an administrator must either specify the data path using expressions of a standard document parsing language such as XPath or JSONPath, or the column order or name of a table-structured document for each parameter in the document the system should ingest.

♦ Storage Services

- Microsoft Azure Table Storage: OptiRTC uses the Microsoft Azure Table Storage service to persist time-series logs of all of its operations data. Careful design allows OptiRTC to leverage the horizontal partitioning. This storage mechanism provides a consistent data service for many simultaneously connected clients, while benefiting from a pay-per-use billing system to keep start-up costs low. Geographic data redundancy included by the Azure platform for data persisted in Table Storage provides protection against hardware or network failures.
- Stores - time series, metadata: OptiRTC uses additional Azure storage resources such as the Azure Cache service and SQL Azure database service to provide highly available system metadata at access times consistent with their usage requirements.
- Take advantage of content distribution network (CDN) services: For large static content such as custom map tiles, generated data reports, supporting engineering documents, or images, OptiRTC uses built-in Azure CDN services to serve users the content from geographically local servers. Retrieving data from a local cached copy ensures the fastest possible user experience with larger data objects that change infrequently.

♦ Data Processing Engine

- Standard Processes, Modeling as a Service, IP Protected Processes: OptiRTC provides a collection of pre-built stream processing routines to allow administrators to configure modular sequences of data processing on new observations as they stream in through the data ingestion service. By stating model input specification in terms including the required history length, the system is able to efficiently distribute these processing tasks across a scalable cluster of servers to meet new processing demand, and avoid making decisions based on data too old for a particular use-case.

- ♦ Enterprise Service Bus: OptiRTC uses the Azure Enterprise Service Bus to coordinate workflows across multiple, independently managed clusters of virtual machines. Enterprise Service Bus queues provide the messaging platform necessary to notify internal services of new jobs in real-time, and allows OptiRTC to provide at-least-once or at-most-once guarantees to the jobs it sends.
- ♦ Publication Services
  - Publication of web pages and dynamic page generation of HTML5 based dashboards: OptiRTC leverages open-source efforts in HTML5, JavaScript, and CSS tools to render data visualizations in browsers across most modern devices.
  - Data publication: OptiRTC provides data export services capable of assembling data files of results for analysis in an external system.
- ♦ Application Programming Interface (API) Web Services: OptiRTC exposes all of its data publication and real-time web portal support services as HTTP APIs. By registering with the DNS host, additional web domains are able to run real-time web applications powered by OptiRTC. Third-party tools can also be configured to poll OptiRTC APIs regularly and run external processes, enabling a wide range of potential extensions for future uses of the data.
- ♦ Alerting (Email, SMS, and Voice): OptiRTC integrates with external SMTP and SMS providers to broadcast alert messages to users' preferred messaging platform. Future integration with voice-based web service providers will involve a similar architecture. The conditions that trigger the alarm, and the schedule of repeated alarm messages for a particular event are determined as part of the modular data processing system configured by system administrators for each project.
- ♦ Data Visualization Services
  - Preprocessing for visualization: For systems with highly bounded sets of possible outcomes, such as a cistern or overflow-equipped storage resource, OptiRTC staff develop highly detailed renderings of every possible system state, which data processing services then use to create a frame-by-frame depiction of the system as perceived by onsite sensors. This approach allows for photo-realistic renderings of current conditions to be displayed by any device with an internet connection.
  - Client side use of D3 and JavaScript-based dashboards: Among other components, OptiRTC web portal dashboards combine the open-source Data Driven Documents (d3) and AngularJS projects to transform lightweight web service responses into live infographics in the browser. During the vast majority of the project, Microsoft Silverlight-based dashboards were used for visualization and dashboard delivery.
  - ♦ Push Services (i.e., continuous feed of data to client side user interfaces): OptiRTC uses dynamic device-specific protocol selection to create bidirectional, open network connections with users of its web portals. Via these connections, OptiRTC is able to minimize the expected latency between the observation of new state in the field and the corresponding update to data visualizations in users' browsers. Furthermore, by keeping connections open, the system reduces the number and size of the network transmissions it must make, improving the responsiveness of the application and reducing the bandwidth needed to run it - an important consideration for modern mobile data plans.

3.1.2 New Bern, North Carolina: Advanced Rainwater Harvesting System

The rainwater harvesting system in New Bern, North Carolina consists of five interconnected 650-gallon cisterns that collect runoff from a 2,950 ft^2 roof area. Harvested water is pumped to hydrants used for irrigation of shrubs and flower beds in a large onsite garden. The tanks are equipped with a single automated 1-inch low-level gravity outlet that can be used to release water to a downstream rain garden in advance of large storm events, and a pair of 3-inch overflow lines that also drain to the rain garden when the tank is full.

Figure 3-1. Site Photos of New Bern, NC with System Control Box.

The DTRC system at the New Bern site ingests and utilizes the following raw data streams:

- Tank level – from pressure transducer.
- Cumulative onsite water use – from water meter.
- 48-hour quantitative precipitation forecast (QPF) – obtained from NOAA web services. The 48-hour forecast is updated by NOAA typically once per hour. The 48-hour forecast period is provided as eight, 6-hour forecast periods.
- 48-hour probability of precipitation forecast (POP) – obtained from NOAA web services. The 48-hour forecast is updated by NOAA typically once per hour. The 48-hour POP forecast is provided as four, 12-hour forecast periods.
- Online status of the DRTC controller.

The DTRC system at the New Bern site calculates in real-time the following derivative data streams as part of the control logic:

- Tank volume based on the tank level and a calibrated stag-storage curve for the tank system.
- 24-hour 70% probable QPF based on the QPF and POP.
- Cumulative volume of onsite water use.
- Cumulative volume discharged to the rain garden based on differential volume calculations during controlled drain periods and calibrated overflow based on depth during overflow periods.

The logic used to operate the New Bern, NC DTRC system is shown in Figure 3-2. This logic was also used at the other rainwater harvesting systems in this study around the country.

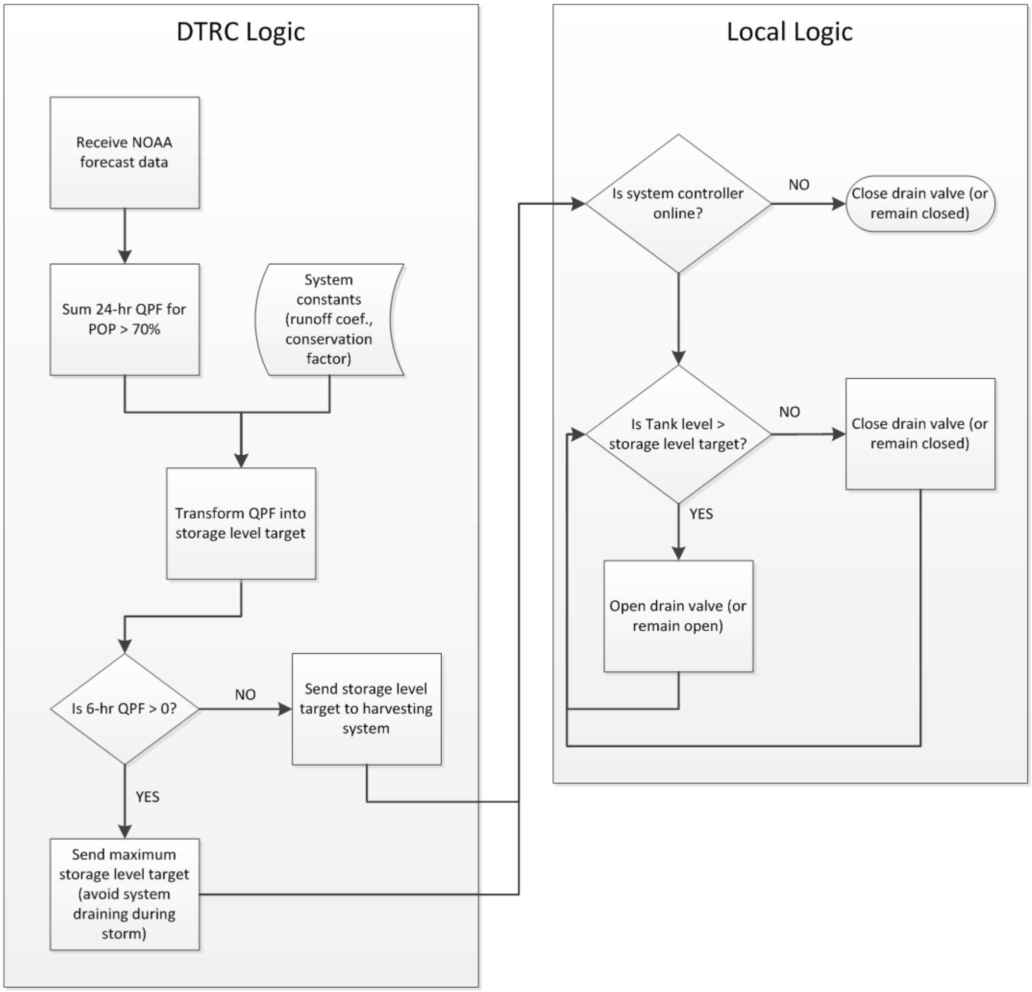


Figure 3-2. Overview of DRTC System Logic for New Bern, NC Pilot Site.

As can be seen from the implemented DRTC system logic, the cistern drains to the appropriate capacity when an incoming precipitation event is forecast. For example, forecast data showing the arrival of Hurricane Sandy in 2012 triggered a release of water from the cistern on October 26th, well before the storm reached the site.

In late April 2012, the pressure transducer desiccant cartridge expired, apparently causing the water elevation signal to be undetectable, leading to information spikes and unpredictable system behavior. More recent information indicates that there may have been a manufacturer defect in the pressure transducer as evidenced by similar failure at more than seven other sites unrelated to this research project. After the pressure transducer was repaired and replaced, it became clear that there was a hole in one of the pipes connecting the five tanks, resulting in prolonged periods of lower water levels than typical. All issues were repaired by August 20, 2012, and the DTRC system functioned well for the remaining period of the study. Data streaming from the site were continuously monitored during the study via an online dashboard as shown in Figure 3-3. During the project, over 237 MB of raw data was collected form the New Bern site.

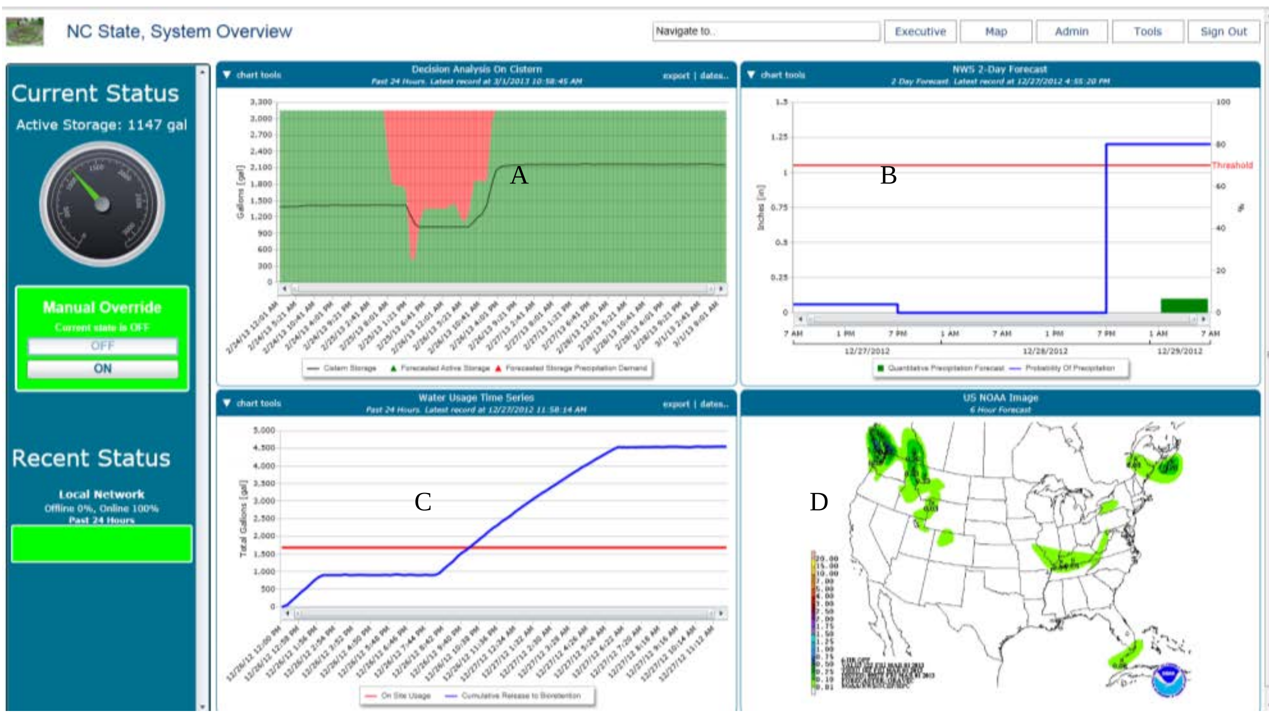


Figure 3-3. Dashboard for System at New Bern that Incorporates Live and Continuous Data Streams from Onsite Sensors and NOAA Forecasts.
Panel A: Red area is cistern storage required based on forecast rainfall events; cistern fills as storm approaches.
Panels B and D: NOAA forecasts are used to predict required cistern storage volume.
Panel C: Onsite water use and release to onsite garden is continuously monitored.

3.1.3 Washington, D.C.: Advanced Rainwater Harvesting Systems

The rainwater harvesting systems located in Washington, D.C. consist of two interconnected 1,900-gallon precast concrete cisterns collecting runoff from a 3,200 ft^2 roof area at the District of Columbia Fire Department (DCFD) Engine House 3 and two interconnected 1,900-gallon precast concrete cisterns collecting runoff from a 5,300 ft^2 roof area at Engine House 25. Harvested water from both stations is available for use in cleaning vehicles and vehicle parking bays, and to fill on-truck water tanks used for first-responder water supply. The tanks are equipped with a "waste" discharge point off of the onsite use force main which can be used to release water to the sewer system in advance of large storm events, and a 6-inch overflow outlet. These systems utilized the same logic and data stream configurations discussed above for the New Bern Site.

Figure 3-4 illustrates the cistern water level and onsite water use at DCFD Engine #3 Fire House during January 2013. Figure 3-5 shows live and continuous water usage data as displayed via the online dashboard. The internet network at Engine House 25 was not reliable for much of the early portion of the study, and therefore real-time monitoring data over the course of the study was more limited than expected. In addition, during portions of the project the diverters from the roof to the cisterns at both sites were not functioning as designed at all times. This was mitigated during the course of the later part of the project. The network and diverters were repaired and upgraded in July 2013. Logic that reduces contribution to CSOs by making storage space prior to storm events was implemented by September 2013.

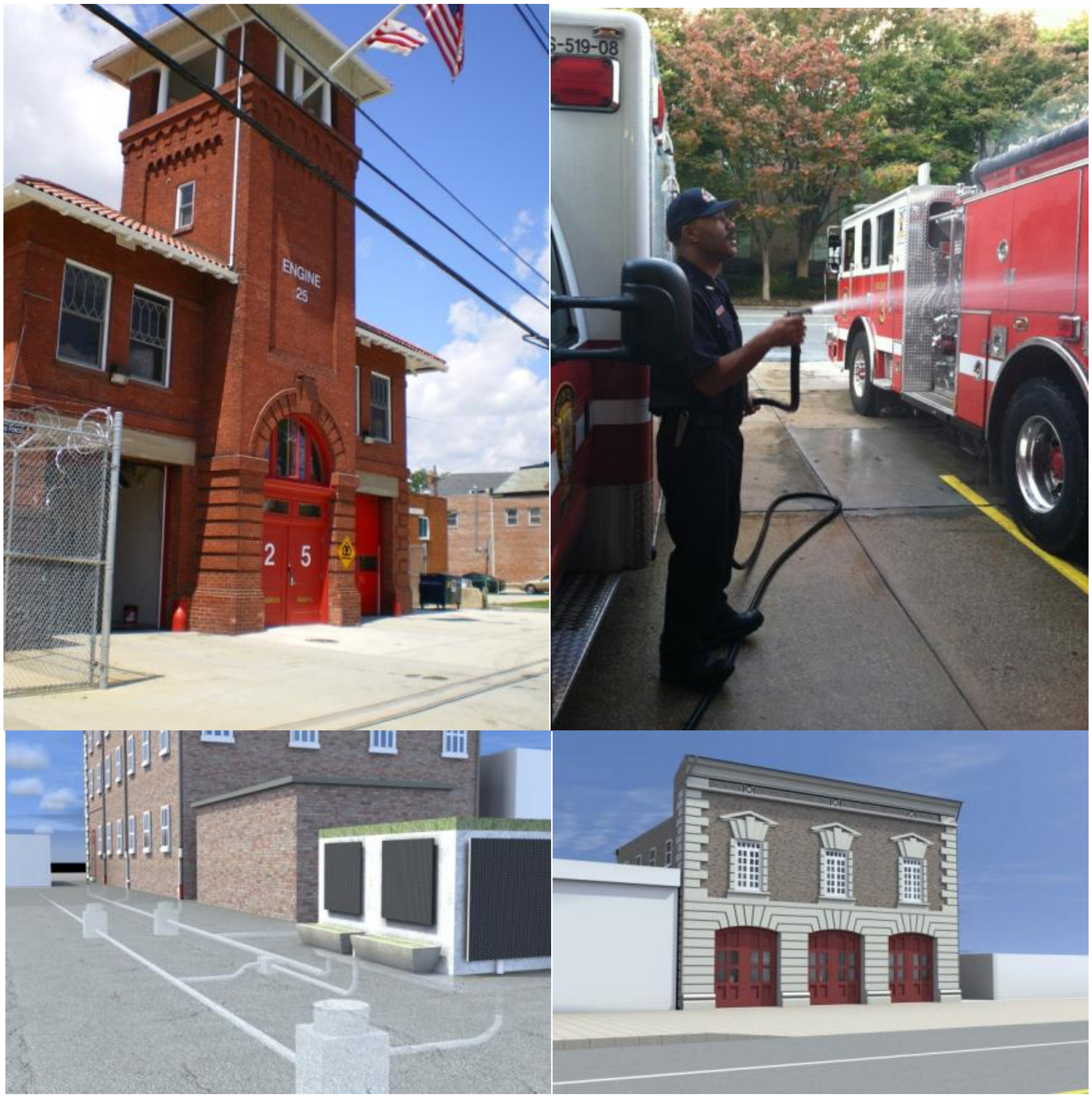


Figure 3-4. DCFD Firehouses 25 and 3.
Harvested water is used onsite.

The design and data collected at Engine House 3 were used as the basis for the cost/benefit analysis provided in Section 4.2 of this report.

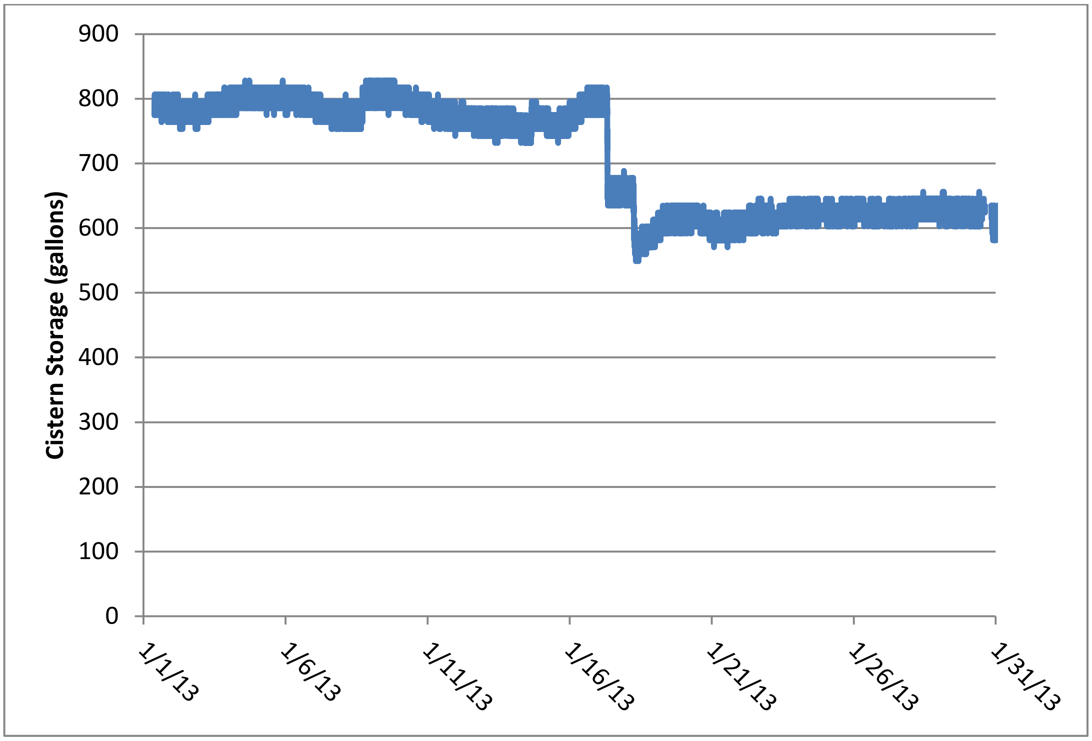


Figure 3-5. Cistern Storage at DCFD Engine 3 Firehouse during the Month of January 2013.
Sharp decreases in storage indicate onsite use.

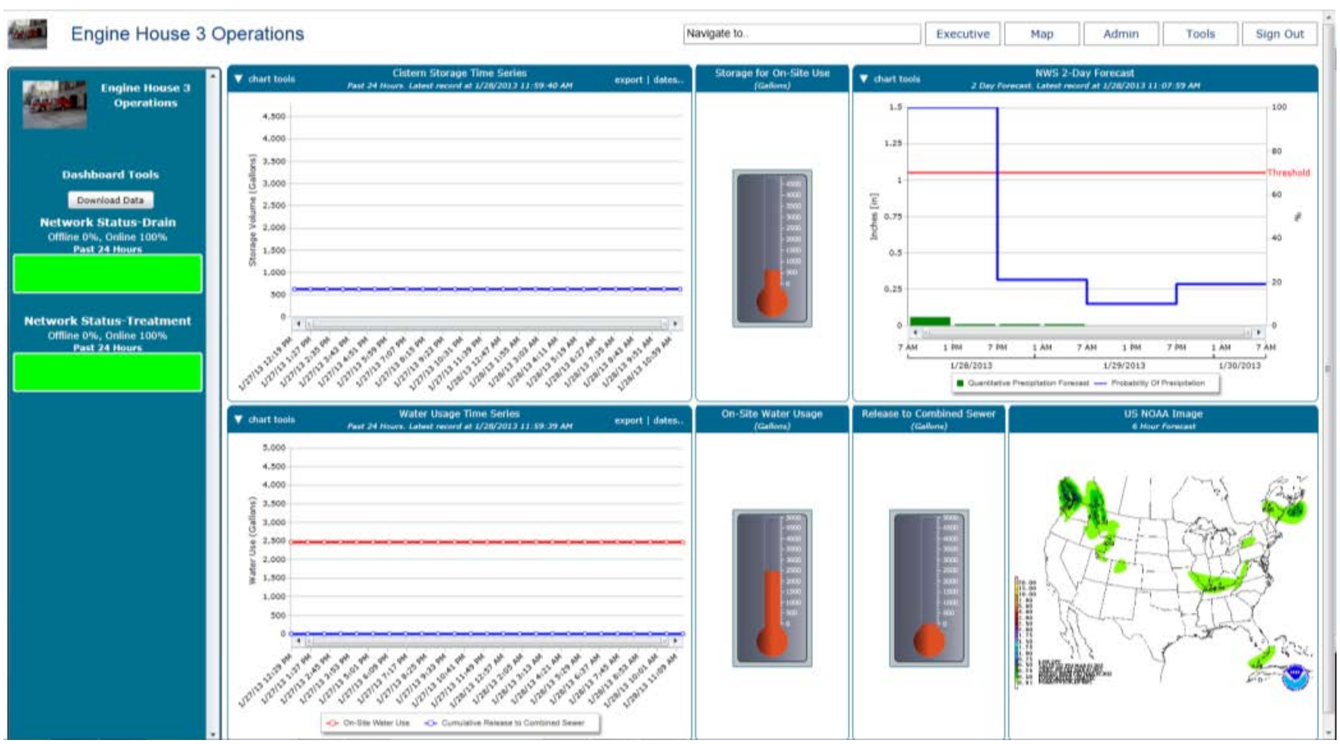


Figure 3-6. Dashboard for System at Firehouse 3 that Incorporates
Live and Continuous Data Streams from Onsite Sensors and NOAA Forecasts.
Cistern storage volume, and onsite water use are continuously monitored and recorded, as are NOAA local forecasts.

3.1.4 Newtown Square, Pennsylvania: Green Roof

The advanced green roof at SAP Headquarters in Newtown Square, Pennsylvania provides a controlled water supply to 3,781 ft^2 of turf grass on the site's roof by maintaining the water level in an access chamber installed within the growing media. When the water level inside the access chamber is below 1.32 inches, the valve opens, allowing sub-surface flood irrigation of the green roof. When the water level is above 1.57 inches, the valve is closed, discontinuing the supply of water to the green roof. These set points were chosen to keep the water level within the root zone of the turf grass.

Figure 3-7. Site and System Photos from SAP Headquarters in Pennsylvania.

The valve assembly and water meter were removed on November 2, 2012 for winterization and replaced on April 19, 2013. Water levels have been otherwise continuously monitored via online dashboard shown in Figure 3-8. Figure 3-9 shows water level on the green roof during the month of January 2013. Logic was updated on June 19, 2013 to include weather forecasting for improved control of stormwater and to reduce water use for irrigation when precipitation is probable.

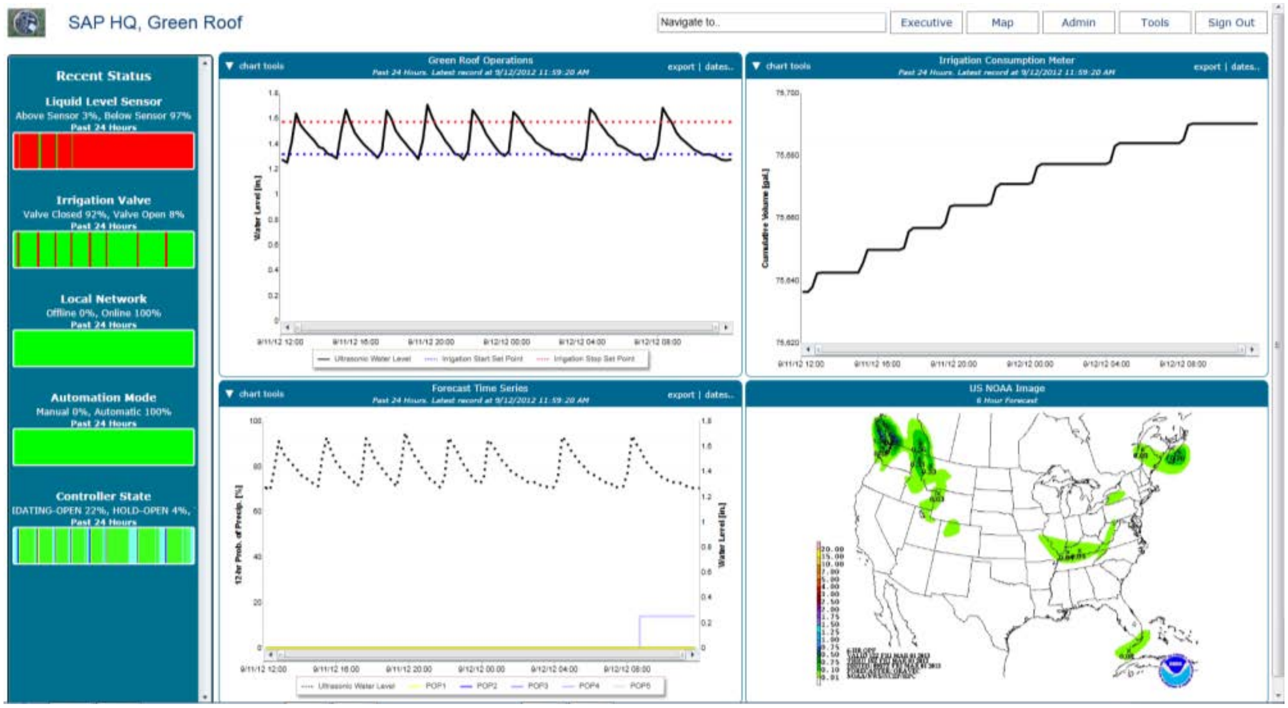


Figure 3-8. Dashboard for System at SAP Headquarters that Incorporates Live and Continuous Data Streams from Onsite Sensors and NOAA Forecasts.
Water level on the green roof is continuously monitored and controlled to remain within ideal boundaries.

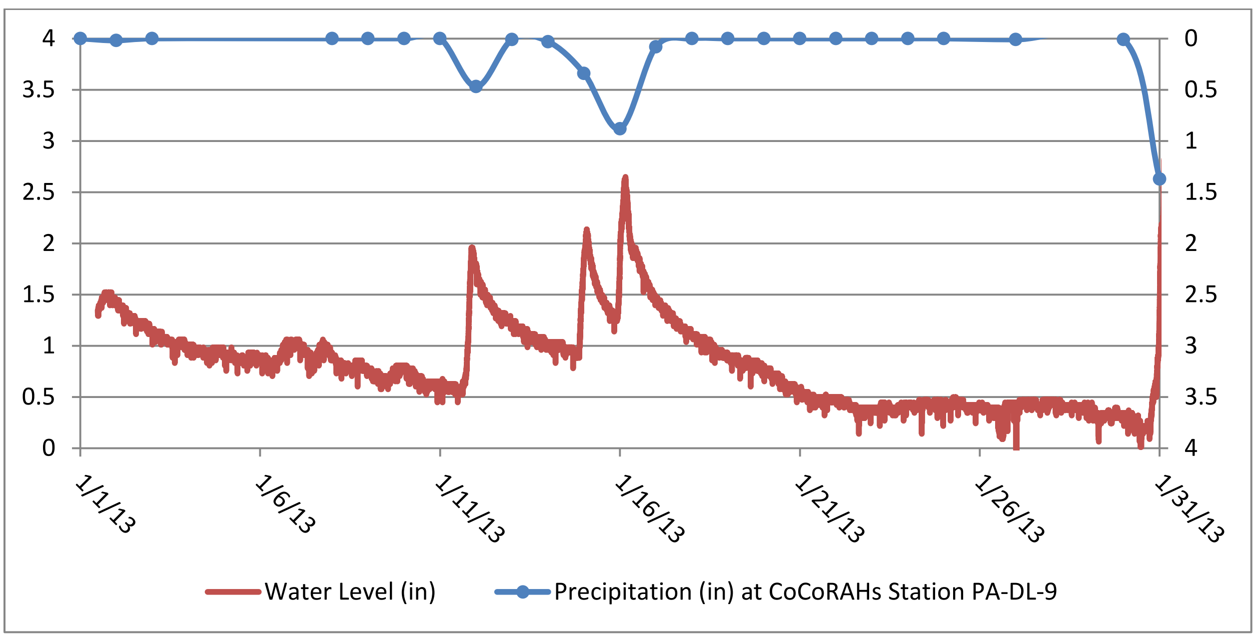


Figure 3-9. Water Level on Green Roof at SAP Headquarters during January 2013.
Spikes in water level indicate precipitation events.

3.1.5 St. Louis, Missouri: Advanced Rainwater Harvesting Systems

Figure 3-10. St. Louis Site Section Showing the Rainwater Harvesting Systems.

Seven advanced rainwater harvesting systems are installed at three developments (Renaissance Place, Cambridge Heights, and King Louis Square) in St. Louis, Missouri. The type of drainage area and number of controlled underground rainwater harvesting systems at each location are described below in Table 3-2. Harvested water from all systems is used to irrigate lawn and shrub areas in the surrounding development. Domestic water is supplied to the site and used for irrigation when harvested water is depleted. Harvested water is released to either a discharge/flushing line back into the storm sewer system or to the irrigation force main.

Table 3-2. Summary of Seven Advanced Rainwater Harvesting Systems in St. Louis, MO.

Location	Number of Cisterns	Drainage Area	Dates Online
Renaissance Place Block C	Five (5) 2,500-gallon cisterns	Parking Lot	6/21/2012 – 10/7/2012 3/13/2013 – 4/11/2013
Renaissance Place Block D	Six (6) 2,500-gallon cisterns	Rooftop and Parking Lot	6/21/2012 – 9/8/2012
Renaissance Place Block H	Four (4) 2,500-gallon cisterns	Rooftop and Parking Lot	9/7/2012 – 10/8/2012 3/17/2013 – present
Renaissance Place Block F	Four (4) 2,500-gallon cisterns	Rooftop and Parking Lot	6/21/2012 – 10/7/2012 3/13/2013 – present
Renaissance Place Block G	Four (4) 2,500-gallon cisterns	Rooftop and Parking Lot	6/21/2012 – 10/16/2012 4/1/2013 –present
Cambridge Heights Block B	Three (3) 2,500-gallon cisterns	Rooftop and Parking Lot	6/21/2012 – 10/8/2012
King Louis II Block A	Five (5) 2,500-gallon cisterns	Parking Lot	6/28/2012 – 10/8/2012 3/13/2013 – 5/28/2013

Water levels in the cisterns and the volume pumped out of the cisterns for irrigation use onsite is continuously monitored via the online dashboard shown in Figure 3-11. The site was winterized from late fall 2012 to early spring 2013 and again from fall 2013 through the end of the project. Water level and usage data has been collected form the entire installation period when the network connections have been supported by the owner. These sites were effective pilot locations for showing the application of the underlying technology and its practical implementation, but the data from the sites was less usefully for evaluating the application of key benefits of DTRC systems beyond effective remote control and monitoring. Explicit use of the systems for combined sewer flow control was quite during the study period. The project team was limited in its ability to effectively use the systems for research purposes to run controlled experiments on the systems during the course of this study. For the majority of the project the systems were used as conventional harvesting systems. These systems do have the potential to be operated in the manner described extensively in this report for improved combined sewer flow mitigation through the application of minor changes to the operating configuration.

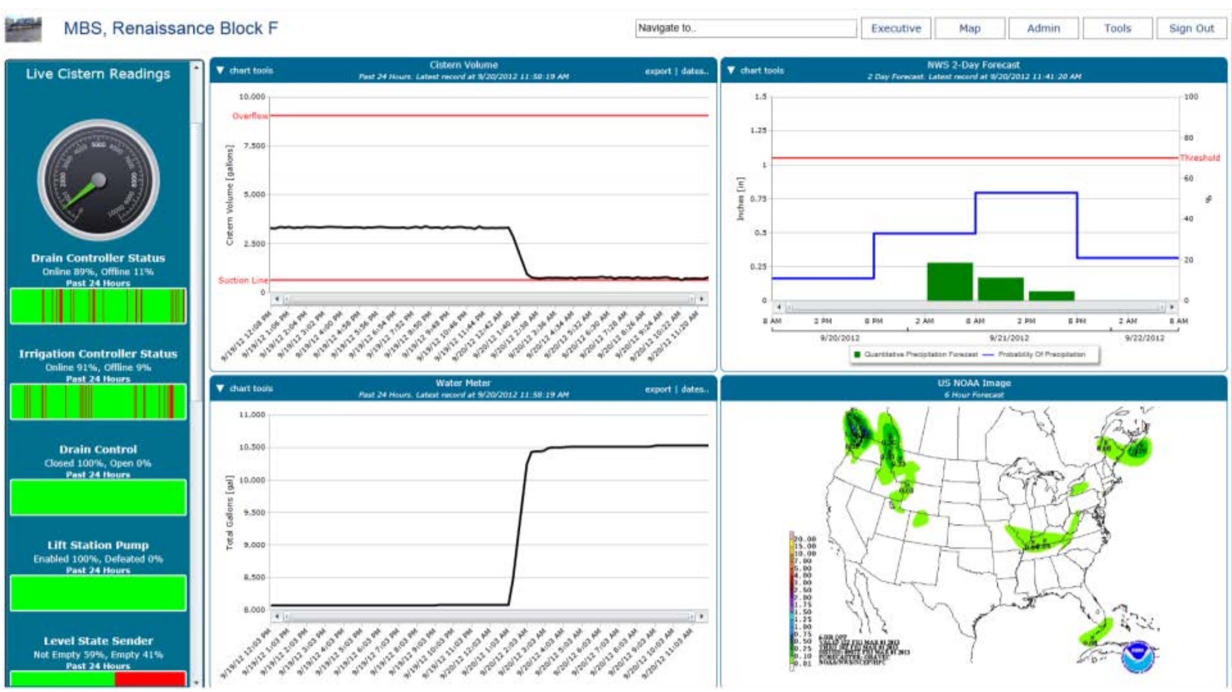


Figure 3-11. Dashboard for System at MBS, Renaissance Block F that Incorporates Live and Continuous Data Streams from Onsite Sensors and NOAA Forecasts.
Cistern volume and water usage is continuously being monitored.

3.1.6 Denver, Colorado: Advanced Rainwater Harvesting System

The rainwater harvesting system at the Denver Green School in Denver, Colorado consists of a 3,000-gallon above-ground cistern collecting runoff from an approximately 7,300 ft^2 roof area. The tank is equipped with a low-level outlet used to release water to the stormwater conveyance system in advance of large storm events, an overflow line that also drains to the stormwater conveyance system, and an additional line that is used for onsite irrigation. The site was winterized in late October 2012, and de-winterized in April 2013. Due to an unexpected late winter storm, the irrigation pump and level sensor needed to be replaced, so the site came back online on May 24, 2013 and was re-winterized in the fall of 2013. Advanced control logic integrating real-time weather forecasts was implemented on June 19, 2013.

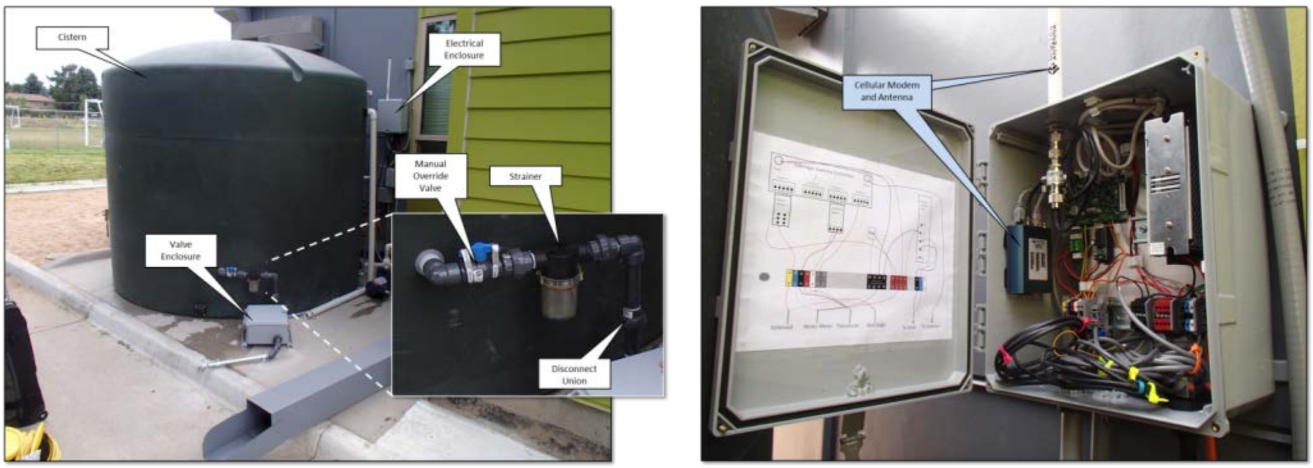


Figure 3-12. Rainwater Harvesting System in Denver.

Water level in the cistern and volume of municipal water used for irrigation are continuously monitored via an online dashboard (Figure 3-13). This system utilized the same basic logic and data stream configurations discussed above for the New Bern Site. A local rain gauge was also ingested as a data stream and is available on the project dashboard and as collected data from the project.

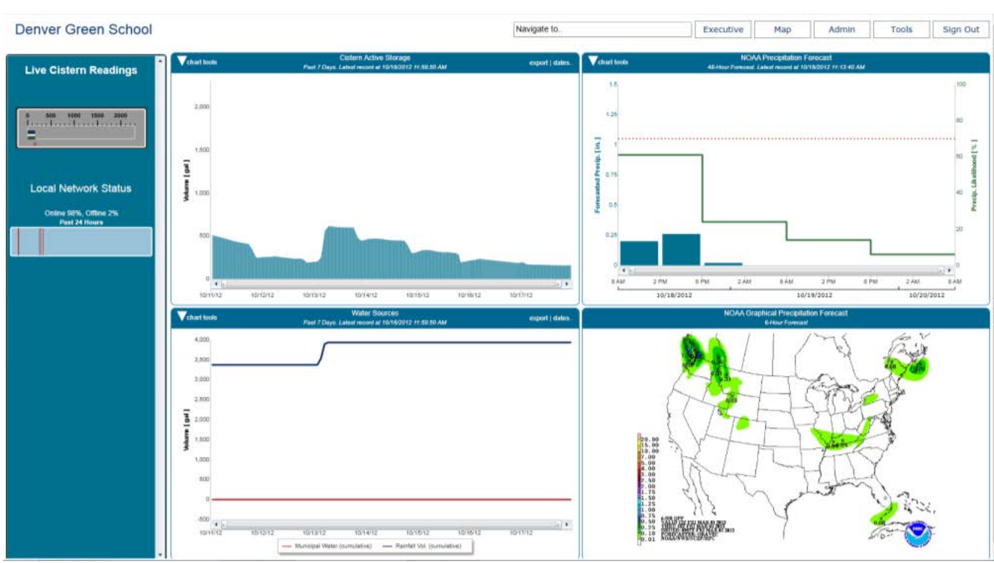


Figure 3-13. Dashboard for System at Denver Green School.
Continuous storage in rainwater harvesting systems and inflows from rainfall and municipal water are monitored and recorded. Real-time decision logic incorporating weather forecasts was implemented in June 2013.

3.1.7 Seattle, Washington: Controlled Detention System

The underground rainwater detention system located below the Law School and University Services buildings on Seattle University's campus collects runoff from approximately 1.27 acres of roof area. The underground storage drains to a downstream manhole which then discharges to the combined sewer through an 8-inch PVC outlet pipe. In mid-October 2012, internet connectivity was established, monitoring equipment was calibrated, and monitoring of water level and valve status commenced.

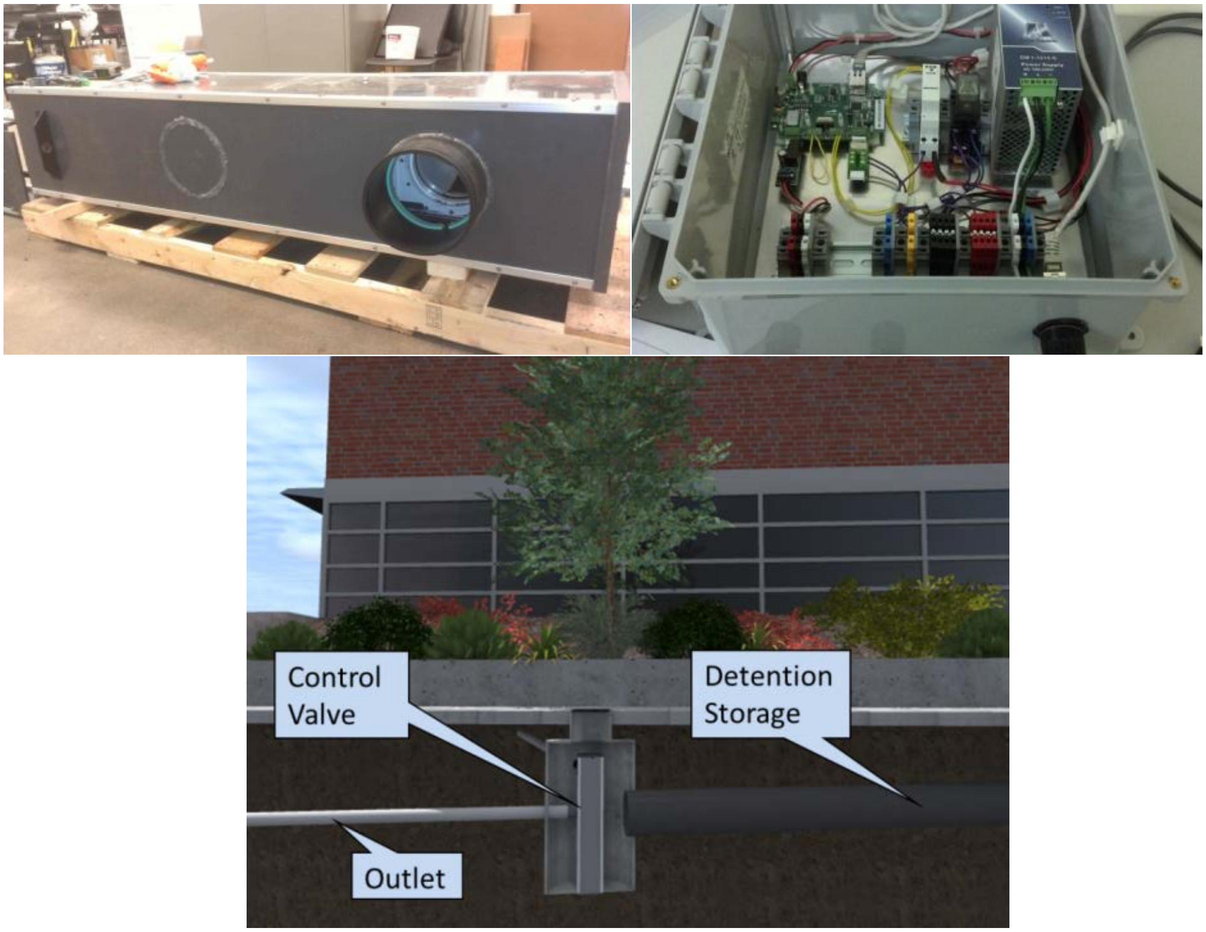


Figure 3-14. Seattle University's Rainwater Harvesting System and Rendering of the Site.

Upon commencement of monitoring via the online dashboard shown in Figure 3-15, it was observed that there was a leak in the system at a rate of 1 to 3 inches per day. Seattle University facilities personnel snaked a camera into the manhole structure and determined that the seal between the outlet and the manhole was not watertight. They addressed the leak in July 2013. Advanced control logic integrating real-time weather forecasts for automated operation of the system was implemented in early May 2013. Once leaks were fixed, the system was fully functional.

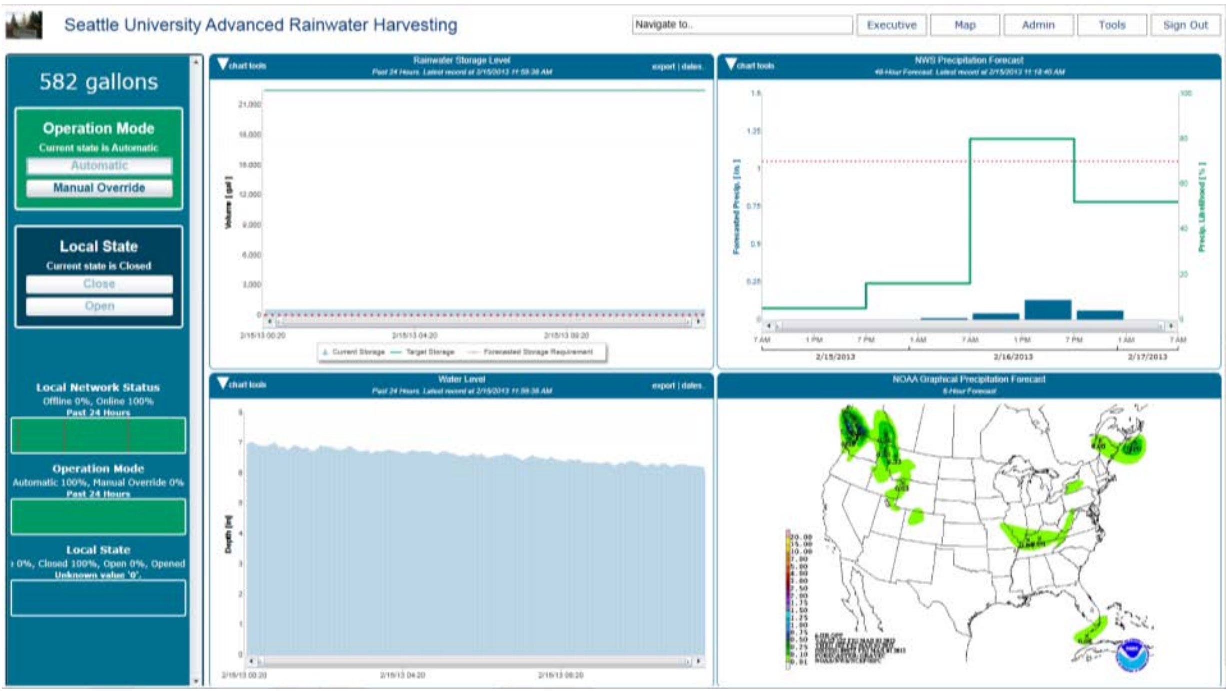


Figure 3-15. Dashboard for System at Seattle University.
Valve status and rainwater storage level are continuously monitored.
Logic incorporating weather forecasts was implemented in early May 2013.

3.1.8 Austin, Texas: Advanced Rainwater Harvesting System

The rainwater harvesting system at the Twin Oaks Library in Austin, Texas consists of two interconnected 2,500-gallon above-ground cisterns that collect runoff from approximately 6,500 ft^2 of roof area and condensate from the Library's HVAC system. Harvested water flows directly into the two cisterns, where it can either be discharged through a drain line or an irrigation zone. The original scope of work was executed in November 2012. However, it was discovered that the existing drain line was clogged due to poor workmanship on the original installation by others, preventing efficient active release of water.

Figure 3-16. Storage Tank Onsite at the Twin Oaks Library in Austin.

In early May 2013, an additional scope of work was executed to correct the existing drain line and re-route it to a new bioretention pond. An approximately 400 ft^2 pond was dug onsite to allow infiltration of water drained from the cisterns. Additionally, an existing irrigation pump was made functional and integrated into the active control system. The irrigation pumps to an additional zone, which includes approximately 45 tree bubblers (Figure 3-17).

Figure 3-17. City of Austin Twin Oaks Library Rain Garden during May 2013 Test of Controlled Release System.

Logic was developed to operate the system in both wet and dry conditions through both the bioretention pond and the irrigation zone. Full wet weather logic and basic dry weather logic were functional by July 2013, and additional dry weather functionality was incorporated over the following months as system data illuminated more optimal irrigation methods for the site. Cistern storage volume, forecasts, and irrigation controller states are monitored and controlled via the online dashboard shown in Figure 3-18.

Figure 3-18. Dashboard for System at City of Austin Twin Oaks Library.
Valve status and rainwater storage water level are continuously monitored.
Logic incorporating weather forecasts will be implemented in the spring of 2013.

3.1.9 Omaha, Nebraska: Pervious Pavement System

The pervious pavement system at the Omaha Police Department parking lot in Omaha, Nebraska is nearly 19,000 ft^2. Stormwater runoff enters the pervious pavement through surface sheet flow and passes through it into an underground aggregate, which then discharges to an underdrain system connected to the combined sewer system. The underground aggregate provides approximately 9,200 ft^3 of storage and discharges through two main outlets (8 inches and 10 inches in diameter).

Figure 3-19. Electrical Enclosure and Actuated Weir in Omaha, NE.

The project involves two phases. Phase I was completed in early December 2012 and consisted of installing level sensors and weirs in two inlets of the porous pavement parking lot. The levels were calibrated with the weir, so both water level and flow were monitored. Phase II, which consisted of the installation of new level sensors in two additional inlets, actuated weir plates in all four inlets in the porous pavement, and control boxes were built during the week of May 6th-10th. In addition to the new level sensors, eight thermistors are installed at various depths in two pervious pavement cores (Figure 3-20). The thermistors record temperature changes beneath the pervious pavement. This data, when combined with water level data in the four pavement inlets, provides information on water depths and transport through the stone reservoir. Photos from the installation are shown in Figures 3-21 and 3-22. Real-time data is shown on the online dashboard in Figure 3-23. Logic that incorporates real-time forecast data was partially implemented in July 2013.

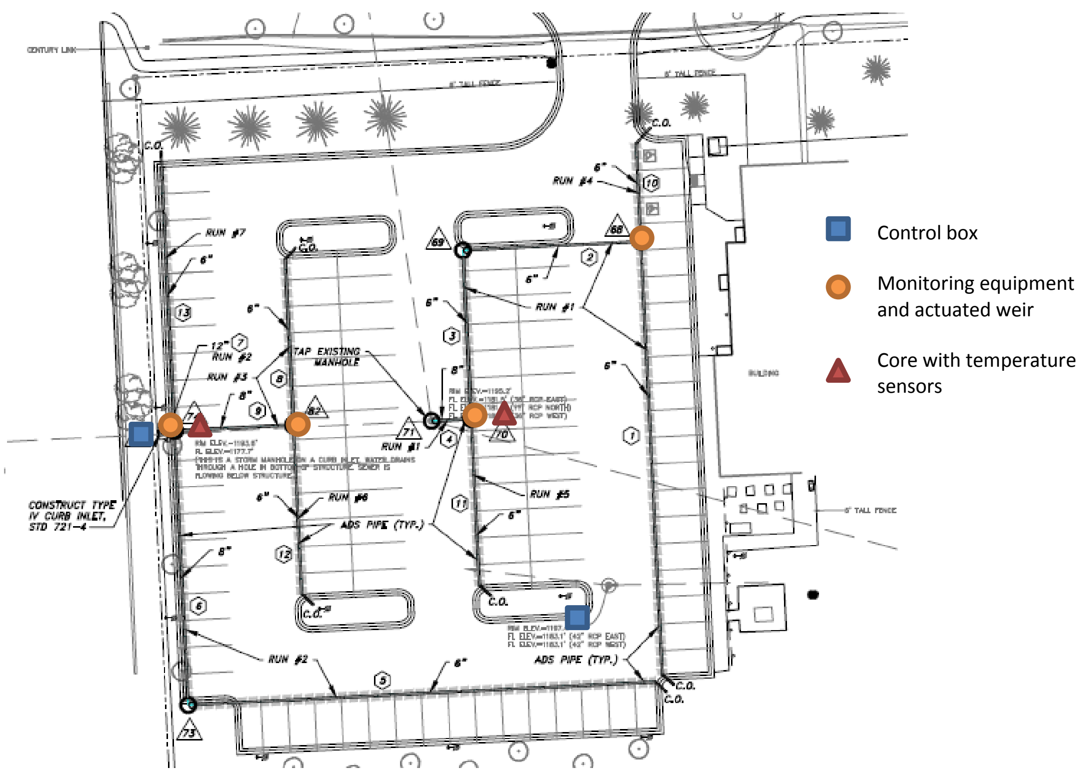


Figure 3-20. Site Plan of Monitoring and Control Components at Pervious Pavement System in Omaha, NE.

Figure 3-21. Eight-Inch Core Removed for Inserting Monitoring Wells with Temperature Sensors at Various Depths into Porous Pavement Surface.

Figure 3-22. Personnel Placing Sealant Around Newly Installed Real-Time Controlled Weir Plate.

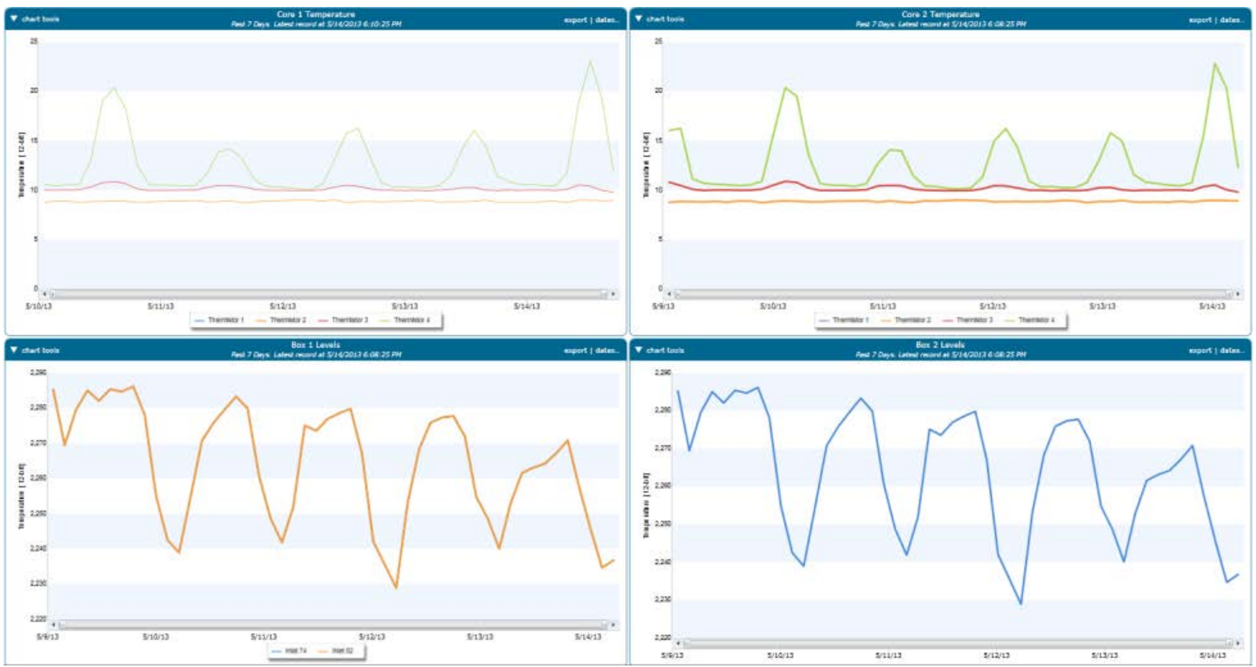


Figure 3-23. Dashboard at the Pervious Pavement Site in Omaha, NE.

3.1.10 Lawrenceville, Georgia: Advanced Rainwater Harvesting and Underdrain Bioretention Systems

The bioretention pond in Lawrenceville, Georgia is designed to adequately infiltrate runoff from the 95th percentile storm event (1.7 inches of rain) from a parking lot at Gwinnett County's Water Resources Central Facility. The bioretention pond receives runoff from an approximately 1.1 acre parking lot area. The bioretention cell also includes a perforated underdrain with a valve (currently shut) that is connected to a catch basin that previously drained the parking lot. Overflow rainfall in excess of the design parameters bypasses directly into the catch basin. A rain gauge and pressure transducer have been installed to track rainfall in the parking lot and level within the bioretention cell. An automated controlled underdrain valve was added to the system so that it can be actuated as needed. The bioretention system rarely fills to a depth that might require a decision to drain the system. For the study, the automated underdrain was of limited use over the short duration following installation during the study, however the installation is the first of its type and proves the approach is viable and effective from a practical standpoint and leads the way toward effectively designed and operated controlled underdrain bioretention systems.

In addition, a 5,000-gallon above-ground cistern exists on site. The cistern collects runoff from approximately 2,500 ft^2 of roof area. The original cistern had two outlets: one bypass outlet to the parking lot, and one hose bib upstream of the bioretention area. A pressure transducer was installed within the cistern to monitor water levels. A controlled release valve system for retrofit onto the supply line to the hose bib was installed along with a harvesting pump in order to automatically and remotely monitor and control the drainage of the cistern to the downstream bioretention area.

The installation of the controlled valves on the bioretention pond underdrain and cistern outlet was completed in September 2013 control logic was implemented at that time.

3.2 Analysis of Selected Pilot Site Results

As described previously in this report, the overall goals of the project were to both evaluate and support the hypotheses that DRTC technologies can greatly reduce contributions to CSOs, reduce stormwater runoff, and retain stormwater for future onsite use and that these systems are practicable. The study obtained vast quantities of data including over 863 MB of raw field data. Given the scope of this project, a complete analysis of all of this data is well beyond the scope of this research alone and will continue for many years. The project team is making the raw data obtained available (subject to the underlying organization's approval) to the public for research purposes concurrent with this final report.

This section of the report describes selected analysis conducted on the collected data to target achieving the stated goals of the project. The project team presents here focused work on the New Bern, NC and SAP Green Roof studies as they both have extensive datasets and best provide empirical support for the underlying methods illustrated in the pilot projects.

3.2.1 New Bern, North Carolina: Advanced Rainwater Harvesting System

Ninety-one storm events occurred between September 20, 2011 and January 31, 2013, equating to 51 inches of precipitation and about 84,400 gallons of runoff at New Bern. A storm event was defined as at least 0.10 inches total precipitation and six hours antecedent dry conditions. A plot of cistern storage volume and precipitation is shown in Figure 3-24.

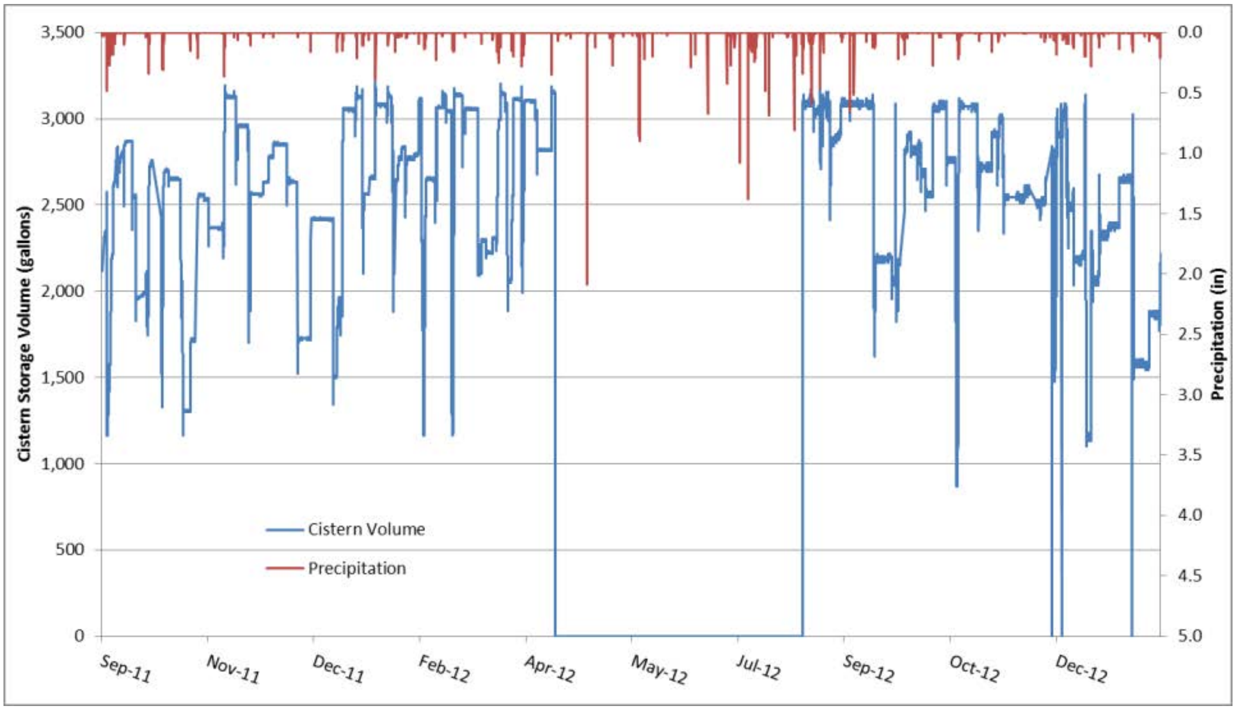


Figure 3-24. Draining and Filling of the Advanced Harvesting Cisterns at New Bern Based on Forecast Precipitation.

Real-time monitoring and control data is available for 59 of these events (equating to 45,445 gallons of runoff). The system did not capture data for 30 events due to issues with the installed pressure transducer (Section 3.1.1), and two events (9/8/12 and 10/1/12) were not recorded because of network issues.

Forecast logic is in effect such that when a storm event is forecast, the cisterns drain to allow for complete capture of the forecast volume. The dynamically controlled cisterns completely captured runoff from 39 storms, and partially captured runoff, resulting in overflow, from eight storms. For 12 storms, the forecast logic did not work as predicted and the outlet valve was opened during rainfall. In September of 2012, the forecast logic was revised so that the system would not release within six hours of a forecast storm event, but release during rainfall still occurred in December of 2012. It is likely that these storm events were inaccurately forecast by the National Weather Service, thus leading to inappropriate draining of the cisterns during rainfall. Assuming these 12 storms captured no runoff, which is unlikely, the total runoff captured by the system is about 27,000 gallons. On average, the cisterns captured 71% of wet weather flow per storm event.

The dynamically controlled rainwater harvesting cisterns were compared to a conventional cistern for a 3.5 month window from 10/11/2011 and 1/18/2012. Thirteen storm events, equating to 5.71 inches of precipitation and 10,678 gallons of runoff occurred in this period. Of these 13 events, partial data was recorded for storms on 11/4/2011 and 12/27/2011 due to power or internet outages as previously discussed. For performance analysis purposes, these events were excluded, and 11 storms equating to 4.77 inches of precipitation and about 8,900 gallons of runoff were analyzed. Of the 8,900 gallons of runoff, the controlled rainwater harvesting system released about 3,700 gallons to the rain garden during dry weather conditions in order to provide adequate storage for the anticipated storm and 4,345 gallons were used onsite to irrigate nearby shrubs and wash vehicles (Table 3-3). During the 3.5 month period, the advanced rainwater harvesting system captured about 91% of the total runoff volume. Only 49% of the total runoff volume would have been captured by a conventional rainwater harvesting system (Table 3-4). The conventional rainwater harvesting system would have released 5.4 times more runoff than the controlled rainwater harvesting system during the 3.5 month analysis period.

Table 3-3. Water Balance of Controlled Rainwater Harvesting System Between 10/11/2011 and 1/18/2012.

Total Rainfall (in)	Total Runoff Volume (gal)	Total Onsite Usage (gal)	Total Release to Bioretention (gal)	Overflow Volume (gal)	Percent Overflow
4.77	8,921	4,345	3,715	843	9.5

Table 3-4. Water Balance of "Conventional" Rainwater Harvesting System Between 10/1/2011 and 1/18/2012.

Total Rainfall (in)	Total Runoff Volume (gal)	Total Onsite Usage (gal)	Overflow Volume (gal)	Percent Overflow
4.77	8,921	4,345	4,576	51.3

3.2.2 Newtown Square, Pennsylvania: Green Roof

Nearly a full year of monitoring data, from August 2012 to present, was collected and analyzed for the green roof at SAP Headquarters in Newtown Square, Pennsylvania. The irrigation was controlled during this period so that the green roof water level remains at the root zone of the planted turf. On June 17, 2013, logic incorporating weather forecasts was implemented. If there is a 70% probability of rain forecast in the next 24 hours, the system stops irrigating and is allowed to naturally drawdown to unsaturated conditions. After the storm event, when no rain is forecast, the system irrigator is turned back on and maintains the constant water level in the root zone.

To observe how this implemented logic functions in practice, an actual storm event that occurred on 9/18/2012 was investigated more closely. The storm consisted of 1.54 inches of rain over 24.5 hours. Figure 3-25 shows the water level in the manhole at the green roof during the storm event. The first peak of the storm occurred at 4:45 am on 9/18/12. The forecast logic would have recognized the storm was coming at 10:30 pm on 9/17/12 and stopped irrigation. In this case, it is predicted that the roof would have captured a significant portion of the storm runoff as shown in Figure 3-25. The system would have turned irrigation control back on at 7:30 am on 9/19/12, six hours after the last precipitation (which occurred at 1:45 am on 9/19/12).

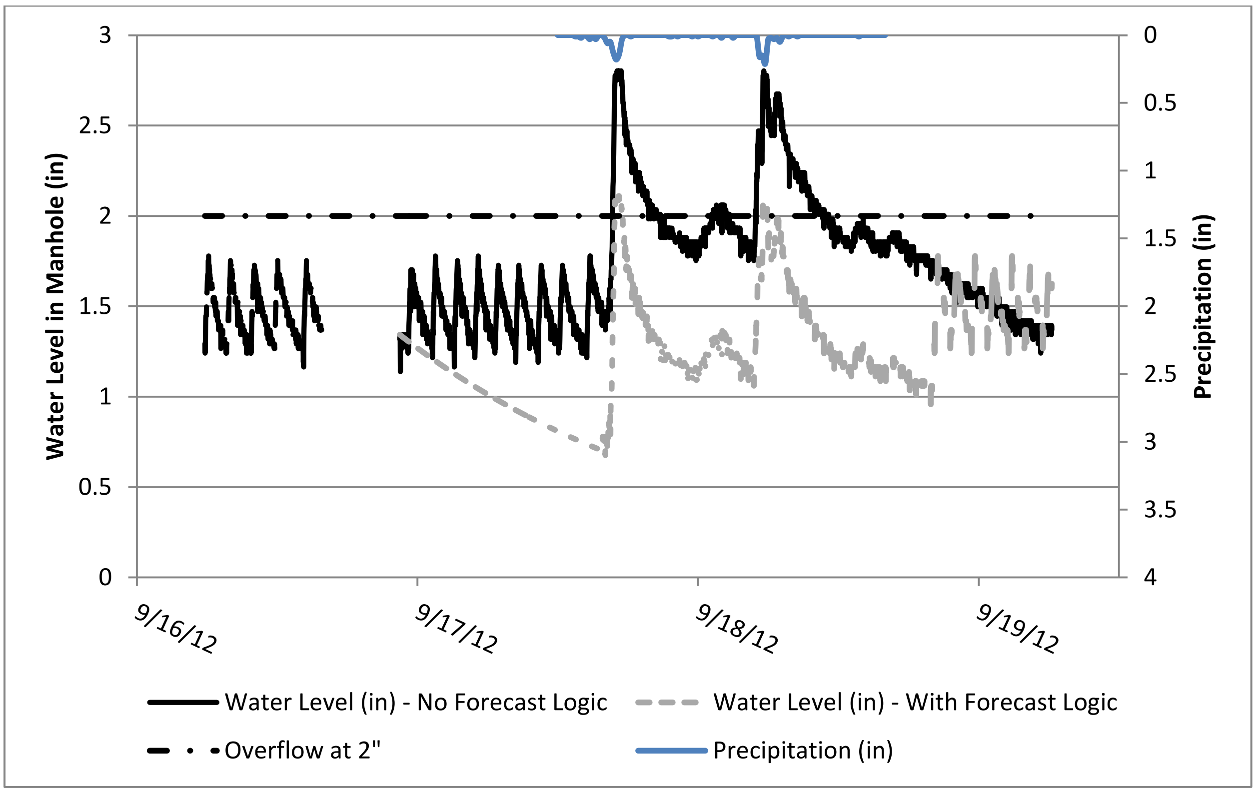


Figure 3-25. Example Response of Green Roof to Implemented Forecast Logic.

In order to assess system performance over an extended period, the research team analyzed seven months of data to describe significant drawdown events. Drawdown characteristics are influenced by a combination of evapotranspiration, infiltration, climate, weather, water level at the start of the drawdown event, and roof construction.

There are three distinct regions of water level where drawdown behavior can be described. Above the two inch overflow, drawdown during non-rainfall periods is approximately linear.

Between 0.24 inches and two inches, drawdown resembles a hyperbolic curve. At 0.24 inches, the system approaches the minimum measurable water level.

Linear Region: Water Levels Above Two Inches

Above the two-inch overflow, stored water in the irrigation layer is rapidly released and discharged as runoff from the green roof. A characteristic overflow drawdown is shown in Figure 3-26.

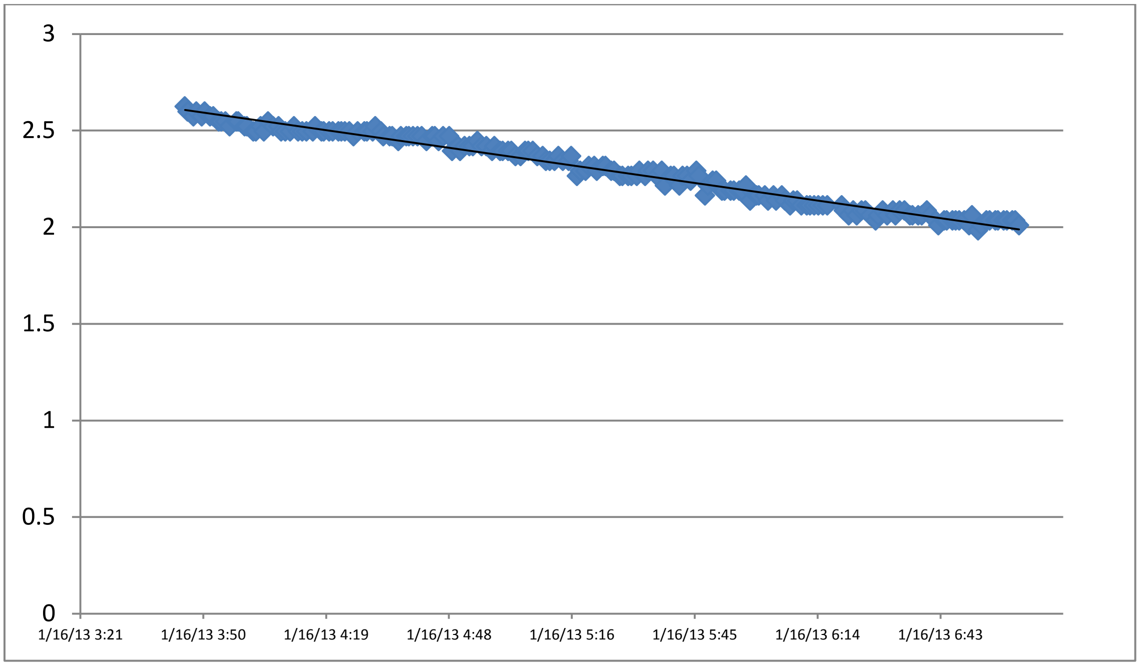


Figure 3-26. Typical Drawdown Behavior When System is Overflowing.

As there were only five events during the period examined where water level exceeded two inches in the analyzed winter months, the research team chose to simply average the drawdown rate to characterize all of these events. An analysis of all overflow drawdowns by month did not appear to show any significant correlation between month and drawdown rate. The average drawdown rate was -6.184 inches per day. It is assumed that this behavior is a result of the simple hydraulic properties of flow in the system and the overflow design. Note that the overflow itself is not physically accessible for observation.

Hyperbolic Region: Water Levels of 0.24 Inches to Two Inches

Regression analysis found that over time, water level during drawdown events closely approximated a hyperbolic function with the equation:

$$y = \frac{a}{(x-c)} + b$$

In this equation, “x” represents time and “y” stands for water level, while “b” is the minimum measurable water level of the roof calibrated to the theoretical asymptote of the hyperbolic curve, in all cases -0.73 inches for this analysis. “a” and “c” are empirically determined constants. To calculate these parameters, the team used a nonlinear regression methodology. The start time of the storm was determined, and then duration in minutes was mapped to water level to create x, y coordinates. These coordinates were then averaged for each 100 data points to speed up regression calculations. For example, 50, 1.7 would mean that the water level was 1.7 inches 50 minutes after the start of the drawdown event. Then, one inch was added to all water levels before conducting the regression, to force the asymptotic value to be positive.

For every month, the team calculated average "a" and "c" parameters to create representative equations. Figure 3-27 overlays the empirically derived hyperbolic regressions with the recorded drawdown events.

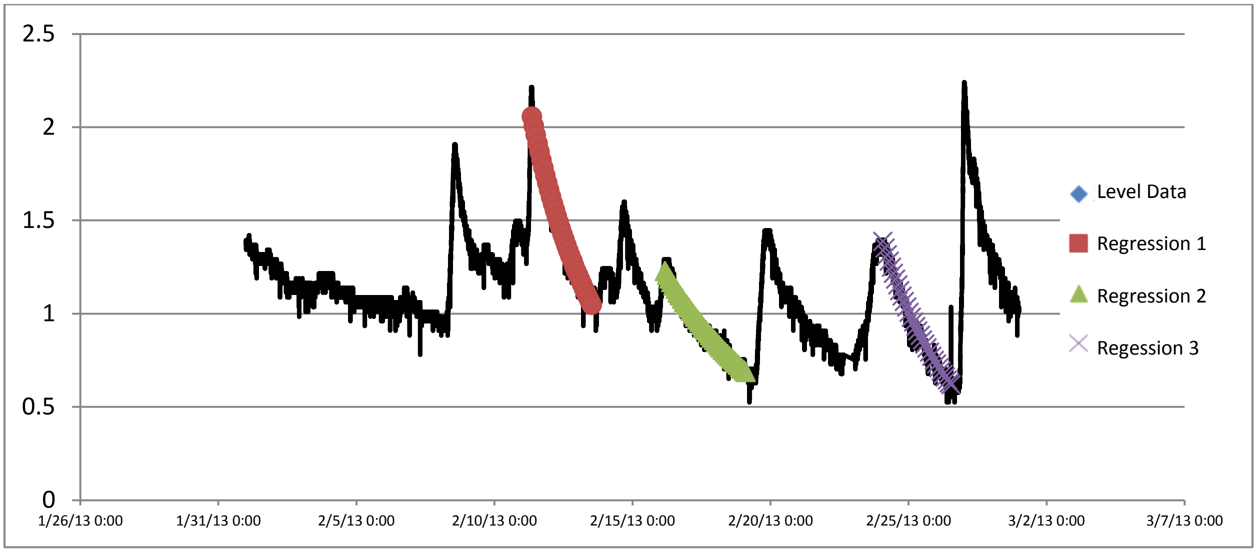
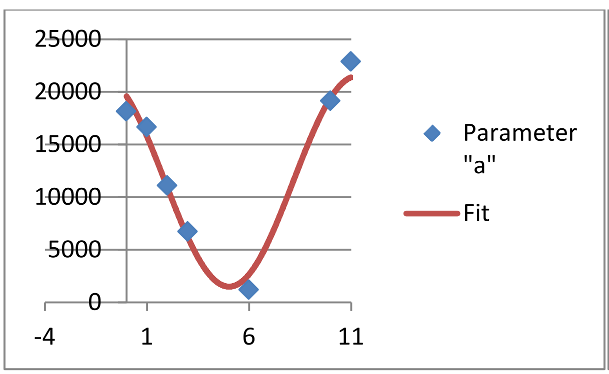


Figure 3-27. Example Drawdown Regression Analysis for February 2013

A long-term analysis found that the "a" and "c" parameters of the equation varied periodically over the course of the year, reflecting the fact that seasonal climate conditions impact drawdown events. In Figures 3-28a and 3-28b, the team plotted the empirical parameters by month, and fit a periodic function to the plot to calculate theoretical constants.



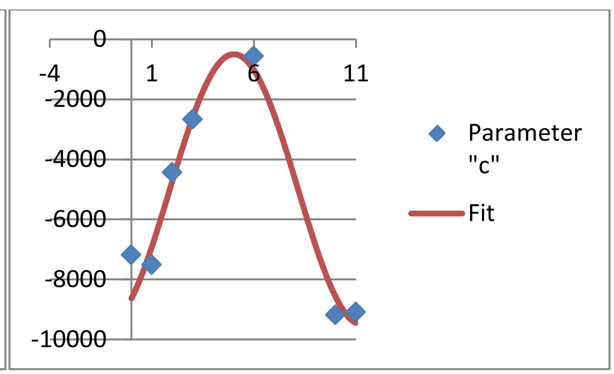


Figure 3-28a (left) and 3-28b (right). Observed Seasonality of Monthly Averaged Regression Equation Parameters. Note: The X values on this plot are months: 0 is January, 1 is February, etc.

While these parameter plots strongly fit the regression lines when parameters from all monthly storm events are averaged, the fit is less compelling when individual drawdown events are analyzed, as can be seen in Figures 3-29a and 3-29b.

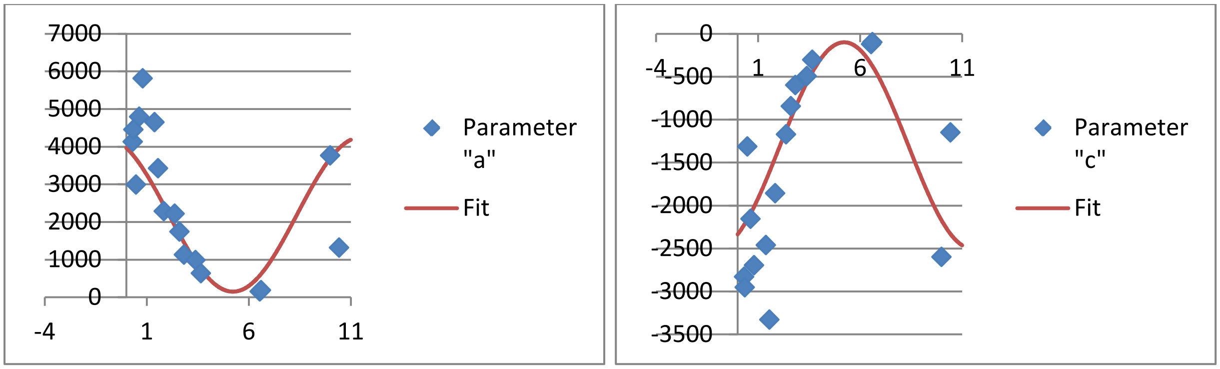


Figure 3-29a (left) and 3-29b (right). Observed Seasonality of Individual Regression Equation Parameters.
Note: The X values on this plot are months: 0 is January, 1 is February, etc.

In some events, there is significant scatter from the fit line. This suggests that several other climactic and temporal factors impact the shape of drawdown events. For example, temperature, cloud cover, and relative humidity were not considered independently in calculating these parameters, but could be used in future iterations of this model and similar approaches to better calibrate parameters to the fit line. Such detailed analysis is beyond the scope of this report, but the data obtained during this study would be an excellent source for conducting additional research on ET rates of flood irrigated turf grass green roofs. The data collected here is likely one of the most complete, if not the only, dataset for this purpose. In addition, time of day was not considered in analysis. However, many of these events spanned several days, and did not have noticeable discontinuities as time passed.

Most significantly, there were no large drawdown events in the summer to test the validity of the periodic fit in the summer months due to the need to maintain water levels. The two July events plotted above were run as experiments where irrigation was manually suppressed, and water was allowed to draw down for 12 hours from the 1.6” irrigated level. However, these drawdown events took place on 100°F days with no cloud cover, so they may be fundamentally different than typical drawdown events occurring before a storm.

Flat Region: Below Water Levels of 0.24 inches

The average minimum measureable water level is .24 inches, and this was set as a minimum value for modeling.

Challenges in Measuring Water Level

The irrigation valve and the water level measurement are located in the same access structure. This means that during irrigation events, the water level measurements in the access structure must be used as an indication, not a direct measurement of water level in the roof because water level is not necessarily evenly distributed. It takes time for the water in the manhole to reach the far edges of the roof. However, as the set points are measured based on water level in the access structure, it is likely that under irrigation conditions the water level in most of the roof does not reach 1.7 inches, as irrigation stops before infiltration to that level occurs at the edges of the roof. This leads to difficulty interpreting how much water is needed from irrigation to produce a given increase in water level on the roof. This also explains why it does not appear to take many gallons of water to cause a sizeable increase of water level on the roof, as the water level in most of the roof does not actually rise as much as the meter would suggest. In storm events, where there is no irrigation and water level is evenly distributed, the meter does accurately measure water level on the roof.

In addition, all drawdown events have slightly different shapes, and many have discontinuities. This led to challenges in trying to find a single system to characterize them all. While the team is confident in the form of the equation it ultimately picked, discontinuities where there is precipitation midway through the drawdown event, or other irregularities, cannot be avoided.

Future Work

Drawdown events must be calibrated for some climactic indicators to better assess the value of theoretical parameters to dictate logic. Current data collected include temperature and dew point, indicating that these may be good parameters to start with.

In addition, there is a significant need for experiments in summer months to test the validity of these conclusions. The best way to run a test would be to wait for a storm event to occur, and then to shut off irrigation and allow the system to draw down as close to the measurable minimum of .24 inches as possible, without killing the grass. These events could then undergo the same regression fit as the other events, and plotted against the theoretical data to test the model.

Once the data here is better calibrated, it should be used to implement future logic for SAP irrigation controls and drawdown prediction. This is an excellent example of the role and potential of adaptive management in DRTC systems: the design can be adjusted to improve and modify performance or alter system goals and functions.

Modeling Introduction

Once these parameters were calculated, the research team used them to model both a conventional and controlled cistern in Microsoft Excel to assess the value of DRTC systems. The models compared water use and water runoff between conventional and controlled models, allowing the SAP Green Roof to be analyzed for performance under two different scenarios. The system was modeled for six months, May-October, as these are the six months where the system is fully operation and not winterized. Winter months provide additional complications such as freezing water and snow.

The system was modeled using perfect forecast data, meaning that the team assumed that the system could perfectly predict both the magnitude and timing of storm events by utilizing recorded precipitation from the preceding year.

The system was modeled under three forecast scenarios. First the system was modeled assuming the ability to predict storm events 12 hours out and to adjust the beginning of the drawdown event based on the exact space needed to store the predicted precipitation amount. Then, these same assumptions were modeled for the ability to predict precipitation 24 hours out. Lastly, the system was modeled under the scenario where it began drawing down immediately when any precipitation was predicted within the next 24 hours, which is the current logic implemented at the actual site. Under the perfect precipitation scenario, there was no marginal benefit of reduced runoff to drawing down immediately, compared to drawing down based on storage needed. In real life where exact precipitation is unknown, drawing down immediately will likely result in some additional storage.

Model Inputs

Both the conventional and controlled cistern models are designed to find the current water level based on the past water level, and storm conditions.

In order to make a representational model, several assumptions were made for inputs. First, one inch of rain was assumed to increase the water level on the roof by two inches, based on the composition of the roof, and observed data which also takes into account evapotranspiration and runoff. Each inch over this threshold was assumed to equate to 592 gallons, based on .25 pore space times the volume in gallons of one inch of water in the green roof. Because the SAP system cannot measure water level over 2.8 inches, the model capped water level at 2.8 inches because it was impossible to characterize water level behavior above this threshold, even where in reality it likely would have risen higher. This assumption likely discounted some of the value of the DRTC system, as it minimized the runoff of non-controlled systems in some instances.

The roof model has several separate water level regimes. The first was normal irrigation with rapid, uniform peaks in water level. The second involved slower increases and decreases in water level during and after storm events. Under the first regime, linear increases in water level were calculated whenever the water level was between the set points and increasing, or whenever the water level was below the lower set point. When the water level was above the upper set point, or was between the set points and decreasing, the model used the regressions above to find the water level.

When the water level was drawing down before or after storm events, the regressions above were again manipulated to determine the change in water level.

To translate the regression analysis above into useable modeling form, the model was set up to have three behavior regions as above, linear, hyperbolic, and constant. In the hyperbolic region, the rate of change of water level in the above regressions was plotted against the water level, as seen in Figure 3-30.

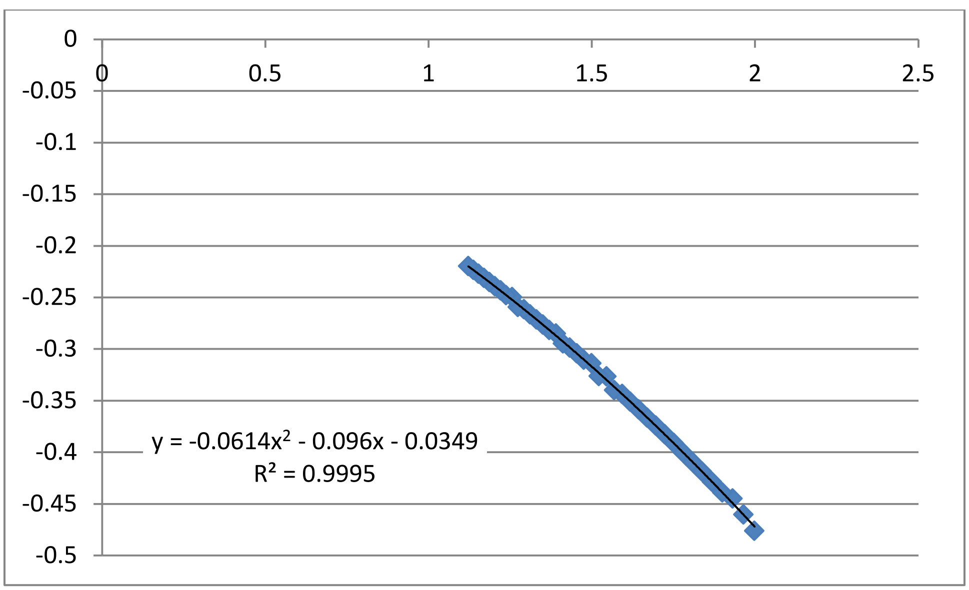


Figure 3-30. Change in Water Level by Water Level for Sample Event with Polynomial Regression.

As can be seen, a regression was taken on this data, and found that a second order polynomial nearly perfectly fit the changing water level, with three parameters, “D,” “E,” and “F.”

The analysis was done on the regressions rather than the actual data because measurement scatter and discontinuities on the raw data obscured trends. From here, regression averages were found for each month. In the model, the goal was to understand how water level changed as a function of time, or how much time was required to draw down to a specific water level. This regression allowed researchers to understand both using two forms of the following differential equation:

$$dh = (D(h^2) + E(h) + F)dt$$

Equation 3-1: Differential equations defining drawdown behavior

and

$$dt = dh/(D(h^2) + E(h) + F)$$

When predicting storms and calculating the time needed to draw down in the controlled cistern setup, the system would use the second form of this equation to determine when to start drawing down. When calculating the water level at any given data point under both the controlled and uncontrolled scenarios, the model used the first form the equation to determine the change in height, which was then added to the previous height to find current height.

Model Calibration

Making the models was a two-step process. The researchers first modeled an uncontrolled system and calibrated it to resemble the OptiRTC data on water level from that month as closely as possible. Then, that model had logic applied to evaluate the marginal benefits of DRTC. To calibrate the model, first raw data was analyzed to determine the number of peaks that should be expected each day under irrigation conditions. The drawdown rate and linear increase in water level were calibrated by a factor so that the number of peaks in each day in the model matched the empirical data. Then, the amount of gallons used per inch of increase in water level was adjusted so that monthly water use matched the observed monthly water use.

Model Conclusions

Figure 3-31 shows the uncontrolled cistern model time series overlaid with the observed raw data time series. Figure 3-32 shows the uncontrolled cistern model overlaid with the controlled cistern model, both for the month of May. The controlled model is based on the 24-hour prediction, water level optimized scenario.

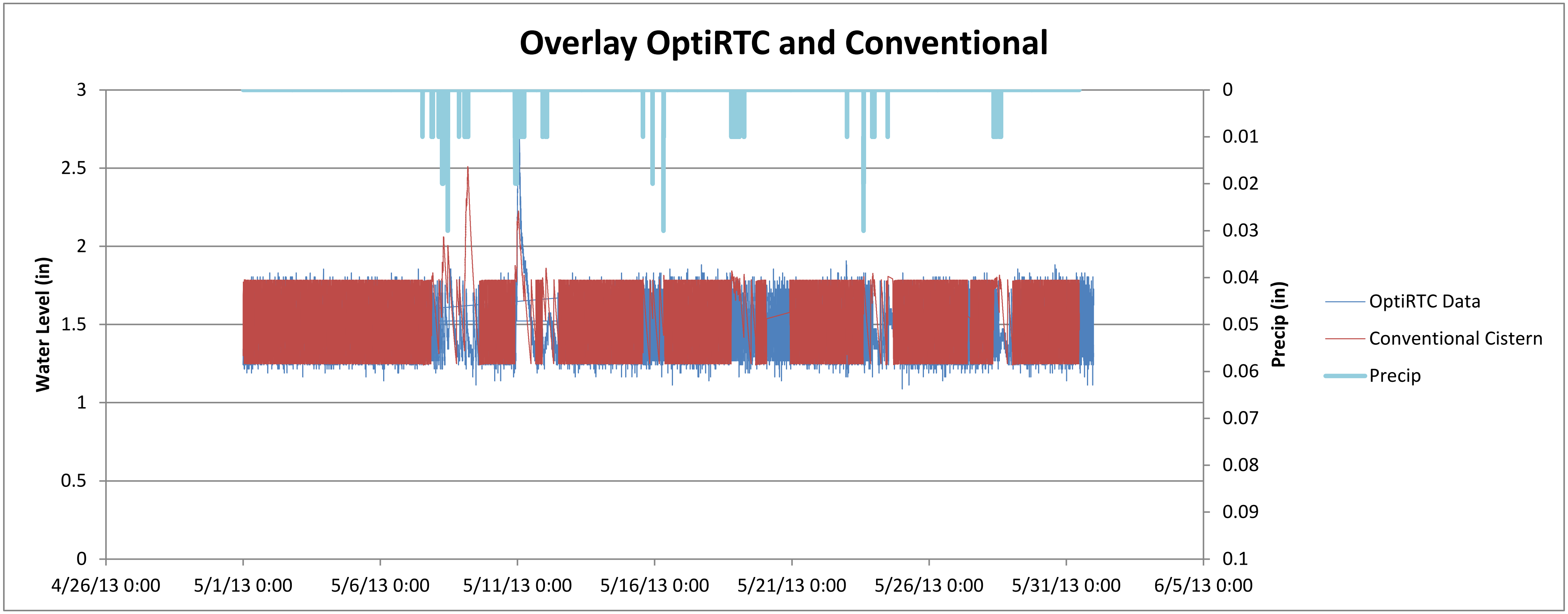


Figure 3-31. Overlay of OptiRTC Data and Conventional Cistern Model.

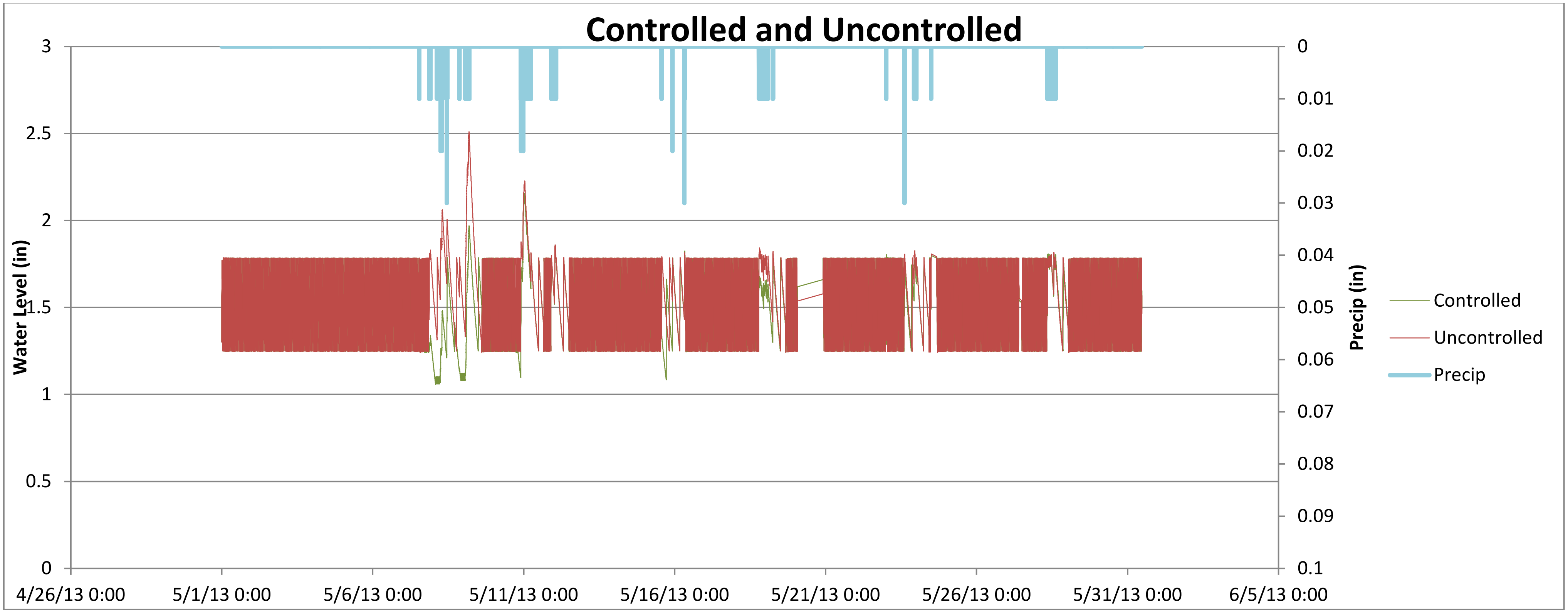


Figure 3-32. Overlay of Conventional and Controlled Cistern Models.

The data presented in the previous figures show a convincing fit between the uncontrolled and raw water levels, and a noticeable performance benefit to the controlled system in May.

A summary of the model water use and runoff data over all six months the model was run is shown in Table 3-5.

Table 3-5. Model Results.

Cumulative Results	Total
Uncontrolled	
Total Gallons Used	24209.23
Total Runoff Produced	15267.57
Controlled	
Total Gallons Used	23342.12
Total Runoff Produced	11456.55
Total Gallons Reduced	867.11
Summary	
Total Percent Gallons Reduced	4%
Total Runoff Reduced	3811.02
Total Percent Runoff Reduced	25%

These results demonstrate the installing DRTC on the SAP green roof results in modest reductions in water runoff, and a small reduction in water usage. Clearly to obtain more significant benefits, the roofing system would ideally be designed to take advantage of the benefits of a DTRC system. However given that the DTRC system in this case costs approximately the same as the required mechanical irrigation system, the marginal cost of adding DTRC in new construction of a flood irrigated green roof is quite low even though the quantitative benefits are also low.

Model Limitations

One of the most significant limitations to this green roof model is that the ASOS station from which rainfall data was obtained was at the Philadelphia International Airport and is therefore located 10 miles away from the SAP site. While the rain data works well in frontal precipitation events, high intensity, localized events such as thunderstorms are not well represented. The fit of the model to the measured OptiRTC data could be greatly improved by installing a rain gage on site. However, the difference between the controlled and uncontrolled model should be representative and a rain gauge is not necessary for the system to function well as forecast logic is more useful for actual operation.

Another large limitation is that the model was run during summer months, while all of the large drawdown events on which the drawdown parameters were calculated happened during winter months. This disconnect in timing will likely impact the accuracy of the data. More drawdown experiments are needed during summer months.

Summary of DRTC Benefits for Green Roofs

When compared to cisterns utilizing DRTC technology, green roofs have several inherent limitations that reduce their performance. The model here demonstrates that DRTC results in a 25% decrease in stormwater runoff. This is significant, but not nearly as large a performance benefit as the use of DRTC systems in other types of green infrastructure as shown in the New Bern Example above. Green roofs have limited storage capacity, and cannot accommodate large volumes of stormwater during larger events. They are also limited by the slow rate of drawdown, as even when full storage capacity is predicted as needed, the flood irrigated roof cannot always draw down to that level effectively in the time allotted. Forecast accuracy also plays a role, as the roof will likely not perform as well with localized, intense events which are not predicted at high resolution.

One way to dramatically increase the performance of DRTC for a green roof would be to install an outflow valve near the bottom of the storage area in much the same way that the cistern tank is able to discharge during dry weather. This would allow the roof to more rapidly draw down its level when a storm is predicted, and not to rely on evapotranspiration alone for drawdown. However, even in this scenario the storage capacity would still be limited by the size of the roof, and large drawdown events could have unintended consequences for the plantings on the roof and would need to be thoroughly evaluated during design.

These models further demonstrate that the DRTC install on the green roof has little impact on water use: about 4%. This is because the majority of water use is during normal irrigation events, and these regimes happen during most of the time, and are mostly common to the controlled and uncontrolled models.

DRTC installs could play a larger role in reducing water use if there was known information about the amount and frequency of water needed to keep the roof plants alive. For example, if the plants only needed to be watered every six hours to stay alive, a DRTC system could automate that process and reduce water use by not overestimating the amount needed to sustain the roof.

Future Work

These models do a very good job of describing all of the possible behavior scenarios of the water level. The fit of the drawdown events in the hyperbolic region can be optimized by running additional experiments in the summer months.

3.2.3 Denver, Colorado: Advanced Rainwater Harvesting System

Data has been collected at the advanced rainwater harvesting system in Denver, Colorado from 9/6/12 to present. A plot of cistern storage volume and precipitation for June 2013 is shown as Figure 3-33. Logic incorporating weather forecasts was implemented on 6/19/2013. When incoming rain is forecast, the cistern drains to allow for storage of predicted rainfall. The data collected from 9/6/12 to 6/19/2013 is useful in demonstrating the performance of a conventional passive cistern. This performance was compared with the subsequent performance of the cistern with control logic in place.

The researchers performed analyses for storm events similar to those performed for the cisterns in New Bern, North Carolina. Denver, Colorado receives about 16 inches of precipitation a year on average, while New Bern averages about 52 inches a year. They can compare the performance of these two similar systems located in different climates, and provide recommendations for optimal operational logic.

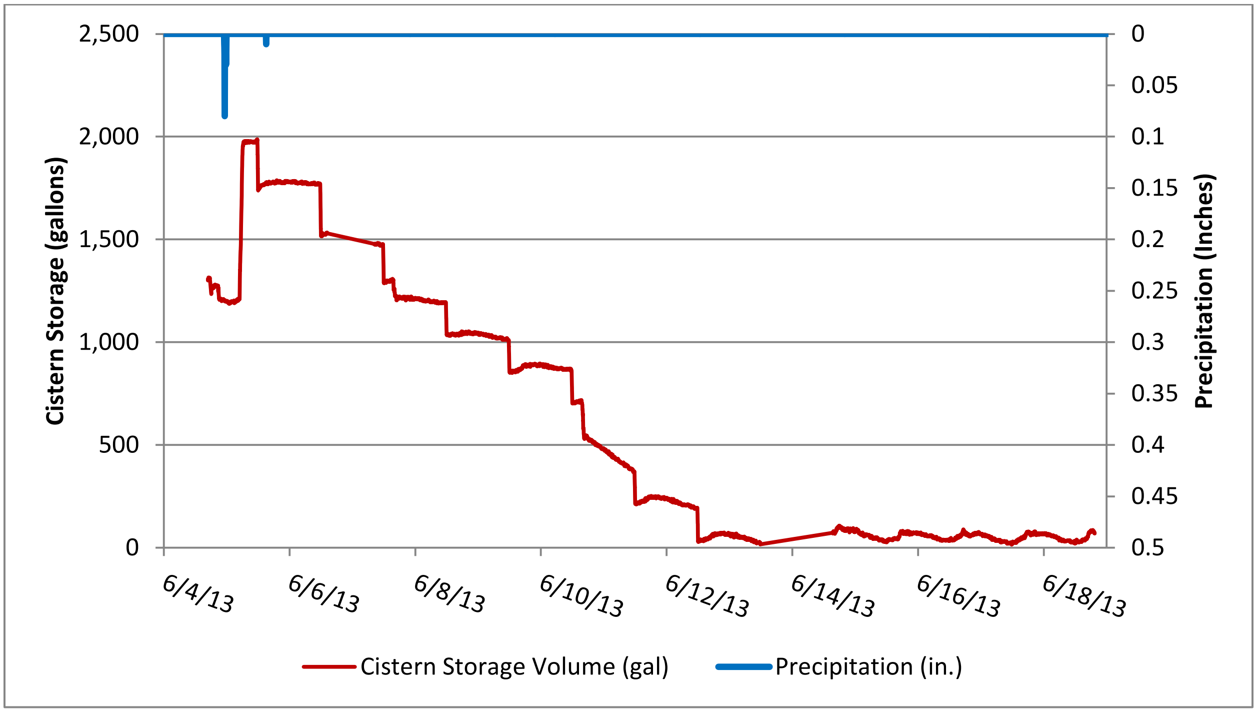


Figure 3-33. Cistern Storage and Precipitation at the Advanced Rainwater Harvesting System in Denver, Colorado. Sharp decreases in volume indicate use for irrigation.

3.2.4 Seattle, Washington: Smart Detention

Immediately after installation of monitoring equipment, it was made clear that the University-installed above-ground cistern had significant leaks (Figure 3-34). This prevented optimization of storage over much of the study, but has illuminated several other observations. Firstly, real-time monitoring allows for early detection and clear determination of system leaks and failures, especially in retrofit or dual-management situations. Secondly, this shows clearly the extensive role that exfiltration plays in existing storm and CSS. Interestingly this leakage limits the use of many potential retrofit systems to being used for smart detention and not capture and reuse.

Seattle University facilities personnel worked to repair the leak in July 2013. Advanced control logic integrating real-time weather forecasts for automated operation of the system was implemented in early May of 2013. Once leaks were fixed, the system was fully functional.

Due to the timing of weather conditions during the study (little intense rainfall with logic implemented), the research team was unable to fully compare reductions in CSO contributions to the performance observed in New Bern.

As more data is obtained, the performance of the system will be able to be analyzed in more detail.

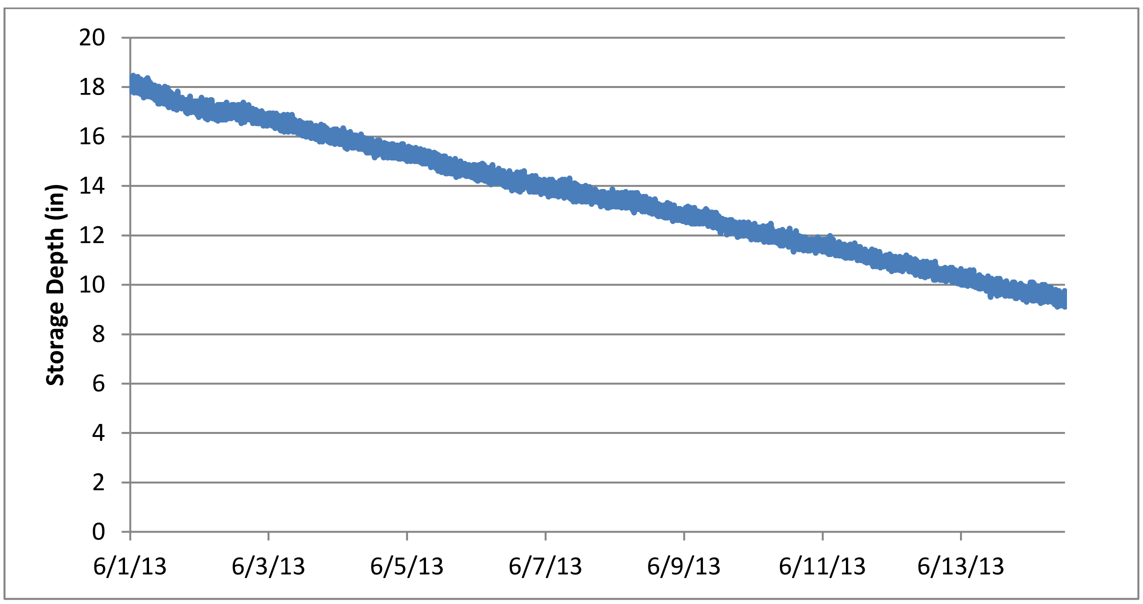


Figure 3-34. Storage Depth of Rainwater Harvesting Cistern in Seattle, Washington Shows Significant Leaks.
Note: Valve is closed during this period.

3.2.5 Austin, Texas: Advanced Rainwater Harvesting System

Data has been collected on the Texas site from January 16, 2013 to present. The originally installed pressure transducer in the cistern provided scattered data due to its proximity to the tank equalization and outflow pipes, so a more reliable ultrasonic level sensor was installed on May 3, 2013. Full wet weather rainwater capture logic and basic dry weather irrigation logic was installed by July 2013. Additional automated irrigation functionality was incorporated over the coming months as system data illuminated more optimal irrigation methods. The team evaluated data from 10 storm events starting on May 3, 2013. These events totaled 7.52 inches and equated to about 27,500 gallons of runoff. A plot of storm events and cistern storage volume during this period is shown as Figure 3-35. During this monitoring period over 6,500 gallons of stormwater were used for irrigation.

This site is the only rainwater harvesting system pilot that incorporates irrigation control and runoff control in the same system (the irrigation controls in New Bern, NC, and Denver, CO, both have separate irrigation controllers); there is the opportunity in future research to evaluate the effect of integrated DTRC/smart irrigation systems on water use efficiency.

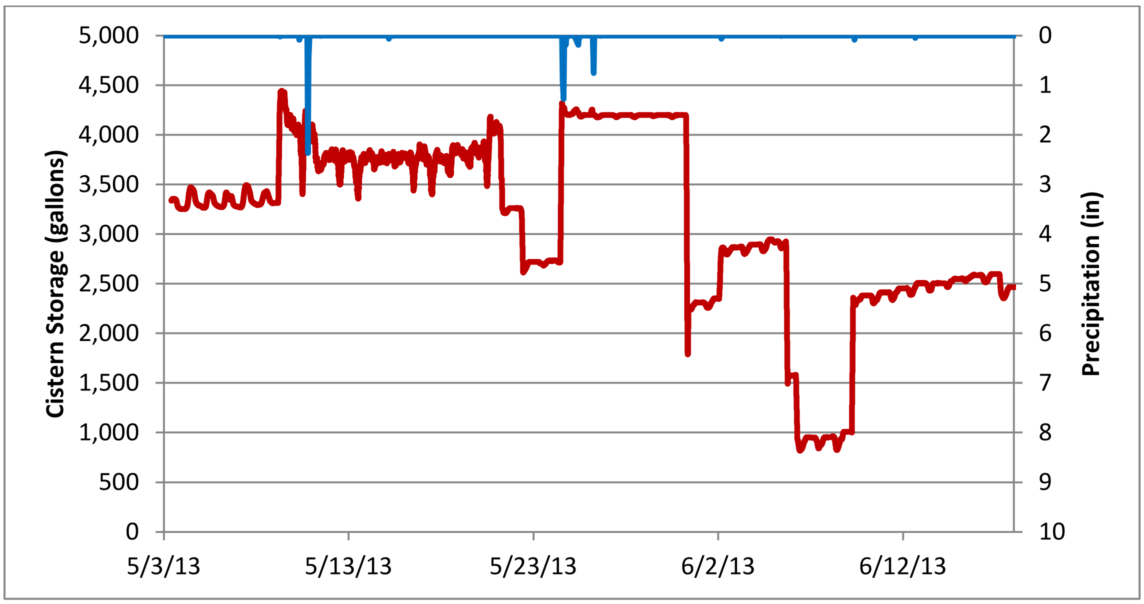


Figure 3-35. Cistern Storage and Precipitation at the Advanced Rainwater Harvesting System in Austin, Texas. Sharp decreases in volume indicate use for irrigation.

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3.2.6 Omaha, Nebraska: Pervious Pavement System

Nine storm events occurred from May 9, 2013 to June 18, 2013, equating to 4.77 inches of rain in Omaha. Storm events were defined as precipitation totals over 0.1 inches with a six hour antecedent dry period. Temperature and water level show response to precipitation events as shown in Figure 3-36. Additional plots of monitoring are provided in Attachment B.2.

Logic that incorporates real-time forecast data was implemented in the fall of 2013. At the time of this report the City is still contemplating the best use of the functionality for control of the system. Full use of the system will not be leveraged until spring 2014.

It is anticipated that during dry weather, the actuated weirs will remain open. When the forecast indicates a small storm that can be entirely captured by the system, the weir valves will close to allow for complete wet weather capture. When a forecast storm volume is greater than the total storage of the system, the weir valves will complete a sequence of open and closed states to reduce system outflow peaks while not overflowing the aggregate storage. This is the only pilot site that might incorporate peak shaving control logic (i.e., aims to capture the peak of large storm events that cannot be fully captured otherwise).

It is hypothesized that dynamically controlled pervious pavement will act similarly to the advanced rainwater harvesting cisterns. Anticipated data include volume and percent of wet weather runoff captured and seasonal infiltration rates. The City of Omaha is also interested in the performance of the pavement during cold weather, as well as the temporal depths of the freeze/thaw line throughout the pavement/aggregate system.

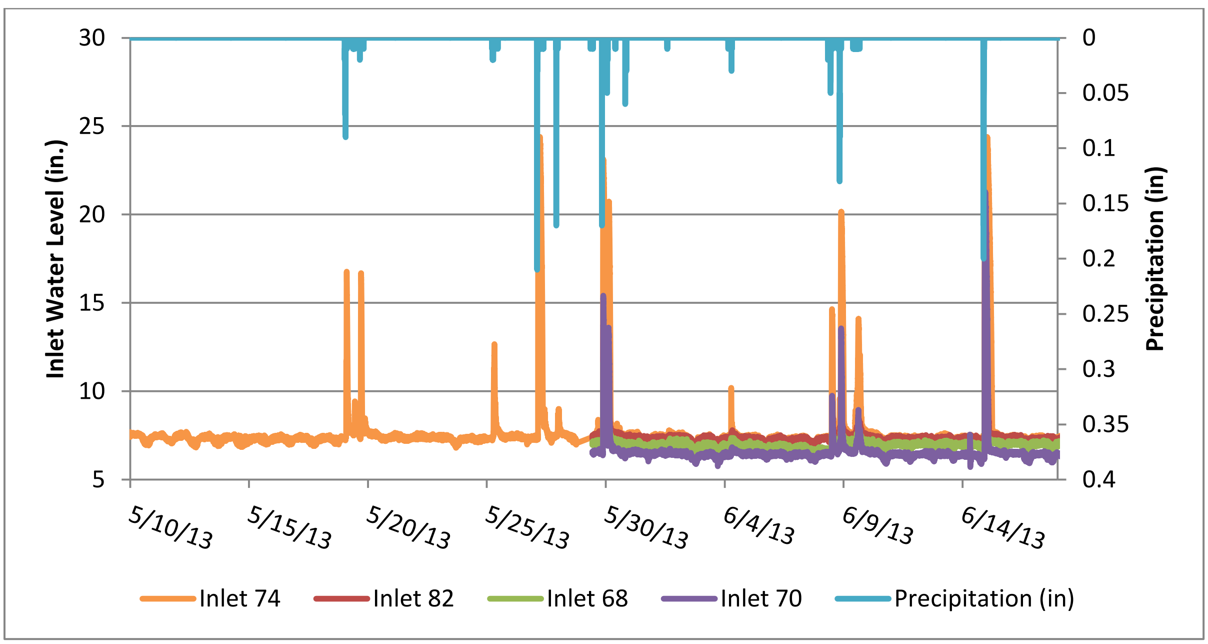

Figure 3-36. Porous Pavement Response to Precipitation Events in Omaha, NE.

CHAPTER 4.0

BENEFIT-COST ANALYSIS

The purpose of this section is to provide a detailed benefit-cost analysis of DRTC green infrastructure for those who have a stake in stormwater management. This includes individual landowners who must comply with the introduction of rigorous regulations and fees to mitigate stormwater contributions, and municipalities which seek low cost strategies to meet increasing infrastructure demands as populations grow beyond the capacity of historical systems. In addition to the measurable economic benefits of DRTC systems, several performance factors further signal the viability of such infrastructure upgrades.

This section first details the emerging trend of stormwater utility fees and credit systems, comparing common structures in case study locations throughout the country. To concretize the economic benefits of DRTC systems to landowners, the section considers a pilot site model and the associated fees and credits at various case study locations. It then calculates the fees and credits for all field pilots where such structures exist. Next, this section outlines the potentially significant cost savings to municipalities who implement DRTC as a strategy for infrastructure upgrades. The section concludes with a discussion of additional DRTC green infrastructure benefits and likely future trends in municipal stormwater policy.

4.1 Stormwater Utilities: An Introduction to Municipal Fee and Credit Systems

Stormwater presents challenging environmental hazards to urbanized areas. Stormwater runoff collects pollutants as it drains from the urban environment which gets deposited in streams. In older cities with combined CSS, even small storm events can overwhelm the infrastructure, resulting in CSOs. CSO events result in significant pollution, as untreated human and industrial waste contaminates waterways.

Municipalities across the United States are increasingly isolating the economic cost of infrastructure and environmental remediation associated with stormwater. The city of New York has estimated that each gallon per year of untreated wastewater discharged into local waterways costs the city $1-2 in remediation (NYCDEP, 2010). Several cities have introduced stormwater management costs to landowners, both to raise awareness and, in many cases, to incentivize onsite stormwater management and best-management stormwater practices (BMPs) at the level of individual lots.

The research team sought to evaluate this trend and determine whether green infrastructure projects, including iterations of the DRTC pilot projects, will see steeply increasing demand in the future. The project team researched the stormwater fee and credit structure of 19 cities, towns, and counties across the United States. Of these, several were selected as case study areas with clear and transparent stormwater fee and credit policies: Philadelphia, Pennsylvania; Montgomery County, Maryland; Washington, D.C.; Richmond, Virginia; Gwinnett County, Georgia; Portland, Oregon; and Seattle, Washington. While varying in size, density, and characteristics of the built environment, six of these municipalities in part rely on CSS, and therefore can confront costly overflows during storms. Gwinnett County does not have a CSS, demonstrating the economics of installing a RTC system in an area with lower stormwater costs.

Among cities that charge residents for stormwater management, several fee structures exist. In almost all cases, the stormwater charge is written as a service fee to a stormwater utility, circumventing regulations requiring votes for new taxes. In several instances, state legislation has mandated the introduction of stormwater fees, as in the case of Maryland's 10 largest counties. Most cities charge residents and commercial landowners for the amount of impervious area on their property, which directly contributes to stormwater runoff. Some cities, such as Philadelphia, charge for the gross lot area as well as the impervious area. Others, including Washington, D.C. charge separate fees for stormwater management and drainage. Often, a combination of GIS analysis for large lots and benchmarking for small lots determines individual fees. Annual stormwater fees for non-residential properties per 1,000 square feet of impervious area ranged from $24.60 in Gwinnett County to $146.88 in Washington, D.C. Small residential sites are charged using several different systems, including impervious area calculations, flat fees and benchmark values.

The credit systems vary considerably across these municipalities. Montgomery County, Washington, Richmond, Gwinnett County, Portland, and Seattle all calculate credits proportional to the amount of impervious area onsite treated by the stormwater management system. Philadelphia assigns credits for the amount of rain that can be managed by the BMP. All cities set a cap on the maximum credit amount, ranging from 10% of the stormwater fee in Gwinnett County per BMP to 97% of the stormwater fee in Philadelphia. Gwinnett County and Seattle weigh the credit amount by the perceived efficacy of the BMP. Gwinnett County and Richmond distinguish between water quality and quantity improvements.

4.2 Case Study Model – Washington, D.C.

In order to test the economic value of DRTC green infrastructure, the research team modeled the site and cistern at Engine House 3 in Washington, D.C., an advanced rainwater harvesting system. The team then calculated the fees and credits that would be associated with the site in each locality. The subject property is a 13,900 sq. ft. (0.32 ac.) parcel consisting of a firehouse, a small building, and a parking lot. Impervious surfaces make up 100% of the total area. Stormwater runoff from the 4,000 sq. ft. roof is directed to two interconnected precast concrete tanks with a gross storage volume of 576 cu. ft. (approximately 4,308 gallons). Harvested water is used to clean vehicles and vehicle parking bays, and to fill on-truck water tanks used for first-responder water supply. The tanks are also equipped with a 1-inch discharge point off of the onsite use force main which can be used to release water to the sewer system in advance of large storm events, and a 4-inch diameter overflow outlet.

The U.S. EPA's SWMM-5 model was used to evaluate stormwater runoff characteristics of the site and performance of the existing rainwater harvesting structure, as well as performance of the system when the discharge orifice is retrofit with an actuated control valve. The actuated control valve operates autonomously based on algorithms that incorporate inputs from real-time onsite monitoring devices and weather forecast information provided via internet feed from the National Weather Service in a manner demonstrated in the field during this research pilot.

The model was run using 10 years of continuous rainfall data (4/1/2000 to 4/1/2010) from the NCDC climate station located at Reagan National Airport, approximately five miles to the southwest of the site. A roof runoff coefficient of 0.94 was used based on pan evaporation data at Sterling Test Lab (Farnsworth and Thompson, 1982).

A baseline condition model was run using the data above for a conventional rainwater harvesting system without active controls. Pilot data indicate that user demand for harvested water is highly variable and unreliable. Harvested water at Engine House 3 is often used for about an hour in the morning, but there are also entire weeks when water is not used at all. As reliable demand for harvested water maximizes the system's effectiveness, the research team plans to educate fire house staff to use more rainwater as part of an upcoming project to monitor the system.

To demonstrate the effects of reliable demand, the model was run for four different demand scenarios: 0, 100, 250, and 500 gallons per day.

A dynamic control scenario where the discharge orifice is retrofitted with a 1-inch diameter actuated valve was also modeled. The valve control logic applied in the model is as follows:

1. When rain is predicted in the next 7-30 hours, the valve is opened until the predicted needed storage volume is available.
2. The valve is closed during all precipitation events.

Model results show that roof runoff is about 81,000 gallons annually. The conventional rainwater harvesting system under different demand scenarios mitigates between 0-84% of wet-weather runoff (Table 4-1). For this analysis, wet weather run-off is defined as stormwater runoff that occurs when a precipitation event is still ongoing. Mitigated wet weather runoff therefore is runoff that occurs after a rain event is complete, and represents remaining discharge from the detention structure after a rain event has finished. Performance of the system with a 1-in. active control valve results in reduction of wet weather flow by approximately 74,571 gallons per year (92%). DRTC systems create reliable demand by draining water before predicted storm events (i.e., essentially discharge of water from storage is analogous to demand from the system.)

Performance of DRTC systems is largely independent of user demand; a DRTC system with no demand achieves greater reduction in wet weather flow (90%) than a conventional system with reliable demand of 500 gallons/day (84%).

Table 4-1. Modeled Performance of Conventional vs. Dynamically Controlled Rainwater Tanks.

Condition	Demand	Storage Volume (Gallons)	Wet-Weather Flow (Gallons/Year)	Reduction in Wet-Weather Flow (Gallons/Year)	Reduction of Wet-Weather Flow (Percent)
Baseline	–	–	81,474	–	–
Uncontrolled	No Demand	4,308	80,909	565	1%
Uncontrolled	100 gal/day	4,308	56,180	25,294	31%
Uncontrolled	250 gal/day	4,308	25,954	55,520	68%
Uncontrolled	500 gal/day	4,308	13,290	68,184	84%
Controlled	No Demand	4,308	8,542	72,932	90%
Controlled	100 gal/day	4,308	7,926	73,548	90%
Controlled	250 gal/day	4,308	7,462	74,012	91%
Controlled	500 gal/day	4,308	6,903	74,571	92%

In addition to the full-sized 4,308-gallon storage scenario, the research team ran several models with reduced tank size (Table 4-2). Assuming 100 gallons per day approximates average use of harvested rainwater at Engine House 3, a 718-gallon DRTC tank achieves roughly the same reduction of wet weather flow (35%) as a 4,308-gallon conventional tank (31%). This shows that DRTC rainwater harvesting systems can achieve the same performance as conventional rainwater harvesting systems when built 1/6th (17%) of the size. This means that the same stormwater credits can be received for significantly less capital cost.

Table 4-2. Modeled Performance of Reduced Size DRTC Rainwater Tanks.

Condition		Storage Volume	Wet-Weather Flow	Reduction in Wet-Weather Flow	Reduction of Wet-Weather Flow
		(Gallons)	(Gallons/Year)	(Gallons/Year)	(Percent)
Controlled	No Demand	479	62,328	19,146	23%
Controlled	No Demand	718	54,474	27,000	33%
Controlled	100 gal	718	53,148	28,327	35%

4.3 DRTC Costs – Infrastructure Costs and Specifications in a Mature Market

Once the technology is fully mature in the marketplace, the research team estimates the cost of retrofitting a single existing rainwater harvesting system with real-time controls and monitoring is about $15,000. This cost includes the setup of supporting information systems including ingestion, processing, and delivery of real-time data streams via a cloud-based web platform. For a breakdown of estimated costs see Table 4-3. Note that this cost is significantly reduced when scaled; the install of 20 or more of these units costs about $6,100 each. In addition to this upfront cost, the team estimates an at-scale cost of about $15/month for operation of the information systems per installed device. The cost of retrofitting existing green infrastructure with real-time monitoring and controls is significantly less than the initial cost of conventional green infrastructure design and install, and these retrofits markedly increase the performance of the system to justify the marginal cost.

Table 4-3. Estimated Marginal Costs for RTC of Green Infrastructure in New Construction At-Scale. (4,000-gallon tank).

Item	Quantity	Unit	Unit Cost	Total Cost
Automatic Drain Valve	1	each	$260	$260
Internet of Things Based Controller and enclosure	1	each	$2,500	$2,500
Ultrasonic Level Sensor	1	each	$370	$370
Procurement/Construction Management/Site Specific Programming and Setup	1	each	$1,800	$1,800
Total Cost per Site (for quantity 100 or greater)				$4,930
Total Cost per Site (for single site)				$14,930

Note: estimated costs are for simple system with one actuated valve and level sensor. Additional sensors such as rain gages, temperature probes, moisture probes and custom site-specific programming is not included in these estimates.

Cistern installation costs vary with size. A typical 7,500-gallon cistern costs $45,000, while a 375,000 cubic foot cistern costs just over $1,000,000. Marginal costs per gallon diminish with tank size. The 4,308-gallon tank in the model has an estimated cost of $32,000, or $7.43 per gallon. The smaller, 718-gallon DRTC tank has a total cost of $10,000, or $13.92 per gallon.

Depending on design configuration, dynamically controlled green infrastructure has numerous benefits that include but are not limited to: protecting water quality by decreasing contributions to CSOs, increasing infiltration, conserving resources, and potentially extending the useful life of existing pipe infrastructure. As a demonstration in a CSO watershed, the researchers have included here an example cost benefit analysis for the advanced rainwater harvesting pilot and modeled system at Engine House 3 in Washington, D.C. The existing detention system is typical of other installations are around the country.

4.4 Economic Benefits – Credits and Capital Costs

To calculate the long term benefits of the system and payback periods, the research team performed a future value calculation of fees and credits based on a 12.2% rate of increase per year, the average observed annual rate of fee increases across all cities (Table 4-4). The aggregate average was chosen as a benchmark because the rate of increase in individual cities was rarely internally consistent, and several cities had no historical published data. As these fees are relatively new, they are likely to continue increasing erratically in the immediate future while cities attempt to accurately value the costs and benefits of stormwater management.

Table 4-4. Example: Engine House 3 Model System Fees and Credits in Various Jurisdictions.[1]

City	Philadelphia, PA	Montgomery County, MD	Washington, D.C.	Richmond, VA	Gwinnett County, GA	Portland, OR	Seattle, WA	Average
Conventional Cistern Cost[2]	$47,000 (4308 gal)							
Equivalent Wet Weather Performance DRTC Cistern Cost[3]	$25,000 (718 gal)							
Annual Charge/1,000 sq. ft.	$112	$37	$147	$31	$25	$132	$83	$81
Annual Fees	$1,589	$511	$1,983	$431	$342	$1,830	$1,155	$1,120
Annual Credits	$359	$73	$469	$62	$10	$63	$78	$159
Reduced Fees	$1,230	$437	$1,514	$369	$332	$1,767	$1,077	$961
10-Year Total Fees @ 12.2% Increase/Year4	$28,149	$9,049	$35,136	$7,644	$6,059	$32,423	$20,462	$19,846
10-Year Total Credits @ 12.2% Increase/Year	$6,357	$1,302	$8,318	$1,100	$174	$1,110	$1,377	$2,820
20-Year Total Fees @ 12.2% Increase/Year	$117,149	$37,661	$146,229	$31,811	$25,216	$134,936	$85,160	$82,595
20-Year Total Credits @ 12.2% Increase/Year	$26,454	$5,419	$34,616	$4,577	$726	$4,621	$5,729	$11,735
Percent Savings	23%	14%	24%	14%	3%	3%	7%	13%
Conventional Payback @ 12.2% Interest (years)	25	38	22	39	55	39	37	31
DRTC Payback @ 12.2% Interest (years)	20	33	17	34	50	34	32	26
Credits Received between DRTC and Conventional Payoffs	$20,603	$19,614	$20,756	$19,504	$18,284	$19,510	$19,650	$20,110
30-Year Conventional Cistern Lifetime Total Return on Investment	$42,998	-$28,565	$70,767	-$31,428	-$44,531	-$31,278	-$27,509	-$7,078
30-Year DRTC Cistern Lifetime Total Return on Investment	$64,998	-$6,565	$92,767	-$9,428	-$22,531	-$9,278	-$5,509	$14,922

[1] Assumes wet weather performance in subject jurisdiction is similar to Washington, D.C. system.
[2] Cistern costs based on Geosyntec BMP cost curves.
[3] Wet weather performance measured as percent reduction in wet weather runoff in storm evens over the course of the entire modeling period.
[4] 12.2% is the average rate of increase in stormwater fees and credits across all studied jurisdictions 2006-2015.

The annual stormwater fee for the Engine House 3 model ranged from $342 in Gwinnett County to $1983 in Washington, D.C., with an average of $1120 among all seven sites. Credits ranged from $9.84 in Gwinnett County to $470 in Washington, D.C., with an average of $159. In 10 years, the total savings jumped between $174 in Gwinnett County and $8,318 in Washington with an across the board average of $2820, and after 20 years the savings ranged from $726 to $34,616 with an average of $11,735. This amounted to an average to an average savings of 12.6% of the stormwater bill.

However, these savings do not justify the capital costs of green stormwater infrastructure to most consumers. As detailed above, the total estimated cost of the model system in a mature market is $47,000, while the cost of the smaller DRTC system is $25,000. Payback periods for a conventional cistern ranged from 22 years to 55 years, while payback periods for the DRTC cistern ranged from 18 years to 50 years, about five years shorter. As the system is estimated to last 30 years, only three cities, Philadelphia, Washington, and Seattle have payback periods shorter than the expected lifespan of the system.

The difference in capital costs between a conventional cistern and a smaller DT RC cistern with comparable performance provides the most compelling justification for an owner considering green infrastructure to choose DRTC systems. In the case of the model site, the upfront cost of a conventional cistern was $47,000. The cost of a DRTC cistern sized to achieve the same performance as the conventional cistern under the 100-gallon per day reliable demand scenario cost $25,000, for a total up-front savings of $22,000. This is particularly persuasive in regions that mandate stormwater BMPs, but do not provide any credits based on performance. In these scenarios, savings on upfront costs represent the total economic benefit of the DRTC systems.

In situations where existing stormwater BMPs are unable to mitigate stormwater runoff for an entire site, retrofitting existing infrastructure with DRTC technology can increase the capacity of the cistern to reduce wet weather flow, allowing landowners to increase their credits for a small marginal cost, as they will not have to buy a cistern.

4.5 Summary of Actual Fees and Credits for Pilot Projects

Table 4-5 summarizes all pilot sites, data available to date, and any stormwater fees and potential credits. Note that the majority of pilot sites are located within municipalities that do not have stormwater fee systems or associated credits for green stormwater infrastructure.

Table 4-5. Actual Potential Pilot Site Summary Fees and Credits.

Project Location	Collaborator	Project Type	Annual Stormwater Fees	Annual Potential Stormwater Credits
New Bern, NC	North Carolina State University	Advanced Rainwater Harvesting	$89	N/A
Washington, D.C.	District Department of the Environment	Advanced Rainwater Harvesting	$1983	$469
Newtown Square, PA	SAP, Inc.	Green Roof	N/A	N/A
St. Louis, MO	McCormack Baron Salazar	Advanced Rainwater Harvesting	N/A	N/A
Denver, CO	Urban Drainage and Flood Control District	Advanced Rainwater Harvesting	N/A	N/A
Seattle, WA	Seattle University	Advanced Rainwater Harvesting	$7079	$793
Austin, TX	City of Austin, TX	Advanced Rainwater Harvesting	N/A	N/A
Omaha, NE	City of Omaha, NE	Permeable Pavement	N/A	N/A
Gwinnett County, GA	Gwinnett County, GA	Advanced Rainwater Harvesting and Underdrain Bioretention	$30,996	$62

Note: N/A indicates that the governing municipality has no stormwater fees or credits for green infrastructure.

4.6 Municipal Benefits

It should be noted that none of the 19 cities researched provide stormwater fee credits based on performance of green infrastructure. Instead, the credit systems are solely based on impervious area treated by the installed BMP. As described in the modeling in this Chapter, adding real-time controls to existing green infrastructure significantly improves performance. In the case of advanced rainwater harvesting, addition of RTC can reduce wet-weather contributions to the combined-sewer by 92%, compared to 0-84% for a conventional cistern. Because of this, the researchers believe that current stormwater fees and credits significantly undervalue the potential benefits of DRTC technologies or do not take into account the increases in performance that can be obtained. DRTC green infrastructure can, however, offer significant benefits to municipalities.

Many cities seek to increase stormwater management capacity by expanding gray or green infrastructure. This is especially important to cities with combined sewers, where increasing the extent of infrastructure can greatly reduce the frequency of CSO events and associated environmental and remediation costs. New York, Kansas City, Portland, Seattle, and Cleveland have all studied the costs of expanding infrastructure in terms of dollars per gallon treated each year.

As a point of comparison, the model demonstrates that adding controls to the Washington, D.C. site prevents 73,548 gallons of overflow per year at a cost of $14,930. This represents a cost of $0.20 per gallon.

Table 4-6 demonstrates the consistently high value all municipalities place on stormwater infrastructure and CSO prevention. Adding RTC retrofits to existing infrastructure has potential to save cities significant amounts of money compared to infrastructure expansion.

Table 4-6. Cost Estimates for Infrastructure Expansion.

	Gray Infrastructure Expansion Cost Estimate ($/gal)	Green Infrastructure Expansion Cost Estimate ($/gal)
New York, NY	$1.75	$1.60
Chelsea, MA	$2.50 - $8.10	$12.15 - $40.50
Kansas City, MO	–	$2.26 - $26.83
Portland, OR	$11.58 - $41.72	$7.45 - $40.40
Seattle, WA	$12 - $40	$3 - $22
Cleveland, OH	$2.92	$1.51
Retrofitting existing infrastructure with RTC technologies	–	$0.20

All of the cities represented in this chart were considering different combinations of infrastructure strategies, accounting for some of the difference in cost estimates. Costs to improve green infrastructure ranged from $1.51/gallon to $40.50/gallon, while gray infrastructure upgrades ranged from $1.75/gallon to $41.72/gallon. A dynamically controlled green infrastructure system costs one or more orders of magnitude less than all alternatives, presenting a tremendous opportunity for municipalities to maximize infrastructure usability at a small marginal cost by deploying smart controls to existing public or private infrastructure. The benefits could be equal to increasing the physical capacity of infrastructure at a much lower cost.

4.7 Discussion of Additional DRTC Benefits

In addition to economic benefits, real-time monitoring offers several performance benefits when compared to conventional cisterns. In a conventional cistern, leaks can easily go undetected, with owners receiving stormwater credits for a poorly functioning BMP. DRTC allows for continuous monitoring of the system online, making leak detection simple and ensuring that infrastructure continues to perform at a high level. Constant monitoring and internet connection also means that systems can be updated and optimized with improved logic to maximize benefits in the long term and adapt to changing goals.

Additionally, several cities offer financing options and credits for stormwater BMPs. Louisville, Kentucky's Capital Recovery Stipend program rebates individuals who install stormwater BMPs based on an indexed value of individual BMPs to the city per treated square foot, up to 75% of the total cost of the project (Louisville Metropolitan Sewer District). Philadelphia offers tax credits of 25% of the cost of installing green roofs, up to $100,000. Seattle will pay up to 100% of residential stormwater BMP installations, with an average rebate of $4,000.

4.8 Stormwater Policy Trends and Potential Improvements

While Gwinnett County imposed stormwater fees beginning in 2006, all of the other study municipalities have implemented their fee programs within the last two years and continue to make adjustments. Washington, D.C. has set up a credit system which has just recently gone into effect. More importantly, equitable stormwater billing appears to be an emerging trend with increased participation across the county, with legislation being debated in such cities as Los Angeles and Charlottesville, demonstrating rapidly growing opportunities for RTC systems.

Importantly, Washington, D.C. and Philadelphia are considered two of the most progressive cities for stormwater management in the country, and other cities looking to establish stormwater fees and credits will likely consider these cities as models for their program. Washington, D.C., the physical site of the model, provides the greatest economic benefit of installing DTRC systems.

Philadelphia's "Green City, Clean Waters" program was passed as a comprehensive 25-year stormwater management program in 2011, and has received extensive press from national media outlets, including *Bloomberg* and *The Washington Post*, and more importantly is frequently mentioned in stormwater management plans in municipalities throughout the country. The city's long-term goal is to green 9,564 acres of land. In 2016 the first progress report will be released. If successful, other cities will be further persuaded to adopt similar programs. Portland, another city in the case study list, in part modeled its program after Philadelphia (U.S. EPA), as did Chelsea, MA. As the economic benefit of installing DRTC in Philadelphia ranked second highest among test sites, this further indicates the increasing profitability of stormwater BMPs in the future.

While the increasing creation of stormwater utilities helps to remediate infrastructure shortcomings and provides opportunities for RTC installations, current policies have several shortcomings which limit their effectiveness. While some cities studied require landowners to apply for credits on an annual basis and submit new instructions, others have a renewal period of up to 10 years or none at all, allowing landowners to continue receiving credits as systems degrade or leak. DRTC allows for constant monitoring, detecting leaks or other issues affecting performance and allowing cities to accurately measure the contributions of the BMP to reducing stormwater on a continuous basis. As these regulations are revised to incentivize on site stormwater management, RTC systems will likely become successfully in additional markets purely driven my market forces.

None of the existing credit systems measure performance, and only require construction of an approved BMP with the capacity to treat a certain impervious area. This means that built systems that underperform, break down, or are not used at all receive the same credits as higher performing BMPs. In cases where high-performing BMPs cost more, these credit structures incentivize owners to build low performing, low cost green infrastructure that may not significantly contribute to a municipality's stated goal of reducing runoff.

To most owners evaluating the financial benefits and payback period of installing green infrastructure, the credits will not provide enough return to justify the cost. More importantly, as cities provide no additional credit for retrofitting existing systems to become higher performing with DRTC, the credit systems alone cannot justify the capital costs because there is no marginal benefit of installing the system. Under these conditions, DRTC systems are mostly valuable in new construction, by reducing the tank or BMP sizing needed to perform to a set standard. By undervaluing the benefits associated with onsite stormwater managements, cities disservice themselves by discouraging high-performance infrastructure upgrades, such as DRTC.

As cities measure stormwater remediation costs in dollars per gallon, a more accurate way for cities to value the reduction in stormwater associated with onsite infrastructure would be to directly measure the gallons of runoff prevented. This would incentivize owners to choose high-performing systems, and later to maintain and utilize them to directly maximize the credits received. In this scenario, DRTC would not only maximize performance for the end user, but the internet monitoring would allow the city to accurately measure and value the reduction in stormwater overflow, relying on real performance instead of pre-construction estimates. If the fee structure were changed to value BMP performance, the cities would be better able to incentivize reductions in volume which directly reduce their treatment costs. The measured economic value of a DRTC system would increase for both the city and individual landowners, resulting in more demand for onsite green infrastructure upgrades.

DRTC green infrastructure provides clear economic and performance benefits for landowners and municipalities. Fee and credit systems across the United States vary widely, and continue to expand. To property owners, the cost of fees and extent of credits available will play the largest role in determining whether DRTC retrofits are economically viable. As current fee structures undervalue the benefit of green infrastructure by measuring impervious area served and not gallons of runoff reduced, revisions that allow credits to reflect the true economic benefit of DRTC installs will further incentivize implementation.

The addition of real-time controls means that a smaller DRTC cistern can serve the same sized site as a conventional cistern, minimizing upfront construction costs. The research team also estimates a reduction in the upfront cost of DRTC systems as more units are produced and installations can be bundled.

Theoretical results show a dynamically controlled cistern can reduce up to 92% of releases to the combined sewer. Preliminary pilot site results show that a dynamically controlled cistern can reduce about 71% of releases to the combined sewer and the team anticipates much higher efficiencies when forecast logic is optimized. These preliminary results indicate dynamically controlled green infrastructure can reduce contributions to CSOs on a significant scale. Unlike conventional green infrastructure, dynamically controlled green infrastructure can be adapted to provide effective performance in a variety of design scenarios and locations. In addition to reductions of CSOs, DRTC technologies have added benefits such as reducing municipal water use, conserving water via optimized irrigation, providing increased infiltration of stormwater, and mitigating flooding.

CHAPTER 5.0

CONCLUSIONS

The application of conventional real-time and dynamic control and feedback systems is commonplace in industrial settings: water supply and treatment, wastewater treatment and conveyance, and CSS management. However, the use of onsite dynamic control systems in sustainable stormwater management has been quite limited.

The application of real-time controls to green stormwater infrastructure is attractive because it combines the known benefits of green infrastructure such as rainwater reuse, increased infiltration, dampening of peak flows, and water quality benefits with the benefits of advanced decision making, automated controls, and real-time monitoring, thus optimizing the known advantages. In addition, dynamically controlled green infrastructure is entirely scalable and adaptable. It has also been shown under theoretical changes in precipitation patterns (e.g., climate change) that DRTC systems are less sensitive and more robust than passive approaches.

Most importantly, cities facing a high cost of expanding stormwater infrastructure with gray or green strategies can achieve the same benefits with a much lower cost by retrofitting existing systems with real-time monitoring and controls. The cost of retrofits is one or more orders of magnitude less than both the cost of infrastructure expansion and the cost of CSO treatment on a per gallon basis. This reality may influence cities to increase credits for DRTC systems, or to retrofit DRTC systems on public infrastructure. Additionally, as the upfront cost of DRTC systems goes down when multiple units are purchased, cities installing many DRTC systems will minimize costs.

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Theoretical results show a dynamically controlled cistern can reduce up to 92% of releases to the combined sewer. Preliminary pilot site results show that a dynamically controlled cistern can reduce about 71% of releases to the combined sewer and we anticipate much higher efficiencies when forecast logic is optimized. These preliminary results indicate dynamically controlled green infrastructure can reduce contributions to CSOs on a significant scale. Unlike conventional green infrastructure, dynamically controlled green infrastructure can be adapted to provide effective performance in a variety of design scenarios and locations. In addition to reductions of CSOs, DRTC technologies have added benefits such as reducing municipal water use, conserving water via optimized irrigation, providing increased infiltration of stormwater, and mitigating flooding.

APPENDIX A

MUNICIPALITY FEE AND CREDIT STRUCTURE (NON-RESIDENTIAL SITE WITH CISTERN)

City	Stormwater Fees	Stormwater Credits for Cistern
Philadelphia, PA	Fee Schedule: Monthly Gross Area Charge: $0.526/500 square feet Impervious Area Charge: $4.145/500 square feet Monthly Billing Charge: $2.53 per account	For a site not discharging to surface water without NPDES credits: IA credit of up to 80% for the portion of the first inch of rainfall managed on site. GA credit of up to 80% under the managed IA and elsewhere where applicable Minimum charge: $13 per month
Montgomery County, MD	Fee Schedule: Annual Water Quality Protection Charge (WQPC): (Impervious Area/ERU)*$88.40 Equivalent Residential Unit (ERU): 2406 square feet	(Impervious Area Treated)/ (Total Impervious Area)* (Facility Credit Percentage)*(WQPC Charge) Full site treatment max. credit: 60% Partial site treatment max. credit: 50% Cistern facility percentage: 50%
Washington, D.C.	Fee Schedule: Monthly Six-Tiered Rate Structure for Impervious Area. For over 11000 square feet: 13.5 ERU, $129.20 Equivalent Residential Unit (ERU): 1000 square feet ERU Rate: $9.57 + $2.67	(Retention Capacity)/(710.75 gal/ERU)*.55*(Fee) Maximum Credit: 55%
Richmond, VA	Fee Schedule: Annual Non-Residential rate per ERU: $45 Equivalent Residential Unit: 1450	(Percent impervious area treated)*.5*(Fee) Maximum Credit: 50%
Gwinnett County, GA	Fee Schedule: Annual Stormwater Service Fee: $2.46/100 square feet impervious area	(Percent impervious area served by cistern)*10%*Fee Cistern maximum credit: 10% Cistern must be able to store runoff from 1.2 inch storm event to qualify
Portland, OR	Fee Schedule: Monthly On Site Charge: (Impervious Area)/(1000 square feet Impervious Area)*$3.84 Off Site Charge: (Impervious Area)/(1000 square feet Impervious Area)*$7.13	(Impervious area served by cistern/1000)*34% Credit Applies of On Site Charge Only
Seattle, WA	Fee Schedule: Annual $83.08*(Property gross square feet/1000)	(Impervious area served by cistern/1000)*(Facility Credit)*(Rate Tier Multiplier)*(83.08) Facility Credit: 24% Rate Tier Multiplier: 97.41% Maximum Credit: 50%

APPENDIX B

PUBLICATIONS

A poster comparing performance and potential economic benefits of the Forrest House controlled rainwater harvesting system to a passive system was displayed at the *Water: Systems, Science and Society (WSSS)* Symposium at Tufts University on April 27, 2012. A draft manuscript assessing dynamically controlled rainwater storage robustness under climate change will be submitted to a peer-reviewed journal. The project team has presented the research as an integral or primary component of:

- American Bar Association, Environmental Section Spring Conference Technical Round Table (March 2013)
- Center for Watershed Protection, "Smart Stormwater Retrofitting in the Urban Environment" webcast (March 2013)
- Conservation Foundation, Beyond the Basics Stormwater Seminar, Keynote Address (March 2013)
- Bay-Wide Stormwater Partners Retreat, Breakout Session, (March 2012)
- Anacostia Watershed Restoration Partnership Steering Committee Meeting Presentation (March 2013)
- City of Austin Presentation and Field Demo at Twin Oaks Library (February 2013)
- Invited presentation to the Industrial Advisory Board of the National Science Foundation funded Engineering Research Center: ReNUWit – Reinventing the Nation's Urban Water Infrastructure (October 2012)
- Invited Presentation to San Francisco Public Utilities on Blue Roofs and Real-time Monitoring and Control (February 2013)
- EPA G3 Initiative Webcast - Next Generation Low Cost High-Performance Retrofit Technologies (July 2012)
- Presentation at the University of New Hampshire Dept. of Civil Engineering, 2012
- WERF Web Seminar – Research Forum 2011
- Presentation to Wright Water Engineers and Urban Drainage and Flood Control District, Denver, CO (November 2012)

Questions about this progress report should be directed to Marcus Quigley, P.E. at Geosyntec Consultants, Inc. 617-992-9065 or mquigley@geosyntec.com.

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Water Environment Services

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South Carolina
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Florida
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