Evaluating Green Infrastructure Performance Using Real-Time Control from a Risk Perspective

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ABSTRACT

As part of the National Science Foundation Partnerships for Innovation: Building Innovation Capacity grant (NSF 13-587), Villanova University has teamed with OptiRTC to design and retrofit existing green infrastructure (GI) systems at Villanova University with real-time control (RTC) technology to evaluate system performance and investigate the role of automated, self-learning controls within traditional GI design.

The performance of the GI treatment train has been monitored since 2012. The GI treatment train was retrofit with RTC in 2016. System hydrologic performance at the GI treatment train was monitored to determine volume capture performance changes with the implementation of real-time controls. Increasing the adaptive capacity of the system potentially decreases the risk of system overflow. Initial modelling comparison of the passive and RTC treatment train show a reduction in volume and frequency of overflow events for the RTC system. Future research at this site will include developing a risk-based method to assess GI practices and determining how implementing real-time control affects the risk of overflow.

Keywords:

Real-time control, green infrastructure, risk, resilience

INTRODUCTION

Many cities are implementing green infrastructure (GI) practices to sustainably capture stormwater runoff. Infiltrating GI practices, such as bioretention, vegetated swales, and infiltration trenches capture and infiltrate stormwater runoff and are used to prevent flooding (MDE 2009; PWD 2014). Infiltrating GI provides water quality benefits by filtering stormwater runoff pollutants (e.g. Nitrogen, Phosphorus), which in excess can degrade water quality (DRBC 2013). Cities such as New York, Washington DC, and Philadelphia are increasingly relying on GI to prevent untreated sewage from polluting watersheds as a result of combined sewer overflows (CSOs) during rainfall events; smaller municipalities are also turning towards GI as a stormwater management strategy. Municipalities and states provide design guidelines for sizing of these infiltrating systems, but increased rainfall volume and intensity could overwhelm these systems leading to increases in flooding, pollution, and water quality degradation. Although GI are commonly designed as static systems (e.g. only storage within the surface ponding and soil is considered in design) for small rainfall events, research has shown the potential of GI systems to capture and retain greater quantities of runoff than designed during extreme weather, increasing the adaptive capacity of a system (Horst et al. 2011; Lord et al. 2013; Lewellyn et al. 2015; Tang et al. 2015).

Real-time controls have been used in the water and wastewater industry in American and European cities to maximize capabilities of existing systems (Pleau et al. 2005; EPA 2006; Cembrano 2002; Schütze 2004). More recently, in efforts to increase performance of GI systems, RTC has been implemented as part of GI systems, including: rainwater harvesting, green roofs, wet ponds, and bioretention (Quigley et al. 2014; Reidy 2010; EPA 2013). The use of RTC with green infrastructure could result in a number of benefits. First, there is potential for RTC systems to further reduce CSOs and increase effluent water quality from GI through adaptable performance. Additionally, the implementation of RTC can offer adaptability to future climate conditions or changes in site characteristics without new infrastructure and with only operation changes.

This study focused on the potential of RTC to decrease risk of green infrastructure system overflow. Risk was defined as the number of annual overflow events per year. Acceptable risk was determined from regulations provided in the "Combined Sewer Overflow (CSO) Control Policy" set forth by the U.S. Environmental Protection Agency (Fed. Reg. 1994). Communities with CSOs are required to develop long term control plans that lead to compliance with the CSO Policy and the Clean Water Act (33 U.S.C). One of the ways to provide an adequate level of control for water quality standards is ensuring, "No more than an average of four overflow events per year occur (the permitting authority may allow up to two additional events per year)." (Fed. Reg. 1994). Therefore, four overflow events per year was used as a baseline acceptable risk.

METHODOLOGY

The GI treatment train at Villanova University was constructed in 2012 and originally captured approximately 2.5 cm (1.0 in) of runoff from a 930 sq. meter parking garage on campus (Figure 1). As part of construction to expand the parking garage (1,300 sq. meter drainage area), a 5,100-gallon cistern was added to the GI system in April 2016 to increase the static storage volume by approximately 1.5 cm (0.6 in). Table 1 shows the design capture volumes for each stormwater control measure (SCM) in the treatment train. Current operational plans at the treatment train keep the volume of water in the cistern at a level which mimics the 2.5 cm capture volume of the previous design. This allows for a comparison of capture performance between each setup. Soil storage in the system was considered negligible and was not included in volume capture totals.

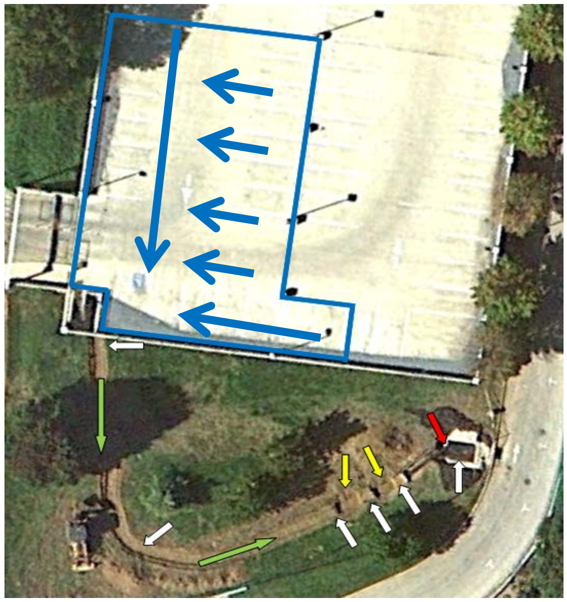

Figure 1: Original Treatment train drainage area and layout. Green arrows depict the vegetated swale, yellow arrows depict the rain gardens, the red arrow depicts the infiltration trench (IT), white arrows depict monitoring stations, and blue arrows and outlines depict approximate flow paths and drainage area boundaries, respectively.

Table 1: Design summary capture volume for the treatment train

	Rainfall Capture – Original Treatment Train	**Rainfall Capture – RTC Treatment Train**	**Estimated Volume Capture**
Vegetated Swale	0.3 in / 0.7 cm	0.2 in / 0.5 cm	240 ft^3 / 6.8 m^3
Rain Gardens	0.4 in / 1.0 cm	0.3 in / 0.7 cm	340 ft^3 / 8.7 m^3
Infiltration Trench (IT)	0.3 in / 0.8 cm	0.2 in / 0.5 cm	245 ft^3 / 7.0 m^3
Cistern	N/A	0.6 in / 1.4 cm	680 ft^3 / 19.3 m^3
Static Volume Capture	**1.0 in / 2.5 cm**	**1.3 in / 3.3 cm**	**1,505 ft^3 / 41.8m^3**

Control logic was developed as part of the initial RTC install using OptiRTC. During rain events, rainfall runoff flows into the treatment train from the parking garage. Runoff from rain events large enough to produce ponding in the second rain garden will be conveyed to the underground cistern. Runoff will overflow from the cistern to the infiltration trench if capacity is reached during a storm event.

The National Weather Service forecast is continuously monitored using OptiRTC. For the treatment train, no actions are performed if there is forecasted rainfall. If there is no rainfall in the forecast, water is pumped from the cistern to the beginning of the treatment train after a period of 12 hours since rain ended. The 12 hour period was chosen to allow for infiltration in the treatment train prior to pumping. Pumping continues until a target volume in the cistern is reached. This operational plan is intended to utilize infiltration capacity of the system and decrease maintenance on the infiltration trench. Algorithms used for the initial operation plans will be adjusted based on system performance.

Sensors are used throughout the treatment train to monitor performance and allow for control of the site. Sensors, including pressure transducers, soil moisture meters are used to monitor and record hydrologic performance at the treatment train. When originally installed in 2016, the site featured 22 sensors and a pump for performance monitoring and control (Figure 2). The only sensor required to operate the site using OptiRTC is the pressure transducer in the cistern. Flow meters and several soil moisture meters were removed from the system in 2017 due to operational issues. The treatment train currently operates using 13 sensors as opposed to the 22 originally installed.

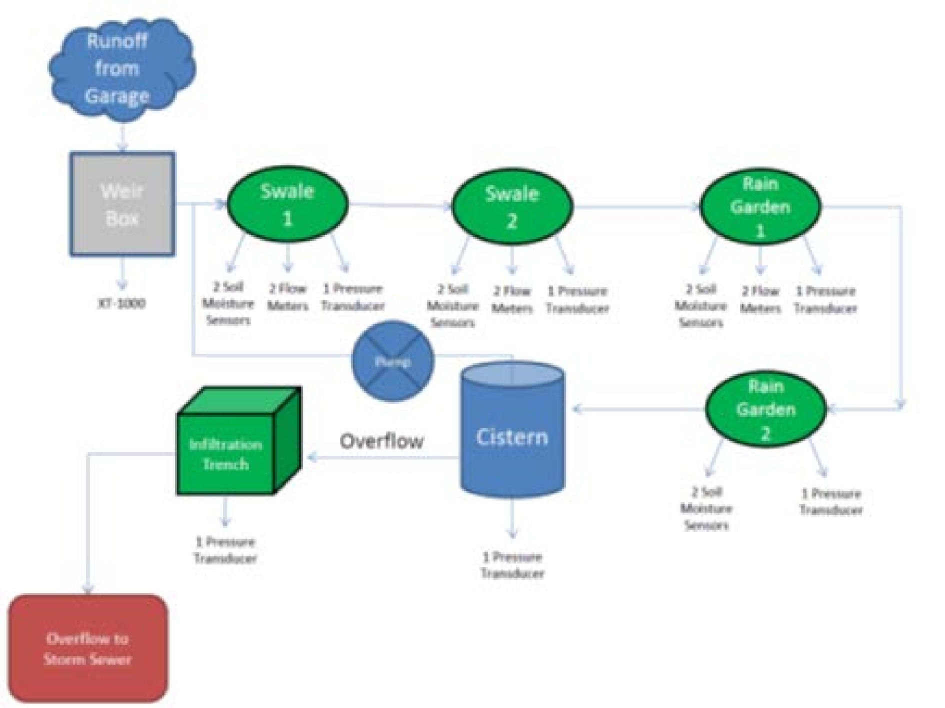

Figure 2: A schematic of the treatment train in 2016 with sensor locations.

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The results of passive and RTC performance between 2013 and 2016 at the treatment train was used along with hydrologic modeling to develop a hydrologic model of each site to compare hydrologic performance over time.

RESULTS AND DISCUSSION

The original treatment train was modeled using the EPA Stormwater Management Model (SWMM). The EPA SWMM model was used because if it's ability to model several different GI practices at once, which was necessary for the treatment train model. Model results were calibrated based on recorded water levels in the infiltration trench during rainfall events during the initial 2013-2015 study period. These calibration events were selected based on the occurrence of overflow and the month in which the rainfall occurred. A previous study (Lewellyn et al. 2015) at the treatment train found that increases and decreases in temperature had a significant impact on infiltration rates. Therefore, monthly infiltration rate multiplicative factors were used to adjust infiltration rates on a monthly basis.

The treatment train with RTC was also modeled using EPA SWMM and rainfall from the 2013-2015 study period of the original treatment train. The RTC model was calibrated using rainfall events between July and December of 2016. Results from the RTC model of the treatment train were compared to the performance of the original treatment train (Table 2).

Table 2: A comparison of modeled performance of the original passive treatment train and the treatment train with RTC for the initial 2013-2015 study period.

Model	Number of Rainfall Events Analyzed	Average Annual Rainfall (cm)	Number of Overflow Events	Total Overflow Volume (cm)	Average Number of Overflow Events per Year	Normalized Total Overflow Volume (cm/event)
Original Treatment Train	201	119.7	20	22	8.3	1.1
RTC Treatment Train	201	119.7	13	14	5.4	1.1

Overall, the treatment train with RTC reduced the number of overflow events and the total overflow volume from the drainage area. The total volume of overflow is reduced by approximately 33% for the study period and the average number of overflow events per year decreases by approximately 2.9. Overflow events in 2013 were reduced from 13 to seven with the RTC treatment train. While both systems are greater than the acceptable risk of four overflow events per year, the RTC system shows the potential for preventing overflow events.

The June 6, 2013 and June 10, 2013 rain events illustrate the difference in performance between the passive and the RTC treatment train models. The June 10, 2013 rain event had a volume of 6.7 cm (2.6 in) and was within 48 hours of a 11.0 cm (4.3 in) rain event that began on June 6,

2013. Figure 4 illustrates the difference in performance between the modeled passive treatment train and the treatment train with RTC.

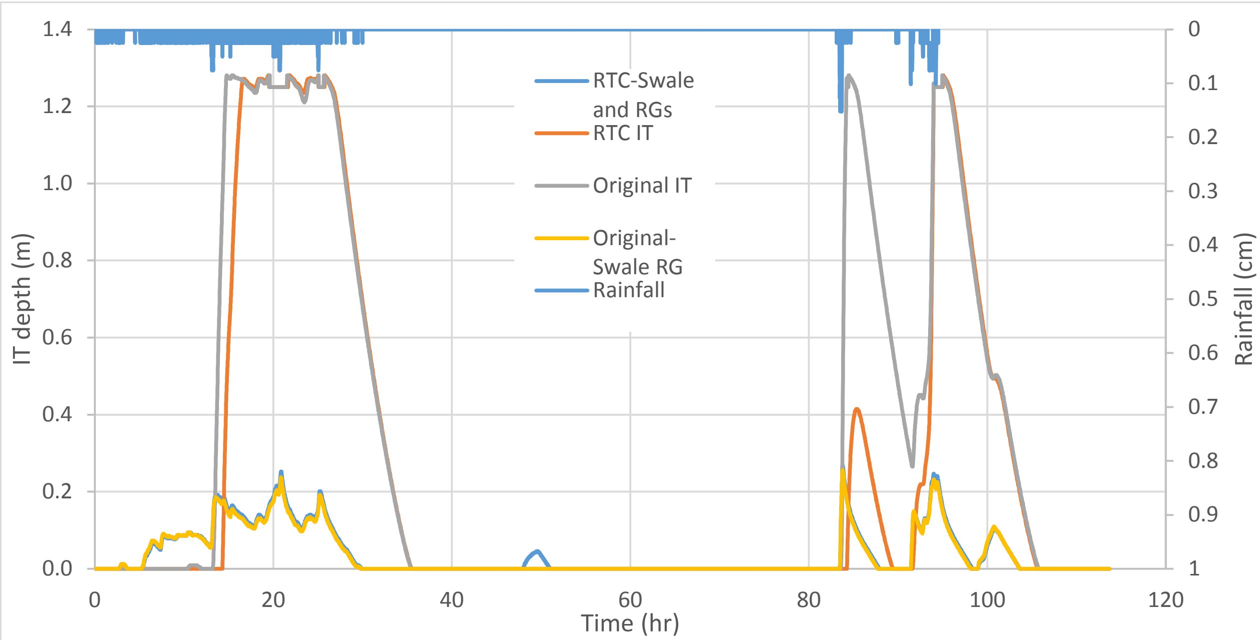

Figure 4: A comparison of passive and RTC treatment train performance for rain events occurring between June 6 (6:30 PM = time 0 hr) and June 10, 2013 (6:30 PM = 96 hr).

Performance for the June 6, 2013 rain event is similar between the passive design and the RTC design. There is a delay in runoff reaching the IT for the RTC design when compared to original design. This can be seen in the IT depth at approximately hour 15 for the June 6, 2013 event. The delay in the IT filling is due to runoff being stored in the cistern prior to entering the IT. The original treatment train has approximately 16.4 m^3 available for storage prior to the IT while the RTC treatment train has approximately 26.6 m^3 available. Following the June 6, 2013 event, water levels in the swale, rain gardens, and IT begin to recede due to infiltration. Approximately 12 hours following the end of the rain event, water is pumped from the cistern to the RTC swale. This is seen in Figure 4 at approximately hour 50 when then depth in the RTC swale and rain gardens increases. The cistern now has capacity to hold additional runoff for the next rain event. When runoff begins from the rain event on June 10, 2013, the additional system capacity is apparent when comparing the depth in the IT at approximately hour 85. The original passive treatment train design overflows while the RTC design reaches a depth of approximately 0.4 meters in the IT. The RTC system performs similar to the passive system once the cistern reaches capacity, as seen by the performance of the IT from hour 15 to hour 35 of the June 6, 2013 event, and hour 95 to the end of the June 10, 2013 event.

SUMMARY AND CONCLUSION

The performance of the passive treatment train and the RTC treatment train were compared as part of this study. Initial performance and modeling show the potential for RTC systems to reduce risk of overflow and increase resiliency. The RTC control treatment train provided an approximate 33% reduction in overflow volume and reduced the annual overflow events by approximately three per year during the same period. The adaptive and absorptive capacity of a bioinfiltration system can be increased through incorporating proper logic and control in RTC designs. Monitoring of the RTC treatment train performance will continue under this proposed work. The logic implemented at the treatment train will continue to be developed to further increase the adaptive and absorptive capacity of the system.

System performance will be used to further calibrate the initial RTC SWMM model to ensure accuracy. The passive and RTC treatment train models will modeled using a 30-year record of historical climate data to provide a long-term simulation to develop a baseline for risk. Further, climate projections will be used to evaluate performance of both the passive and RTC treatment train and determine potential increases in risk to each system. The results of the climate change modeling will be used to inform future passive and RTC GI designs with the goal of decreasing risk of overflow through increasing resiliency of systems.

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