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Article

Performance of Two Advanced Rainwater Harvesting Systems in Washington DC

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Abstract: Combined sewer overflows (CSOs) are a concern for many cities managing stormwater through combined sewer systems, including the District of Columbia (DC). Advanced rainwater harvesting (ARH) is an innovative approach to managing stormwater and has the potential to minimize CSOs and maximize water conservation. ARH systems use continuous monitoring and adaptive control (CMAC) technology to store or release water from a rainwater harvesting cistern. This study assessed the efficacy of ARH systems to mitigate wet weather discharges at two firehouses in DC. Continuous monitoring data was collected over a period of three years for the systems that were installed in 2012. The collected data indicates that the systems were effective at mitigating wet weather discharges, with average event harvesting rates greater than 95%. These results suggest that if implemented on a larger scale, ARH systems would be a valuable tool in effectively managing stormwater.

Keywords: rainwater harvesting; water conservation; runoff control; green infrastructure; low impact development; adaptive control

1. Introduction

The District of Columbia (DC) conveys stormwater through two types of systems: a combined sewer system (CSS) and a municipal separate storm sewer system (MS4). One-third of DC is part of the CSS, and the remaining two-thirds are in the MS4. In a CSS, domestic sewage and stormwater runoff from rooftops, roadways, sidewalks, and other impervious and pervious surfaces is collected into one pipe. Under normal conditions, this combined stormwater and sewage is transported to a wastewater treatment plant for treatment before it is discharged to a water body. The volume of wastewater can sometimes exceed the capacity of the CSS or treatment plant (e.g., during heavy rainfall events or snowmelt). When this occurs, untreated stormwater and wastewater, discharges directly to nearby streams, rivers, and other water bodies as a combined sewer overflow (CSO). CSO is a water pollution priority concern for the nearly 860 municipalities across the U.S. that have CSSs [1].

In an MS4, stormwater runoff is collected separately from sewage and discharges through the storm drain system, directly to the receiving water body without treatment. Stormwater runoff can carry elevated pollutant loads, including total suspended solids, nutrients, metals, and bacteria, to receiving waters that can cause or contribute to water quality degradation. Population growth and the development of urban and urbanized areas are major contributors to the amount of pollutants in the runoff as well as the volume and rate of runoff from impervious surfaces. Together, they can cause changes in hydrology and water quality that result in habitat modification and loss, increased flooding, decreased aquatic biological diversity, and increased sedimentation and erosion of receiving streams and rivers [2].

State and local governments as well as private enterprises have made significant investments in stormwater Best Management Practices (BMPs) for CSO control, flood attenuation and water quality treatment. As regulations become more stringent due to changes in permit requirements, including the National Pollutant Discharge Elimination System (NPDES), and Total Maximum Daily Load (TMDL) requirements and numeric nutrient criteria, investment in enhancing stormwater BMPs will be needed to meet future flow control and pollutant reduction requirements. Despite these more stringent water quality regulations, many State and local governments continue to experience budget cuts that limit their ability to invest in stormwater BMPs. As a result, innovative approaches are needed to optimize the effectiveness of BMPs in both retrofit and new construction scenarios to provide the maximum cost benefit.

Both traditional BMPs (e.g., detention systems, wet ponds) and green infrastructure or low impact development (LID) systems (e.g., rain gardens, porous pavement) have almost entirely been designed as passive systems governed by a fixed control structure designed to achieve a target water quality and/or quantity objective (i.e., treatment volume, attenuation). Passive systems however, rarely represent optimal solutions. For example, a typical wet detention pond detains then discharges a fixed amount of runoff downstream through a static control structure regardless of storage volume remaining within the pond at any given time. Runoff that could be retained during inter-event periods to increase residence time (for treatment) or used as a resource for irrigation (harvesting), is discharged. As a result, the full pollutant load reduction and stormwater harvesting potential of the capital investment in on-site storage is not fully realized.

Recent advances in information technology infrastructure, hardware systems, and software are providing a foundation for a future of digitally connected and dynamically controlled stormwater BMPs. Due to the advances in low cost, internet accessible controller systems and wired and wireless communications, real-time and dynamic controls of BMPs are now viable, cost-effective options for new construction as well as retrofits. These technologies allow these BMPs to be monitored and controlled in real time via the internet.

In March 2012, advanced rainwater harvesting systems (ARHs) were installed at two DC firehouses to pilot the technology and assess the efficacy of the systems to mitigate wet weather flow. The ARH system is designed to minimize or eliminate stormwater runoff discharges during wet weather and maximize potable water conservation. ARH systems use continuous monitoring and adaptive control (CMAC) technology to store or release water from a rainwater harvesting cistern [3]. The CMAC system collects water level measurements from on-site sensors installed in the cisterns and weather forecast information from the National Oceanic and Atmospheric Administration (NOAA) to trigger actions (e.g., opening or closing a valve) based on programmed logic commands. In anticipation of a forecasted precipitation event, the system determines whether to drain the cistern (typically via an automated valve) during the dry weather prior to the forecasted precipitation to restore the cistern's storage capacity to capture runoff during the forecasted wet weather event. Implementation of these systems has the potential to reduce CSOs and wet weather peak runoff rate and associated urban flooding (which is important for systems in both the CSS and MS4) by reducing or eliminating the wet weather runoff from the site.

The goal of the study was to demonstrate an innovative technology with a high potential for reducing the quantity and altering the timing of stormwater runoff, while also providing significant water conservation benefits.

2. Materials and Methods

The two sites that received the ARH systems were DC Fire Department (D.C.F.D.) Engine House 3, located at 439 New Jersey Avenue NW, and D.C.F.D. Engine House 25, located at 3203 Martin Luther King Jr. Avenue SE. Engine House 3 is in the CSS portion of DC, and Engine House 25 is in the MS4 portion. Figure 1 includes a study area map showing the two site locations.

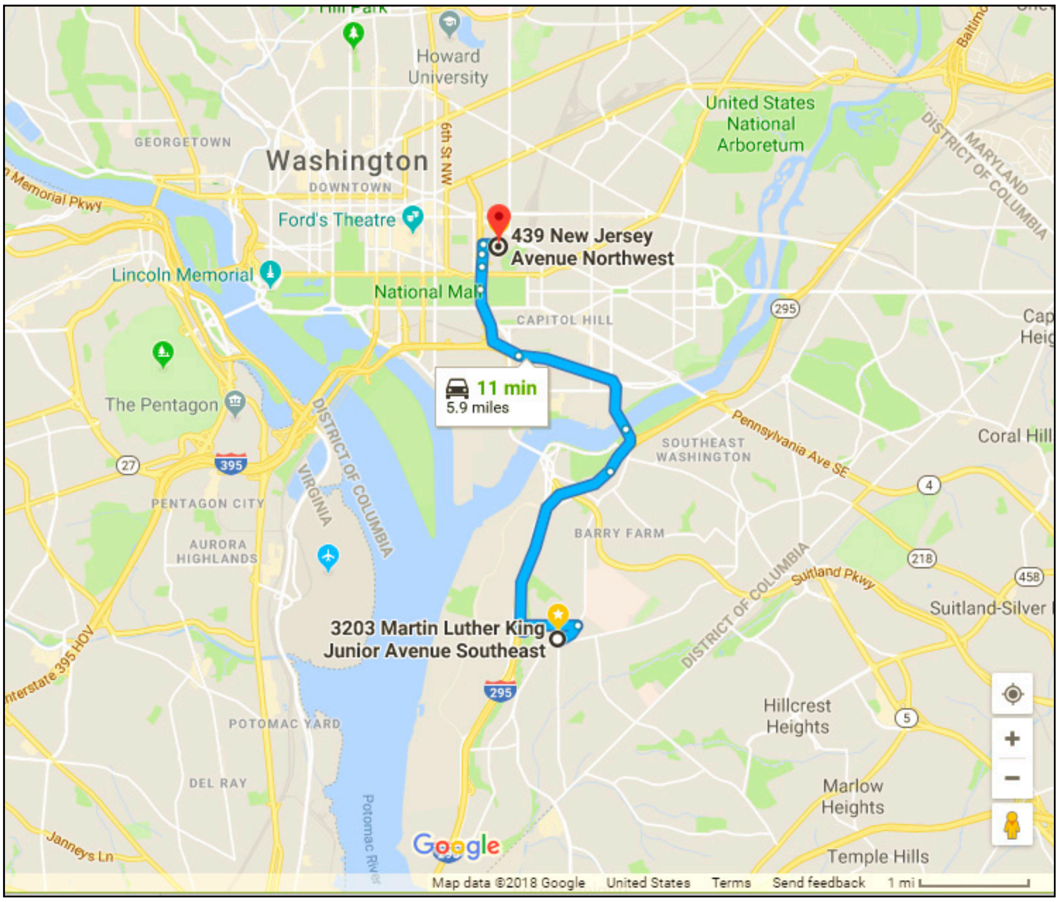

Figure 1. Study Area Map (Image from Google Maps 2018).

Stormwater runoff from the roof area at Engine House 3 (approximately 270 m^2 (2900 ft^2)) was redirected via a new roof drain system into an aboveground cistern. The cistern is made up of two precast concrete cubes (named "green tanks" after their vegetated green roof) with a storage capacity of 7485 L (1975 gal.) in each cube. The two precast concrete cubes that make up the cistern are connected by internal piping to create a combined unit with a total storage volume capacity of 14,970 L (3950 gal.). Water is stored in the cistern for reuse by firehouse staff for refilling onboard fire engine water tanks and vehicle cleaning.

Stormwater runoff from the roof of Engine House 25 (approximately 112 m^2 (1200 ft^2)) was also redirected into an aboveground green tank cistern of the same combined storage capacity as Engine House 3 (14,970 L (3950 gal.)) and stored for on-site reuse. In addition to the roof area at Engine House 25, runoff from the entire parking area (approximately 455 m^2 (4900 ft^2)) was routed through two stone filter box systems and subsequently pumped to the cistern for reuse. Figure 2 provides a rendering of the cistern system installed at the study sites.

The systems installed at Engine House 3 and Engine House 25 collect runoff from the engine house rooftops (Engine House 25 also collects runoff from the pavement) and conveys that runoff to the cistern. The cisterns at Engine House 3 and Engine House 25 were sized to capture the 5.6 cm (2.2 in) and 2.5 cm (1.0 in) precipitation event from the contributing impervious drainage area for the sites, respectively, and were designed to fit into a typical parking space with outside dimensions of 2.1 m by 4.2 m (7 ft by 14 ft). The runoff is stored in the cistern until it is discharged for reuse or it is discharged to the CSS (Engine House 3) or MS4 (Engine House 25) by the ARH system logic using the CMAC technology provided by OptiRTC, Inc. (Opti, Boston, MA, USA; www.optirtc.com).

When the water from the cistern is needed, the stored water is run through two consecutive bag filters (the first with a micron rating of 50 and the second with a micron rating of 5) to remove suspended particles from the water and then through an ultraviolet (UV) disinfection system to remove bacteria, before being used. Figures 3 and 4 provide the system configuration for Engine House 3 and Engine House 25, respectively.

Figure 2. Cistern rendering showing concrete green tank structure with vegetated roof, planter with green screen and overflow pipe.

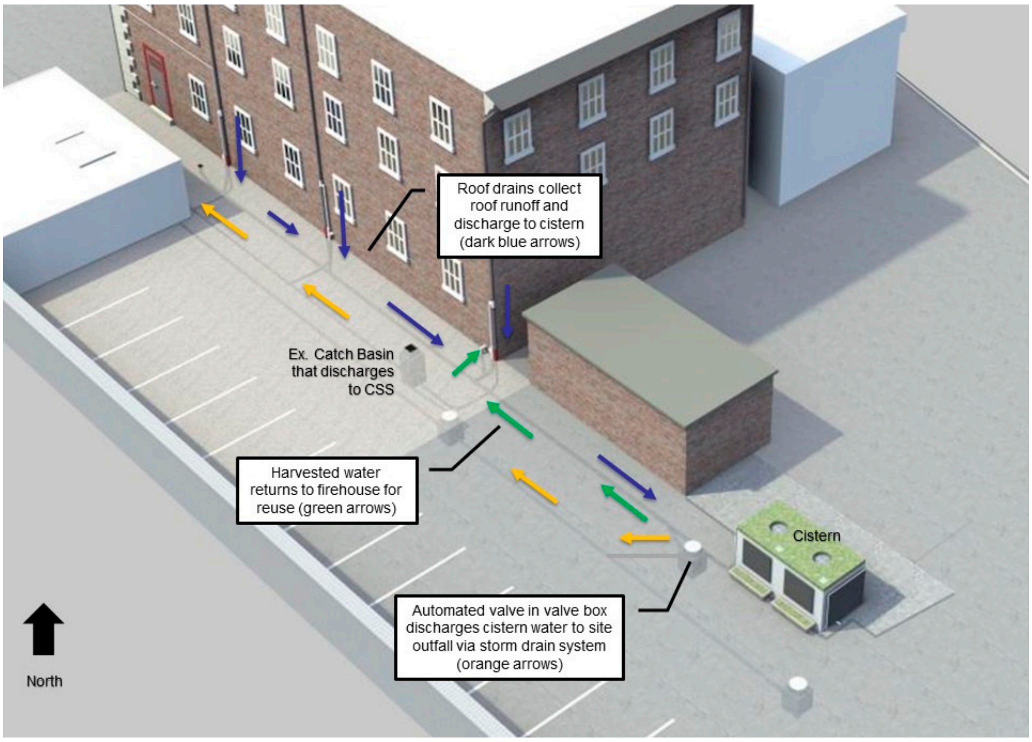

Figure 3. System configuration for Engine House 3.

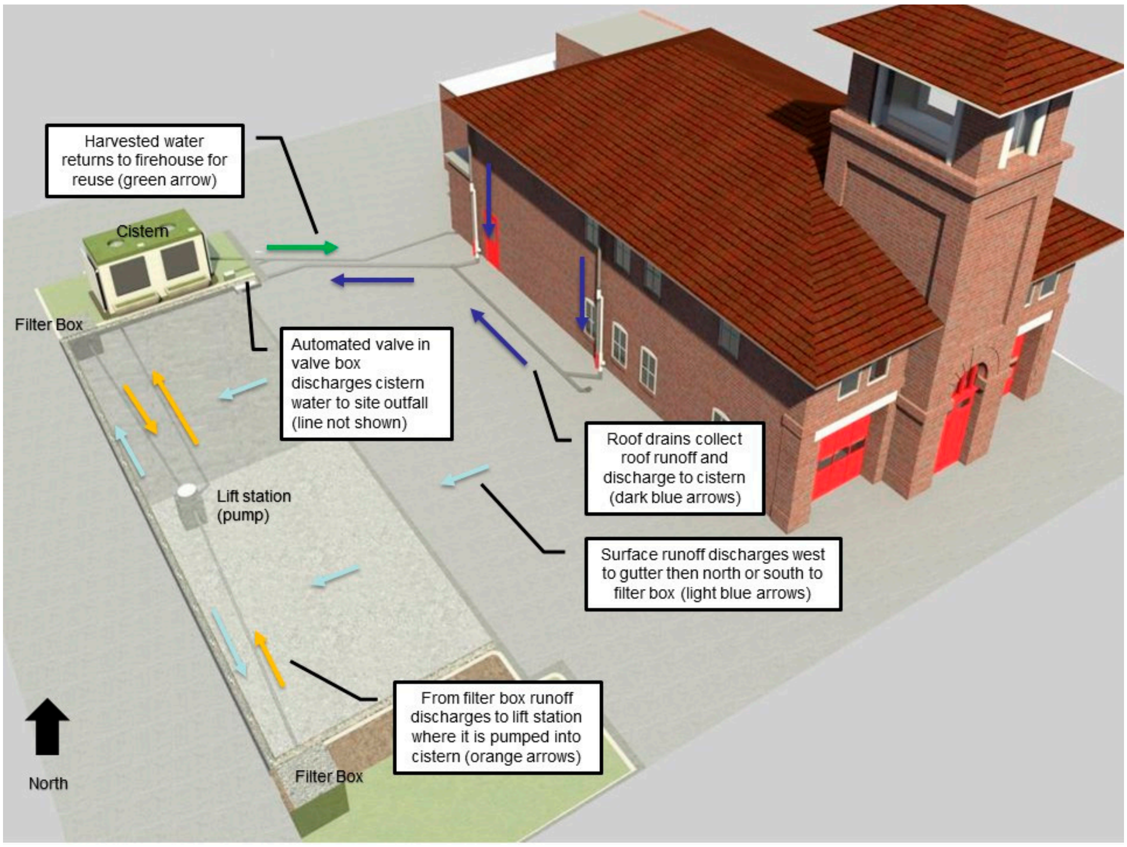

Figure 4. System configuration for Engine House 25.

The CMAC technology determines when to release water from the cisterns by evaluating if the available space in the cistern is sufficient to hold the runoff expected from the forecasted rainfall event. The CMAC technology makes this determination by following a few simple steps.

1. The system continuously monitors water level in the cistern and converts water level to volume using the internal dimensions of the cistern. Therefore, the system is always aware of how full the cistern is and how much additional capacity is available in the cistern.
2. The system continuously monitors the NOAA weather forecast and calculates the runoff expected from the forecasted rainfall by multiplying the rainfall event depth by the area draining to the cistern, times the pavement or roof runoff coefficient (the system uses a runoff coefficient of 0.95 for roofs and 0.90 for pavement).
3. Prior to the forecasted rainfall event, the system determines if the volume of expected runoff is greater that the available storage volume in the cistern.
4. If the expected runoff volume exceeds the available storage volume in the cistern, the system will send a command to the automated valve on the cistern discharge line to open and allow water in the cistern to discharge prior to the forecasted rain event (during dry weather). Opening the automated valve allows water from the cistern to discharge through the site's storm drain system to the site outfall and to the off-site CSS or MS4 system, thus providing additional storage capacity in the cistern for the forecasted rainfall event.
5. If the expected runoff volume is less than the available storage volume in the cistern, the system will take no action (i.e., the valve on the cistern discharge line will remain closed). In this case, the system has made the decision that no action is needed to fully capture the forecasted rainfall event.

The goal of the ARH system is for the cistern to be full at the end of each rainfall event without having to discharge any water from the cistern during wet weather. Since weather forecast predictions are not 100% accurate, there is a potential for the cistern to not fill completely during a rainfall event (actual rainfall was less than predicted) or to overflow during a rainfall event (actual rainfall was greater than predicted). Overflow from the cistern occurs when the water in the cistern reaches a certain depth. Once that depth is reached, water begins to discharge through an overflow pipe. Overflow can be mitigated by programming the system to be more conservative (i.e., not try to fill up the cistern completely during an event); however, having the cisterns at or close to full maximizes the water available for reuse and the potential potable water savings for the site.

Our study focuses on the benefits of modified stormwater runoff timing provided by temporary storage. We evaluated the performance of the ARH systems based on how much water was collected and made available for reuse, the corresponding potable water savings (in liters of harvested water used), and the reduction in volume of stormwater discharged to the CSS and MS4 systems during wet weather. The following were the objectives of the ARH system study:

1. Quantify the amount of stormwater runoff harvested, used, and discharged from the site.
2. Determine efficacy of ARH system to mitigate wet weather discharges to the CSS and MS4.
3. Determine cost and volume reduction equivalency metrics between ARH technology and other structural best management practices (BMPs) associated with passive low impact development (LID) practices.

To evaluate system performance, we calculated hydraulic event statistics from water quantity data collected at each site. To evaluate the performance of the ARH system, we used summary statistics calculated from the event statistics. Summary statistics include the following information:

- Total estimated runoff volume—calculated as the sum of harvested runoff volume and the estimated wet weather overflow volume for all events within the analysis period.
- Total harvested runoff volume—calculated as the sum of harvested runoff volume for all events within the analysis period.
- Total reuse—the sum of volume discharged from the point of use within the firehouse.
- Average event overflow volume for storms greater than or equal to 3 cm (1.2 in.)—the average event overflow volume within the analysis period, for only those storms with 3 cm (1.2 in.) or more of rainfall (the minimum BMP design standard set by the DC Department of Energy and the Environment (DOEE in the 2013 Stormwater Notice of Final Rulemaking [4]).
- Average event harvesting efficacy—determined as the average of the percent of runoff volume harvested for all events within the analysis period.
- Average cistern post-event percent full—calculated as the average of the post-event tank elevation divided by the calibrated overflow elevation.

For all calculations, we converted the cistern water level to volume based on the stage-storage relationship for the cisterns. A flow meter was installed to directly measure water discharged for reuse. Since no direct measurement (i.e., flow meter) was present to calculate overflow out of the cisterns, we used the orifice equation below to estimate the overflow volume for each event.

$$Q = CdA\sqrt{2gh}$$

where Q = flow (cubic meter per second (m^3/s))
Cd = coefficient of discharge (0.80)
A = area of orifice (m^2)
g= acceleration of gravity (9.81 m/s^2)
h = head acting on the centerline (m)

The orifice equation uses the diameter of the overflow pipe (10.2 cm (4 in.)) and the relative elevation of water in the cistern to calculate head and determine the volume of water discharging through the outlet. Water begins to overflow from the cisterns at both sites when it reaches a depth of 2.2 m (7.3 ft).

3. Results and Discussion

3.1. Harvested Water Quantities

The systems were installed and operational in March of 2012, but the study was limited to a two-year monitoring period and did not begin until March 2014. The systems were set to monitor water quantity data continuously throughout the study timeline; however, an equipment malfunction at Engine House 25 prevented rainwater harvesting from September 2016 to December 2017. Therefore, for the Engine House 25 study, we analyzed water quantity data and statistics collected from March 2014 to August 2016. For the Engine House 3 study, we used water quantity data and statistics collected from March 2014 to December 2017.

Summary statistics for the ARH systems are included in Table 1. Throughout the analysis period, the system at Engine House 3 harvested a total of approximately 388,079 L (102,530 gal.) of runoff and the system at Engine House 25 harvested a total of approximately 191,726 L (50,650 gal.) of runoff. We compared the total runoff harvested to the length of time analyzed at each site and found an average annual harvested runoff over the analysis period of approximately 103,640 L/year (27,380 gal./year) and 79,782 L/year (21,080 gal./year) for Engine House 3 and Engine House 25, respectively.

The American Water Works Association (AWWA) estimates the average total water use at 651 L per capita per day (lpcd or 172 gal. per capita per day (gpcd)), with 382 lpcd (101 gpcd) coming from outdoor uses, 262 lpcd (69.3 gpcd) coming from indoor uses, and 6.4 lpcd (1.7 gpcd) from unknown or unidentified indoor or outdoor use. Respective percentages of total indoor uses are estimated to be showers (16.8%), clothes washers (21.7%), dishwashers (1.4%), toilets (26.7%), baths (1.7%), leaks (13.7%), faucets (15.7%), and other domestic uses (2.2%) [5]. Toilets have the highest percentage of indoor use (26.7% of the total indoor use of 262 lpcd or 69.3 lpcd), which makes them an ideal potable demand replacement using harvested water.

If we extrapolate these per capita per day findings over a year, toilets alone provide a demand of 25,550 L per capita per year (6750 gal. per capita per year). Using the harvested volumes for the firehouse sites together with the AWWA demand estimates, the ARH systems provided sufficient harvested water to serve the equivalent toilet use demand for four firemen at Engine House 3 and three firemen at Engine House 25.

Table 1. Advanced rainwater harvesting (ARH) System Water Quantity Summary Statistics.

Statistic	Engine House 3	Engine House 25
Analysis Period	March 2014–December 2017	March 2014–August 2016
Total Estimated Runoff Volume (L)	470,225	195,100
Total Harvested Runoff Volume (L)	388,079	191, 726
Average Annual Runoff Volume Harvested (L/year)	103,640	79,782
Total Reuse (L)	69,205	59,519
Average Annual Reuse (L/year)	18,482	24,767
Percent of Harvested Water Reused	18%	31%
Avgerage Event Overflow Volume (L) for Storms $\leq$ 3.0 cm	189	12
Percent of Total Runoff Volume Harvested	83%	98%
Average Event Harvesting Efficacy	96%	99%
Average Cistern Post-Event Percent Full	69%	48%

We determined reuse volumes from the volume of water discharged from the point of use inside the firehouse at each site. For the analysis period, a total of approximately 69,205 L (18,290 gal.) of stored water from Engine House 3 and 59,519 L (157,250 gal.) of stored water from Engine House

25 were reused. This gives an average annual reuse of approximately 18,482 L/year (4,880 gal./year) and 24,767 L/year (6540 gal./year) for Engine House 3 and Engine House 25, respectively. These totals mean that only 18% of harvested water from Engine House 3 was reused, and only 31% of the harvested water from Engine House 25 was reused. Considering that these reuse volumes are only a fraction of the total volumes harvested, significantly more water was discharged to the CSS and MS4 systems during dry weather conditions in preparation for incoming rainfall events than was reused by firehouse staff.

While a significant amount of stormwater runoff was harvested by the ARH system, only a small fraction of that runoff was reused. Although a higher rate of reuse would be beneficial (as it would further decrease the amount of runoff entering the CSS and MS4), the low reuse rate does not affect the ARH system's ability to limit discharges during wet weather because the system is automated and is able to release water before forecasted rainfall events.

The DOEE *Notice of Final Rulemaking on Stormwater Management, and Soil Erosion and Sediment Control* [3] requires a stormwater runoff retention standard of 3 cm (1.2 in.). We evaluated the ARH systems performance relative to this DOEE standard by determining the average overflow volume (volume of the runoff discharged during a rain event) for storms less than or equal to 3 cm (1.2 in.). Because the ARH systems were designed to capture the stormwater runoff volume associated with this DOEE standard rainfall event, if the ARH functioned perfectly, there would be zero overflow for events less than approximately 3 cm (1.2 in.). Nevertheless, since the ARH system is programmed to discharge (during dry weather) the minimum volume of water required to make space for capturing the runoff from the next forecasted rainfall event, in cases when the forecast underestimates the total rainfall amount, discharge can occur during the rain event. For rain events less than or equal to 3 cm (1.2 in.), the average overflow volumes were 189 L (50 gal.) from Engine House 3 and 12 L (3 gal.) from Engine House 25. Some rain events had overflow discharges that were significantly higher than the averages presented here, but most events had no overflow discharge at all (i.e., 100% capture).

A significant amount of stormwater runoff, representing almost all the runoff within the site drainage areas, was harvested throughout the monitoring program. While overflows did occur on occasion (due to heavier storms than forecasted), the majority of runoff was successfully stored in the cisterns and made available for reuse.

3.2. ARH System Efficacy

ARH systems mitigate wet weather discharges by harvesting runoff and storing the water until it can be reused or discharged from the site during dry weather conditions.

We determined the efficacy of the ARH systems by comparing the total harvested runoff volume (the sum of volume captured in the cistern for each rainfall event) to the total estimated runoff volume (the sum of the estimated volume of runoff produced for each rainfall event) over the analysis period. The estimated runoff volume was calculated for each event as the sum of the harvested runoff volume and the estimated wet weather overflow volume (calculated using the orifice equation). The ARH system at Engine House 3 harvested 83% of the total estimated runoff throughout the analysis period, with an average event harvesting efficacy of 96%. The ARH system at Engine House 25 harvested 98% of the total runoff volume with an average event harvesting efficacy of 99%. Both systems significantly reduced wet weather discharges for their respective sites.

We also evaluated the efficacy of the ARH systems by reviewing the water level in the cisterns at the end of each rain event to calculate how close the systems were to full. The ARH systems estimate runoff volume to the cistern and make decisions on how to drain the systems; the system goal is to be full or close to full at the end of each rain event, providing the maximum volume of water available for reuse. The average post-event cistern percent full was 69% for Engine House 3 and 48% for Engine House 25.

There are a couple of reasons why the cistern would not be full at the end of an event: (1) the forecast may have predicted higher rainfall amounts (more runoff) than the actual rainfall event produced; or (2) the predicted runoff volume estimated by the system was larger than the actual runoff volume. In either of these cases, if the system anticipated more runoff than was produced, it would have discharged more stored water than necessary prior to the rain event. Since both systems are significantly below full on an average event basis, it is more likely that the system is overestimating the runoff volume rather than the forecast being incorrect that often. This overestimation of expected runoff could be because the original estimate of drainage area is not accurate for the systems or because maintenance of the systems is required to restore flow paths (e.g., roof drains are blocked and require cleaning). The average post-event cistern percent full was significantly lower at Engine House 25 than at Engine House 3. This may be due to issues with runoff from the full drainage area making it into the cistern for each event. At Engine House 25, the pavement is also directed to the cistern, but if flow patterns are interrupted by debris or if pump issues occur, not all the expected runoff may make it to the cistern (i.e., runoff may bypass the system entirely).

After evaluating the results of this study, we determined that ARH systems are very effective at mitigating wet weather discharges to the CSS and the MS4. Both systems achieved average event harvesting rates greater than 95%. This indicates that while some storms were not fully captured, most were either fully captured or nearly fully captured. Rainfall events that were not fully harvested were large storms that exceeded the capacity of the cisterns or may have been events that were larger than forecasted.

The ARH systems did tend to operate conservatively, the systems tended to drawdown more than required prior to the rainfall event. This means situations of underestimating forecasted rainfall and required drawdown may not be the primary cause of the system inefficacies during events where overflow did occur. The more likely cause is overestimation of the volume of overflow from the system during overflow events due to the sensitivity of the water level sensor in the cisterns. An overflow event is triggered when water level in the cistern reaches a certain threshold (which was updated periodically over the course of the analysis period due to sensor drift), and the overflow volume is calculated for the time that the water level sensor readings remained over this threshold. In some cases, the sensor took several hours to return to a level below the elevation of the overflow outlet and overflow was calculated over the entire period; therefore, the water level sensor itself may have added some error into the overflow calculations for this analysis.

Regardless of whether the overall efficacy or the average event efficacy is used to evaluate the ARH systems, the data shows that the systems significantly reduced the amount of runoff that entered the stormwater management systems within their drainage areas during wet weather. This suggests that if implemented on a larger scale (i.e., numerous systems throughout an urban area), ARH systems would prove to be a valuable tool in effectively managing stormwater runoff for both the CSS and the MS4 areas.

3.3. Cost Comparison

We compared the ARH system technology to other passive LID practices that have been installed in DC and throughout other urban areas to determine its volume reduction benefits and cost equivalency metrics. For this comparison, we used conventional (i.e., passive) cisterns, bioretention/raingardens, and permeable pavement as the more conventional LID practices. Table 2 provides a comparison of cost per acre for the ARH and the other LID practices. These costs are based on sizing each practice to capture 3 cm (1.2 in.) of runoff from 0.40 hectare (1.0 acre) impervious area.

Table 2. Comparison of ARH System with Other low impact development (LID) Practices.

Practice	Design & Construction Costs	Surface Area Needed (m^2)	Assumptions
Green Tank ARH System (cistern)	$250,000	74	Cost of an aboveground green tank system (i.e., reinforced precast concrete cistern with green roof). Estimate assumes concrete precast tanks with hatch, green screens/planters and green roof (16 units), transportation, roof drain connections, power, internet, pumps for use lines, water-level sensor, automated valve and drain lines, filtration/ultraviolet (UV) treatment system, continuous monitoring and adaptive control (1-year ARH service).
ARH System (cistern)	$76,000–$138,000	30–64	Estimates assumes an aboveground high-density linear polyethylene (HDLPE) tank. Estimate includes cistern, transportation, 3/4 HP pump and necessary fittings for installation. Estimate also includes water-level sensor, automated valve and drain lines, filtration/treatment system, and continuous monitoring and adaptive control equipment and service fees (1-year ARH service).
Rainwater Harvesting (cistern)	$56,000–$113,000	30–64	Estimates assumes an aboveground HDLPE tank. Estimate includes cistern, transportation, 3/4 HP pump, and necessary fittings for installation.
Permeable Pavement	$21,000–$74,000	390	Permeable pavement may include pavers, concrete, or asphalt. Costs can vary depending on the material selected. Estimate assumes permeable asphalt or concrete and includes demolition of existing pavement, excavation, 7–10 cm (3–4 in.) of bedding layer, installation of 23–30 cm (9–12 in.) reservoir layer, an underdrain system tied into existing storm drain system, and permeable pavement installation.
Bioretention	$100,000–$165,000	112	Estimate assumes a traditional bioretention cell and includes demolition of existing pavement or sidewalk, excavation, 0.9 m (3 ft) of storage layer with filter media, an underdrain system tied into existing storm drain system, and landscaping. Assumes 15 cm (6 in.) ponding depth.

Primary benefits of an ARH system include its ability to capture runoff during the rain event and delay stored water discharge until dry weather conditions when the systems are not overloaded or eliminate its discharge by reusing captured runoff water. This catch, store, and discharge system can reduce the frequency of CSOs and reduce peak runoff to the MS4 systems.

These primary benefits of the ARH system are achieved with relative ease due to the internet-based automated control capabilities and the system's ability to operate with minimal manual intervention. An ARH system designed for using the green tank cistern design (i.e., a series of precast concrete cubes with vegetated green roofs) would cost approximately $250,000 (including design and construction) to manage 3 cm (1.2 in.) of runoff from 0.40 hectare (1.0 acre) of impervious area and would require a surface area of approximately 74 m^2 (800 ft^2). The green tank cistern in our study was designed to fit in a typical parking spot but still had a significantly higher cost than other controls in the table due to the cost of the concrete form with green roof, the advanced treatment system (filter bag system plus UV treatment system), and the increased construction cost (i.e., crane required for placement). For less expensive cistern types (e.g., plastic cisterns) and treatment system (i.e., filtration only), an ARH system can range from approximately $76,000 to $138,000 to manage 3 cm (1.2 in.) of runoff from 0.40 hectares (1.0 acre) of impervious area.

Passive cisterns offer the most direct comparison to ARH as they offer most of the same features as ARH, except that they are not controlled or monitored in real-time and do not incorporate forecasting information. They offer the same storage capabilities and volume reduction efficiency as the ARH system with the condition that stored runoff would require manual calculations of runoff volume predicted from the rainfall event and manual discharge or reuse prior to a rainfall event in a volume that is sufficient to allow storage of the incoming event. Passive cisterns can be manufactured in various materials other than precast concrete, resulting in lighter-weight, lower-cost cisterns. There are advantages and disadvantages of each material. An HDPE cistern would cost between $56,000 and $113,000 and would require a surface area of approximately 30 to 64 m^2 (320 to 690 ft^2) depending on the depth of the cistern used (Table 2).

Bioretention and raingardens are BMPs that use soils and woody and herbaceous plants to remove pollutants from stormwater through infiltration or filtering. Runoff is conveyed to the bioretention area where it collects, ponds, and infiltrates into the engineered soil media where it either infiltrates into the subsoils or is conveyed to the stormwater management system [6]. Bioretention and raingarden systems are effective solutions to improve stormwater management in many situations; however, they offer limited benefits in an urban environment when compared to an ARH system. Bioretention systems have a limited capacity for reducing runoff volumes due to the area required to provide sufficient storage and the amount of time it takes for runoff to infiltrate into the engineered soil media, which typically has an infiltration rate of approximately 12.7 to 254 cm/h (5.0 to 100 in/h). Because ARH systems or passive cisterns are compact and can be implemented in a much smaller footprint, they offer the benefit of small space requirement, which is important in an urban environment. That said, bioretention systems do, however, offer an advantage over cisterns in that the runoff naturally infiltrates into soil, eliminating the need for reuse or discharging prior to a forecasted rain event. Bioretention or raingarden systems cost between $100,000 and $165,000 to manage runoff from 0.40 hectares (1.0 acre) and would require a surface area of approximately 112 m^2 (1200 ft^2) which is approximately 240% larger than the surface area an average passive cistern requires.

Permeable pavement is another common LID technique that offers a variety of benefits. Permeable pavement systems reduce runoff volumes by allowing stormwater to drain through a paved surface, to an underground storage bed for infiltration into subsurface soils [7]. The ability of permeable pavement to provide volume reduction or a delay in the peak runoff depends on the underlying soil infiltration rate and the volume of the reservoir layer. Although permeable pavements can be very effective in reducing surface runoff, they are susceptible to clogging if not maintained properly. If clogging does occur, the infiltration through permeable pavement surfaces can be significantly reduced. A benefit of an ARH system over permeable pavements is that the ARH system is easier to maintain and is less likely to require complete system replacement. A permeable pavement is estimated to cost between $21,000 and $74,000 to manage 3 cm (1.2 in.) of runoff from 0.40 hectares (1.0 acre) and requires a surface area of at least 390 m^2 (4,200 ft^2), which is about 800% larger than the surface area an average passive cistern requires. That said, the footprint of the permeable pavement is less restrictive since it provides multiple uses (i.e., stormwater management and parking area). Although capital cost for permeable pavement is the lowest among the systems discussed herein, rigorous maintenance is needed to keep permeable pavement surfaces clean, and the life cycle cost may be higher than other LID technologies discussed.

ARH provides a significant advantage in potential for runoff volume reduction in a small footprint when compared to other structural BMPs. While ARH would typically come at a higher initial cost than other BMPs associated with more conventional LID practices, its benefits in runoff volume reduction far exceed other technologies, especially when space is a constraint or infiltration should be avoided (e.g., contaminated subsoils or high groundwater table). The ARH system is also relatively easy to operate and maintain; this benefit is not available for most of the other technologies considered. ARH represents a strong challenger to conventional, passive LID practices for effective stormwater management in urban areas.

3.4. System Maintenance

The ARH systems installed at Engine House 3 and Engine House 25 were two of the first installations of these ARH systems in the country. During this study of this innovative technology not all the system's components functioned equally well. For example, the valve actuator at Engine House 25 that controlled the active discharge of stored water from the cistern was placed below ground in an area that flooded several times, and as such, the actuator had to be replaced twice. This lesson learned provided for a new design specification that actuators stay aboveground, outside of flooding levels.

The ARH systems are compact and easy to operate. But, regular maintenance of these systems is necessary for proper function and optimal performance. The following is a summary of key operation and maintenance procedures:

- Under normal conditions, the system will operate without the need for user intervention; nevertheless, the system operation should be evaluated following any abnormal conditions (such as power outage) and occasionally during normal conditions, to ensure the system is properly functioning.
- The system requires routine maintenance, including cleaning, inspecting, and replacing parts as necessary. For example, the cistern should be inspected for sediment approximately every two years and cleaned out as needed.

The nature of the system allows for real-time monitoring that could be used to set alerts that would trigger maintenance personnel to conduct certain activities or to check on a system element. For instance, if water level change is not observed in the cistern during rainfall events or cistern drainage issues occur during dry weather, an alert could be triggered to notify personnel that inflows to or outflows from the cistern may be blocked. This would help keep the system operating properly with little need for maintenance checks when the system is running smoothly.

4. Conclusions

This monitoring program has demonstrated the utility and effectiveness of ARH systems to (1) harvest water for reuse and potable water use reduction, and to (2) manage stormwater runoff to reduce discharge to the CSS and MS4 during wet weather periods when capacity is limited in these systems. The results of this evaluation have shown that ARH systems are ideal for distributed use in urban areas where space is constrained and where infiltration to the subsurface may not be possible (i.e., high groundwater table) or desired (i.e., contaminated subsoils).

The ARH system at Engine House 3 achieved an average event harvesting efficacy of 96%, and ARH system at Engine House 25 achieved an average event harvesting efficacy of 99%. Some improvement of the systems could be realized by updating the ARH system logic to more accurately represent the drainage area of the sites, so the systems do not over drain prior to forecasted rainfall events; further improving the efficiency of the systems. This monitoring program has demonstrated that ARH systems can significantly reduce wet weather discharges to stormwater systems providing for multiple benefits, including CSO reduction, peak flow reduction, and peak volume reduction, while providing opportunities for water conservation and potable water savings.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/5/667/s1, Figure S1: Proposed Improvements, D.C.F.D Engine #3 Firehouse. Figure S2: Schematic Elevation/Profile & Expanded Layout, D.C.F.D Engine #3 Firehouse. Figure S3: Proposed Improvements, D.C.F.D Engine #25 Firehouse. Figure S4: Schematic Elevation/Profile & Expanded Layout, D.C.F.D Engine #25 Firehouse. Figure S5: ARH Hydraulic Event Data for System at Engine 3. Figure S6: ARH Hydraulic Event Data for System at Engine 25.

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