Continuous monitoring and adaptive control—the internet of things transforms stormwater management

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ABSTRACT | Both traditional (gray) and green stormwater management practices have almost entirely been designed as passive systems governed by a fixed control structure to achieve a target water quality and/or quantity objective (i.e., treatment volume, attenuation). Passive systems, however, rarely represent optimal solutions. Advances in low-cost, Internet-accessible controller systems and wired and wireless communications have made real-time and dynamic controls of distributed stormwater facilities now viable, cost-effective options for new construction as well as retrofits. The physical setup of continuous monitoring and adaptive control (CMAC) stormwater systems includes three primary components: a water level sensor to provide data on the facility's current state, an actuated valve to control its hydraulics (typically outflow), and an Internet connection most often provided in remote locations by cellular data. CMAC facilities have been deployed throughout the United States to enhance underperforming facilities and optimize designs for multiple objectives, such as flood protection, water quality treatment, water reuse and channel protection.

KEYWORDS | Stormwater management, adaptive control, design optimization, green infrastructure

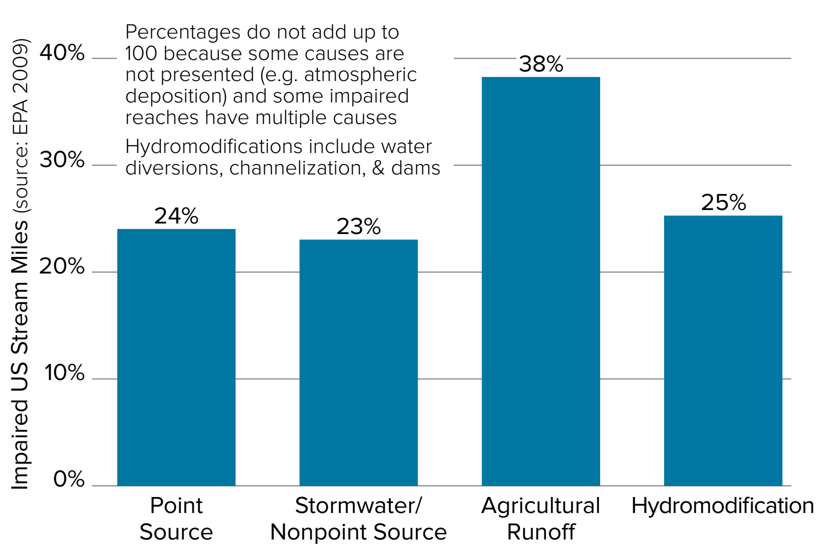


Figure 1. Nonpoint sources have surpassed point sources as the largest cause of river and stream impairments in the United States

INTRODUCTION

All infrastructure must be designed to a level of service. Stormwater management facilities are typically designed to achieve some combination of stated objectives. The most decisive objectives, for example, typically concern the lifetime of the infrastructure and its cost, a calculated design storm frequency and its regulatory or environmental function. Designing facilities to meet stated objectives certainly contributes to the successful management of stormwater, yet optimized design necessitates that the objectives are quantifiably well informed.

The reality in water infrastructure is that the level of service has become a moving target. Stormwater and flood control systems are often designed to treat up to or protect from a statistical storm event (e.g. the 1-inch [2.5-centimeter] event or the event with a 100-year recurrence interval). However, these targets assume stationarity in natural systems. Climate variability and anthropogenic changes have compromised this assumption as it relates to water resources (Milly et al. 2008). Recent studies have observed an increasing historical trend in both average precipitation and extreme events in New England. There is also consensus among researchers projecting an increase in temperature, a decrease in snowpack and an increase in precipitation volume of extreme events in the region (USACE 2015). Future water resource designs must be adaptable to the changing climate, the changing built environment and the changing response from the natural environment.

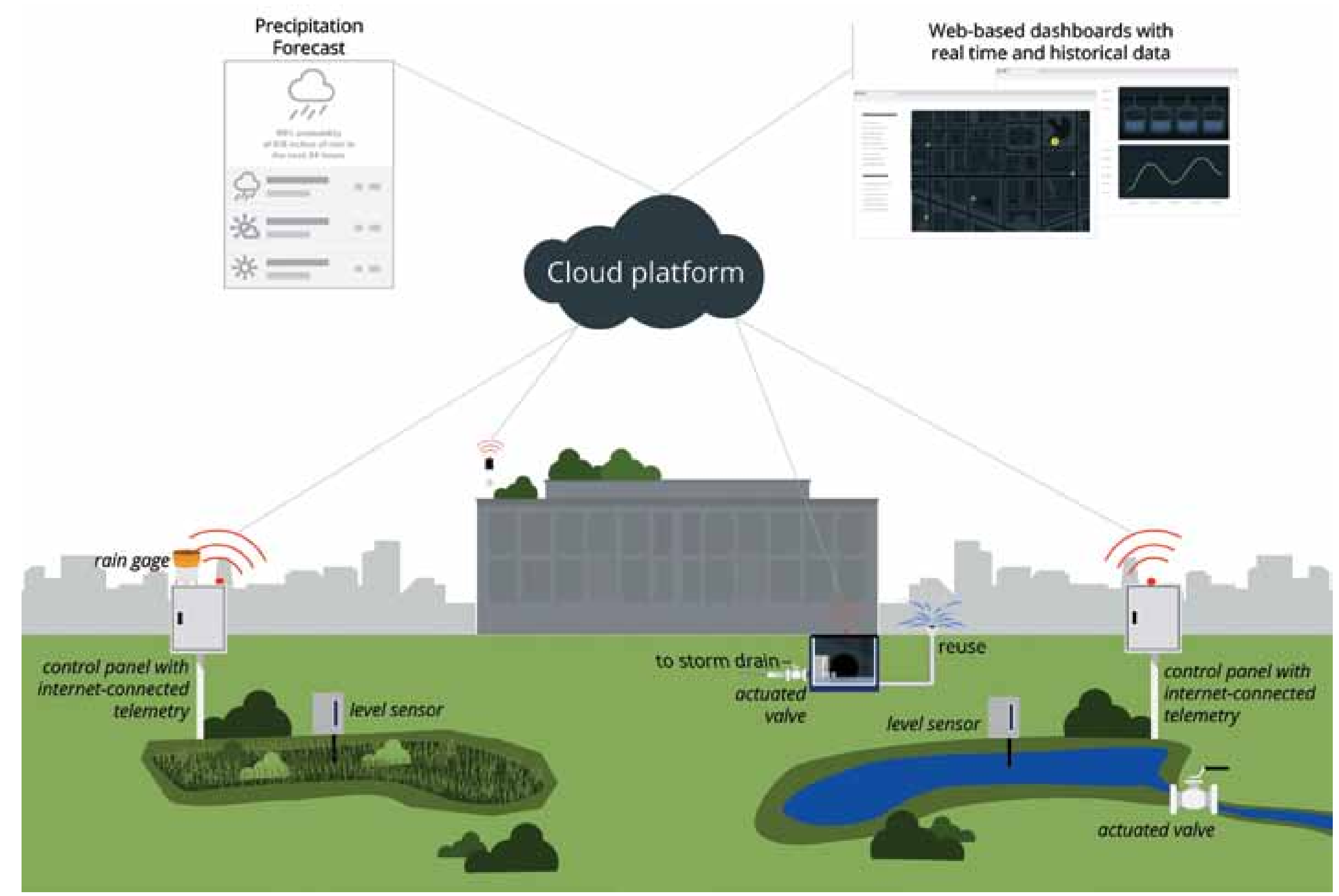


Figure 2. A schematic of CMAC for green and gray infrastructure; field-deployed sensors and Internet connectability provide the ability to verify and improve the performance of distributed stormwater infrastructure

In addition to designing for an uncertain climate, stormwater managers must design systems at the expense of competing objectives and with limited information about the actual site conditions. Distributed stormwater management and treatment systems are difficult to monitor, and as a result we have limited data to inform the best possible designs. Current performance standards and designs are based on specifications and standards that are not precise on a local or individual facility level. Ideally, stormwater facilities could be designed around the local watershed with adaptive, long-lasting performance standards. Intelligent design would also empower a range of functionality to achieve what are typically considered competing objectives, such as water-quality treatment and flood protection. In the past it has been difficult and costly, if not impossible, to maximize multiple objectives with static design and limited insight.

Advances in environmental sensor and communication technology now allow us to monitor and control stormwater facility performance and to adapt static designs to meet new objectives and optimize achievement of existing ones. The technology that enables these improvements is known as the Internet of Things (IoT). IoT is the network of physical objects embedded with electronics, software, sensors and network connectivity, which enables these objects to collect and exchange data. IoT allows objects to be sensed and controlled remotely across network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems. In the context of stormwater management, IoT applies directly to the continuous monitoring and adaptive control (CMAC) of stormwater control facilities. Continuous, remote monitoring allows stormwater managers to monitor for facility-level performance data, which leads to informed maintenance and regulatory confirmation. Adaptive controls can act on the data collected by continuous monitoring and intelligently adjust facility hydraulics to increase performance over a wider hydraulic range of conditions while optimizing for multiple objectives.

CMAC technology is not only feasible, it is used by stormwater managers across the United States. It has been successfully deployed to meet a range of stated stormwater management objectives, including: 1) reducing discharge to a combined sewer system while maximizing water available for reuse in a rainwater harvesting system; 2) increasing water-quality treatment while maintaining flood protection of a wet pond; and 3) irrigating a green roof efficiently while providing proof for green infrastructure design. In each case, CMAC consistently and predictably achieves stated objectives while simultaneously providing the data needed to inform intelligent management decisions and planning. By incorporating CMAC into the design of stormwater facilities, the industry can significantly improve asset performance.

BACKGROUND

As with other water management and treatment infrastructure, the performance of distributed stormwater management facilities depends on a variety of site-specific factors. Design assumptions and manuals can go only so far in describing the behavior of any facility. Comprehensive efforts to quantify the performance of stormwater management strategies exist, including the International BMP Database and references developed by individual states and regulatory entities. While these references are well-supported by literature, such as the New Hampshire Stormwater Manual, site-specific factors and maintenance affect the performance of all facilities. Understanding BMP removal efficiencies on a finer scale is critical for stormwater management planning, regulatory enforcement and verification.

In the decades since the Clean Water Act was passed, leading to the National Pollutant Discharge Elimination System (NPDES), regulation has greatly reduced the influence of point sources on water-quality violations in the United States. This success is largely attributed to point source dischargers meeting permit criteria and verifying facility performance through monitoring. As the pollution contribution from nonpoint sources, including urban and agricultural runoff, continues to increase relative to point sources (Figure 1, U.S. Environmental Protection Agency 2009), we must measure treatment and management strategies to verify compliance. By refocusing on verifying nonpoint source controls, the burden can shift away from under-funded POTWs that continue to face increasingly stringent discharge limits in the name of meeting ever-decreasing instream targets.

Throughout the country, to varying degrees of implementation, stormwater regulations rely on design standards and visual inspections to enforce NPDES permit requirements. Direct quantification of distributed facility performance on an individual or aggregated level has not been possible on a large scale due to the high cost of implementation. Advances in low-cost sensor and communication technology are shifting that paradigm. Furthermore, those same technologies are available to improve stormwater designs through active hydraulic control.

These new stormwater management systems are being deployed on cloud-based platforms that automatically monitor the weather forecast and calculate expected runoff volume from future storms. The remote software communicates directly with hydraulic controls and sensors at the stormwater facility, making decisions about how to prepare for incoming storms and how to manage stormwater after events. This active water management solution is particularly powerful in urban areas where space is not available for more traditional stormwater management. The flexibility of intelligent, predictive controls is also evident in its adaptive management. Managers can monitor, evaluate and adjust the logic to optimize performance over time, a cost-efficient solution in an industry often tied to costly construction projects and design modification. Introducing real-time monitoring and control of facilities—be it gray or green infrastructure—allows performance to be directly quantified as a benefit to improved design and function.

METHODOLOGY

These new stormwater management systems require integrated hardware and cloud-based software to function. The hardware needed is an actuated valve, a water-level sensor and a control panel with telemetry. Figure 2 shows how these components function together at stormwater management facilities. The components can be installed as a retrofit or in new construction to enhance the functionality of a facility. Many types of green and gray stormwater infrastructure can be enhanced with CMAC, including bioretention cells, wet ponds, dry ponds, infiltration basins, green roofs, cisterns, rainwater harvesting and site connection tanks.

These hardware components must be robust and able to function in harsh environments so that service is rarely, if ever, interrupted. As such, solenoids, slide gates and butterfly valves have shown high reliability for hydraulic control along with pressure transducers and ultrasonic sensors to measure water level. Also critical is access to the cloud-based control system through an Internet connection. Cellular data connections are often the most robust option at distributed locations.

These hardware components communicate through a cellular modem connection at the control panel with a cloud-based control system. While the logic on these systems can vary, it generally follows this sequence:

- Inspect the current 24-hour probability of precipitation (POP) and quantitative precipitation forecast (QPF) from NOAA.
- Calculate the expected runoff volume into the facility based on watershed characteristics and the qualifying parts of the forecast (usually set at 70 percent POP and 0.02 inches [0.5 mm] QPF).
- If the expected runoff volume is greater than the available volume in the facility: Open the valve to release water, until the next statement is true.
- If the expected runoff volume is less than or equal to the available volume in the facility: Close the valve.

This sequence is repeated on an interval such that the system can constantly adjust to changing forecasts and changing water levels. This enables a robust feedback loop that allows the system to self-correct as the forecast or actual rainfall, and thus water level, changes.

Also essential in these systems is the integration of fail-safes where data could be wrong or communication could be lost. The first is sensor trust; subroutines can be enabled so that alarms are sent and logic is changed if data from a sensor is implausible. The second is loss of Internet connection; local logic is always needed such that if connection to the Internet is lost the system can default to a safe state. And finally, the loss of power must be planned such that a valve will return to a safe state using a battery backup or an auto-return actuator.

The system described above provides the basics of these modern stormwater control systems. Additional logic and parameters can be configured for more sophisticated outcomes. These include maximizing retention time, modulating a valve to control release rate and preparing systems for very large events. Figure 3 shows two logic configurations targeting different primary objectives: 1) rainwater harvesting, to maximize retention time and water availability; and 2) smart detention, to minimize wet weather discharge and meet a specific retention time.

Essential in all of these applications are data on which to base control decisions, and inherent in the cloud-based systems is access to these data.

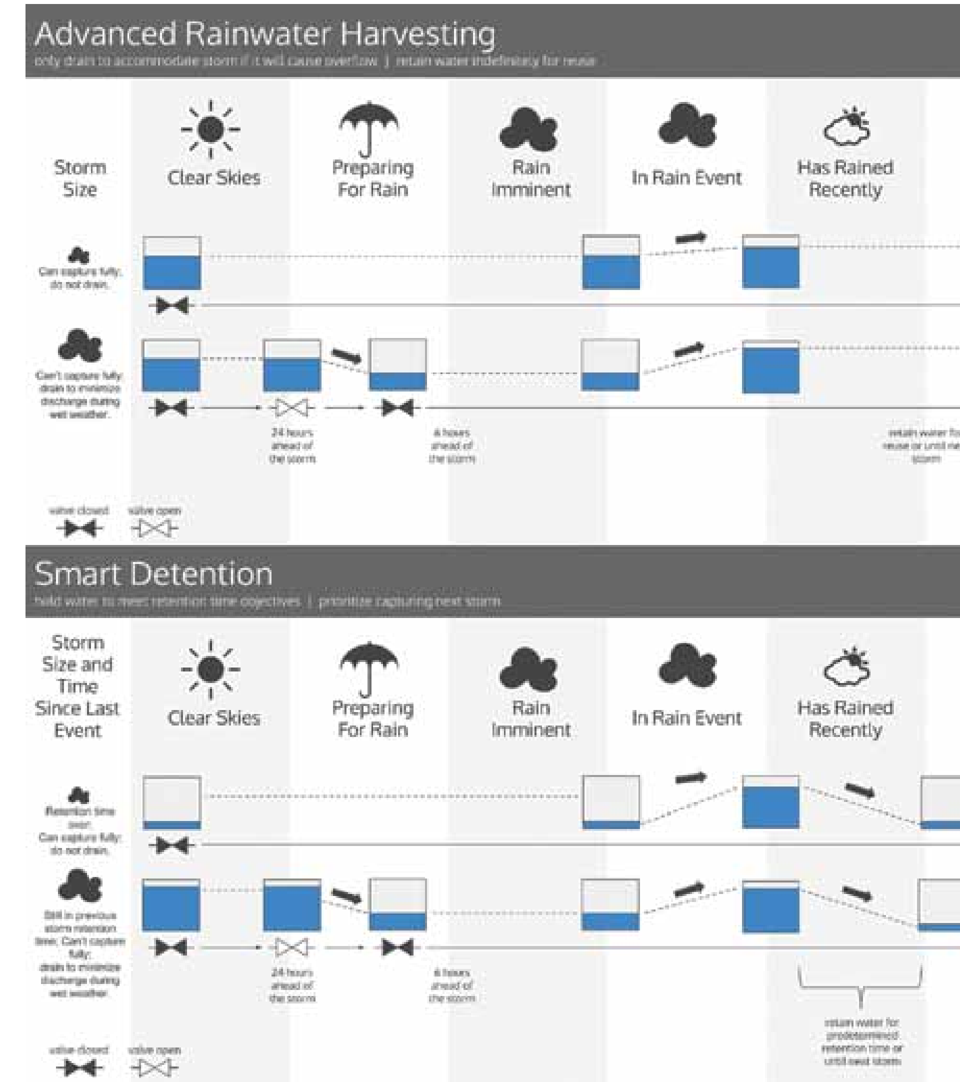


Figure 3. CMAC logic diagrams of advanced rainwater harvesting (top) and smart detention (bottom)

Data access often takes the form of a web-based dashboard that allows a user to view, explore and download data. In addition, these dashboards can deliver remote, manual control of these systems. The data presented on a web-dashboard offer the ability to continuously monitor performance. Other sensors, such as water-quality sensors (total suspended solids, nitrate, pH, temperature, dissolved oxygen, etc.), can be added to monitor water quality impacts and performance of a facility in real-time.

Security is paramount for complete vertical integration of these systems. Communication between hardware and the cloud-based platform uses hardware-driven, message-level encryption for robust security without excessive power consumption. Permissions to access data on the web-based interface are granted based on a user's role, allowing for granular control and transparency around who can view the data and execute remote control operations. Communications with the web browser are secured with modern versions of industry-standard Transport

Figure 4. Six, 1,000-gallon (3,790-liter) cisterns in the basement of EPA headquarters in Washington, D.C., collect runoff from the building roof to be used for on-site irrigation. Adaptive control of the cisterns has reduced wet weather flow to the combined sewer by 80 percent.

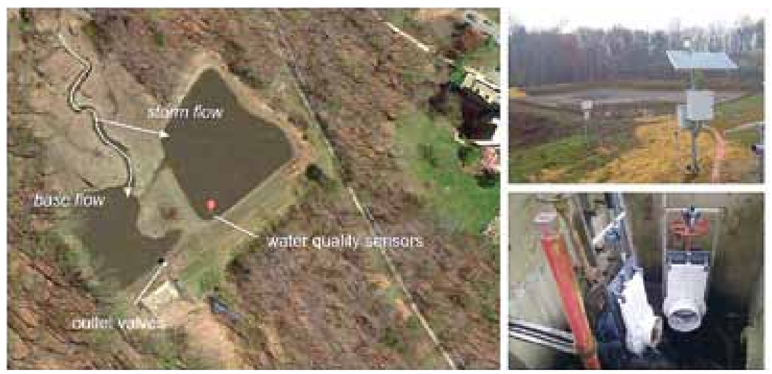


Figure 5. Aerial image of 15 acre-foot (18,500-cubic meter) retention pond with 440-acre (180-hectare) watershed on Sligo Creek in Montgomery County, Maryland (left); solar-powered control panel with cellular data connectivity (top right); and retrofitted outlet structure with actuated slide gate valves passing only baseflow (bottom right)

Layer Security (TLS). All these measures result in a secure and robust automated control system.

The components and methods described above provide a vertically integrated system for intelligently controlling distributed systems under challenging conditions.

CASE STUDIES AND RESULTS

Improve function using CMAC in design

Rainwater harvesting (RWH) systems are used worldwide as an alternative source of water. In the humid regions of the United States these systems often supplement potable water for landscape and lawn irrigation (Debusk et al. 2013). Such was the case for an RWH system installed at EPA headquarters in Washington D.C. Six 1,000-gallon (3,790-liter) water-storage tanks (cisterns) collect runoff from approximately 10,000 square feet (930 square meters) of rooftop to irrigate roughly 13,500 square feet (1,254 square meters) of landscaped area (Figure 4). The six tanks were hydraulically connected such that they function as one individual system.

In addition to being a supplemental water source, RWH systems also can provide stormwater management control by decreasing the volume and rate of stormwater leaving a site. The cistern acts as a temporary holding facility for stormwater runoff. When the stored water is used for irrigation or in other ways, part of the tank is emptied, creating storage capacity for runoff to be generated by the next rainfall event. However, if minimal water is extracted from the system, there is no storage room available inside the cistern when it rains, and the runoff leaves the site unmitigated as overflow. As with most systems installed for irrigation in humid regions, usage of the collected rainwater at the EPA site was minimal: Over the span of one year, less than 5 gallons (19 liters) of stored rainwater was extracted from the system for irrigation. Thus, before CMAC was deployed, the system provided no mitigation for stormwater leaving the site.

The CMAC system was implemented at the EPA site in April 2014 and was fully online and operational by May 1, 2014. As no water was being used for irrigation, the stormwater management benefit achieved by the RWH system relied solely on the CMAC system. Data collected between May 1, 2014, and May 1, 2015 were used to evaluate the performance of the RWH system. Of the 110 storm events that occurred during the one-year period, only 21 (19 percent) resulted in wet weather release (release during a rain event). For the 89 storms that did not result in wet weather release, the volume and peak flow reduction was inherently 100 percent. However, incorporating CMAC still significantly reduced wet weather volume releases and peak flow rates for storms that did release water during a rain event. Reductions for these storms alone averaged 82 and 86 percent for volume release and peak flow rates, respectively, bringing overall average system reductions to 97 percent for both volume and peak flow rates.

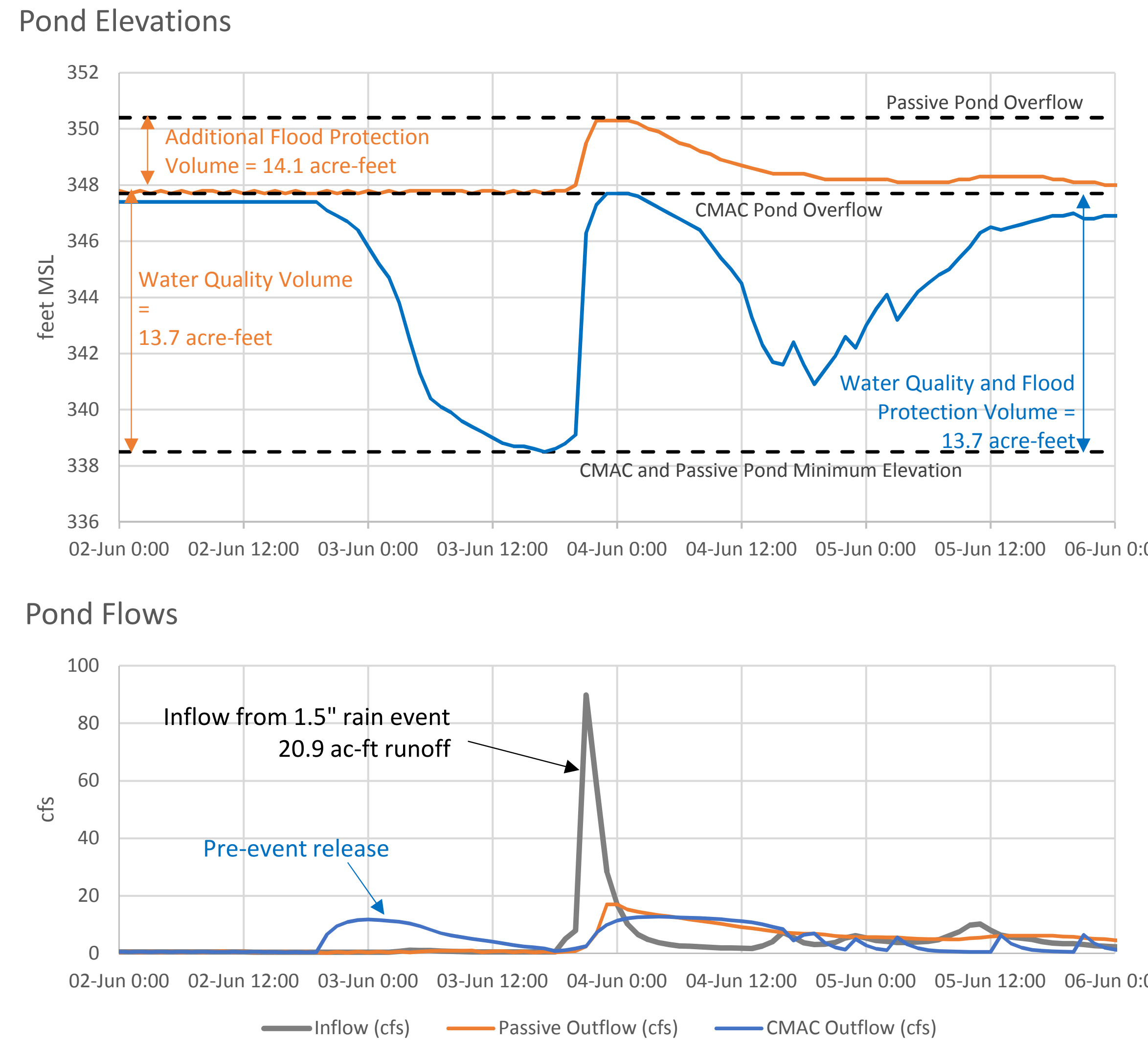
Enhance existing stormwater management

Both green and gray infrastructure systems using static methods can eventually underperform as site conditions and regulations change over time. CMAC retrofits can increase the efficiency and performance of existing systems using compact sensor and outlet control technologies. Two recently deployed CMAC systems, one at a large wet pond and another at a green roof, have effectively doubled the stormwater retention and treatment capacity of the existing BMPs.

Wet Pond, Sligo Creek headwaters, Montgomery County, Maryland

Sligo Creek is a tributary of the Anacostia River, which is impaired for nutrients, sediments, fecal bacteria, impacts to biological communities and toxics—polychlorinated biphenyls (PCBs) and heptachlor epoxide, trash/debris, and PCBs in fish tissue in tidal waters (MDE and DOEE 2008). Eventually draining to the Chesapeake Bay, this site is part of the 64,000-square-mile (166,000-square-kilometer)

| CONTINUOUS MONITORING AND ADAPTIVE CONTROL |



Average Stormwater Retention Time (hours)

	Passive Design	CMAC Design
Long Term	195	170
Wettest Month	80	60

Figure 6. Single-event time series graphs and summary results from a long-term model simulation showing that a passive pond would need to be twice as large as a CMAC pond to achieve similar treatment of stormwater runoff

watershed subject to EPA's "pollution diet" calling for a 25 percent reduction in nitrogen, 24 percent reduction in phosphorus and 20 percent reduction in sediment (EPA 2010). A 15-acre-foot (18,500-cubic-meter) wet pond (Figure 5) collects and retains stormwater draining from 440 acres (180 hectares) at the headwaters of Sligo Creek. The pond provides 24-hour retention of just 3 acre-feet (3,700 cubic meters), falling short of Maryland's requirement to treat 1 inch (2.5 centimeters) of rainfall runoff from impervious surfaces in the drainage area.

A CMAC retrofit, supported by a National Fish and Wildlife Foundation (NFWF) grant, was implemented in November 2015 that installed actuated valves at the outlet structure and a water-level sensor, and connected both remotely to cloud-based software. The software uses real-time forecast information from NOAA to determine the timing and expected volume of incoming storm events. In advance of the storm, the outlet valves are closed such that only Sligo Creek baseflow passes. During and after the storm, the pond retains up to approximately 9 acre-feet (11,000 cubic meters) of runoff volume for a predetermined length of time, currently configured to be 48 hours. After the retention period ends, the software sends a signal to open the valves to release the water downstream. If another storm event is forecasted during the retention period, the software will prepare the pond for the expected incoming volume, thereby maintaining critical flood prevention capacity when it is needed.

Figure 6 shows the results of modeling, illustrating pond behavior with and without CMAC design. The pond without CMAC technology would need

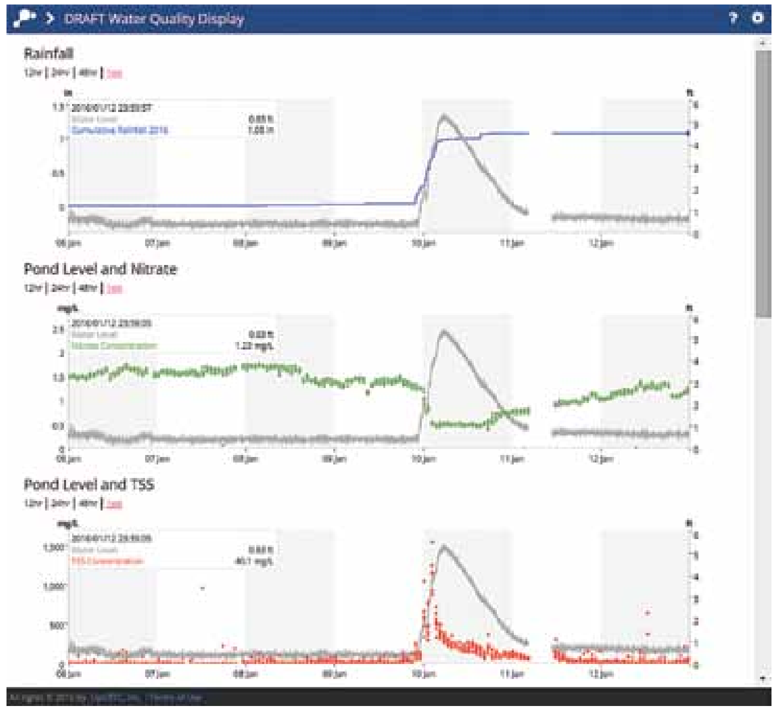


Figure 7. Example real-time and continuous water-quality data available on a web-based dashboard from CMAC systems to verify performance

Figure 8. The CMAC green roof at Villanova University (bottom); indoor cistern collecting runoff from additional, non-green roof to be used for irrigation of green roof (top left); control panel and weather station (top right)

to be twice as large to achieve similar performance over time. The project continuously monitors temperature, nitrate, total suspended solids, conductivity, pH and turbidity to evaluate the CMAC retrofit performance over one year. Figure 7 shows real-time environmental data streaming to a web-based interface, making it immediately available for viewing, download and analysis by project stakeholders.

Green roof, Villanova University, Pennsylvania

Through the Villanova Urban Stormwater Partnership, Villanova University conducts research to understand and optimize BMP performance and promotes innovative designs and technology to the industry. As part of a National Science Foundation (NSF) grant, the university installed a CMAC solution for an existing green roof site. A cistern that collects runoff from a non-green roof is dynamically connected to the green roof to use the evapotranspirative capacity of the vegetated roof year-round (Figure 8).

The green roof covers 750 square feet (70 square meters) and is used for research as well as reduction in stormwater runoff to the university's storm drain system. The 500-gallon (1,890-liter) cistern collects runoff from an additional 840 square feet (78 square meters) of non-green roof and has a water-level sensor, actuated valve and connection to the cloud-based decision software. The software maximizes runoff capture from the non-green roof and optimizes irrigation to the green roof. Between storms the intelligent irrigation logic releases water from the cistern to the green roof based on real-time soil moisture sensor readings. In advance of a storm, the software calculates the timing and expected runoff volume of the event, stops irrigation to the green roof and discharges water from the cistern to the storm drain as needed to make room for the incoming runoff. These automated steps prepare both the green and non-green roofs for maximum runoff capture while reducing potable water demand for irrigation. During an event the green roof performs as designed to capture direct rainfall, and the cistern valve is closed to capture the non-green roof runoff. The researchers can also monitor dozens of sensors on a single web-based interface, shown on Figure 9.

CONCLUSIONS

Advances in sensor technology and Internet connectivity offer an important opportunity for stormwater managers to design smarter, more cost-efficient facilities. Continuous monitoring and verification of performance on an individual facility scale is now possible. Designers and operators of distributed infrastructure can leverage the capabilities of IoT to directly control the hydraulic behavior of facilities based on real site conditions and local weather forecasts. Moving away from static design assumptions is critical to adapt to the changing climate and nonstationarity in water resources conditions.

Both green and gray stormwater infrastructure can benefit from more intelligent, adaptive design approaches. CMAC installations across the country prove that this technology is viable and cost-effective. Many more projects than could be included in this article demonstrate positive performance over time. The small subset presented here shows that:

- Adding CMAC to an underused rainwater harvesting system has eliminated 80 percent of discharges to a combined sewer during wet weather.
- An underperforming pond retrofitted with CMAC will achieve similar target water-quality treatment objectives as a passive storage facility twice its size.
- Green infrastructure designed only to capture and treat its own direct runoff, such as green roofs, can be retrofitted with CMAC storage to capture and treat uncontrolled runoff from other impervious surfaces without compromising existing performance.

CMAC offers a promising solution to the persistent stormwater issues that regulators, municipalities and private landowners continue to face: water availability, water quality, protection of property and protection of public health and safety.

Figure 9. Web-based dashboard view of green roof sensor and weather data

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- Ms. Lefkowitz is a professionally registered civil engineer with a focus on water resources. She holds a bachelor's and master's degree in engineering from Villanova University. She worked for eight years at CDM Smith on large-scale watershed management and integrated water supply planning studies in New England and around the world, providing computer modeling analysis of these water systems to support decision-making with sound science. She joined OptiRTC, Inc., in 2015 to develop a new and powerful way to manage water, by combining web-based technology with readily available field sensors.
- Ms. Sarmanian manages marketing and communications at Opti. She works to develop clear and consistent communication around critical new technologies in stormwater management. She holds a bachelor of arts in international relations from Boston University.
- Mr. Quigley is the founder and CEO of Opti. He has more than 20 years of experience in solving complex engineering problems as well as leading and managing major projects and organizations. Before founding Opti, he was a principal at Geosyntec Consultants and past member of the board of directors. Mr. Quigley holds a master of science in civil engineering from Oregon State University and a bachelor of science in environmental engineering from Notre Dame.

REFERENCES

- DeBusk, K. M., W.F. Hunt and J. D. Wright (2013) Characterization of Rainwater Harvesting Utilization in Humid Regions of the United States. Journal of the American Water Resources Association (JAWRA). 49(6): 1398-1411
- International Stormwater BMP Database. Developed by Wright Water Engineers, Inc. and Geosyntec Consultants for the Water Environment Research Foundation (WERF), the American Society of Civil Engineers (ASCE)/Environmental and Water Resources Institute (EWRI), the American Public Works Association (APWA), the Federal Highway Administration (FHWA), and EPA
- Maryland Department of the Environment (MDE) and District of Columbia Department of Energy and Environment (DOEE). (2008) Total Maximum Daily Loads of Nutrients/Biochemical Oxygen Demand for the Anacostia River Basin
- Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundezewicz, D.P. Lettenmaier, R.J. Stouffer (2008) Stationarity is Dead: Whither Water Management? Science. Vol. 319
- New Hampshire Department of Environmental Services. 2008. Stormwater Manual Volume 1: Stormwater and Antidegradation, Appendix E - BMP Pollutant Removal Efficiency
- USACE (2015). Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions—Water Resources Region 01, New England. Civil Works Technical Report, CWTS-2015-20, USACE, Washington, DC
- U.S. Environmental Protection Agency (USEPA) Office of Water. (2009) National Water Quality Reporting Inventory: Report to Congress. EPA 841-R-08-001
- U.S. Environmental Protection Agency (USEPA) (2010) Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus, and Sediment

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