



From passive to dynamic storage

Retrofitting a stormwater retention pond with continuous monitoring and adaptive control technology helps Philadelphia address combined sewer overflows

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During the past decade, the Philadelphia Water Department (PWD) has emerged as a leader in efforts to address combined sewer overflows (CSOs) by innovative means, particularly through green infrastructure. Rather than controlling overflows solely by storage tunnels and other traditional gray infrastructure, PWD adopted its nationally recognized Green City, Clean Waters program in 2011.

The groundbreaking effort promotes the widespread implementation of green infrastructure practices designed to capture and manage stormwater onsite, reducing the volume of runoff entering the city's combined sewers. In keeping with this cutting-edge approach to stormwater management, PWD recently implemented continuous monitoring and adaptive control (CMAC) technology on a project for the first time.

◀ **Retrofitting this retention basin with continuous monitoring and adaptive control technology brought the facility into compliance with Philadelphia's stormwater management standards.** OptiRTC

Used to retrofit an underperforming retention pond, the technology enables remote monitoring and dynamic control of stormwater management facilities, improving performance cost effectively while providing real-time sensor data to facilitate analysis of system performance.

Preventing runoff, reducing overflows

Philadelphia is far from alone in its efforts to address CSOs. Urban stormwater management represents one of the most pervasive, significant environmental issues in the U.S. More than 770 U.S. cities having a total population of approximately 40 million people have combined sewers, the overflows from which represent a major source of water pollution. Aggressive enforcement actions by the U.S. Environmental Protection Agency (EPA) and states have led to widespread efforts by municipalities with combined systems to reduce CSOs. As they strive to meet federally mandated mitigation requirements, communities seek cost-effective, innovative solutions.

Through its Green City, Clean Waters plan, Philadelphia aims to avoid costly storage and treatment solutions by preventing runoff from entering its combined sewer system. For its part, PWD has committed to reducing 29.9 million m³ (7.9 billion gal) of overflows by managing the first inch of runoff from 3870 impervious ha (9564 impervious ac) by 2036.

This milestone will be achieved through public capital improvement projects and a combination of private redevelopment and incentivized retrofits. For example, PWD's Stormwater Management Incentives Program provides capital funding and reduced annual stormwater fees to encourage nonresidential customers to retrofit or install stormwater management practices voluntarily. In this vein, PWD's incentives program has facilitated innovative opportunities to enhance the performance of existing stormwater assets that were built between 1980 and 2015 by using new technologies.

Optimizing storage

CMAC technology offers a cloud-based approach for assessing and operating stormwater facilities. Figure 1 (right) shows the basics of how CMAC works.

By monitoring weather forecasts and water levels in a storage system, CMAC technology facilitates automatic remote control of outflows from the system to maximize its effectiveness and efficiency. In essence, the approach converts passive infrastructure into a dynamic system that can use

storage much more cost effectively compared to expanding existing infrastructure. Besides improving storage capabilities, the approach also helps achieve such goals as peak-flow reduction and improved water quality.

As part of its strategy to meet the Green City, Clean Waters milestones, PWD has recognized that advancements in sensing and control technologies have an important role to play in mitigating CSOs through runoff reduction. CMAC enhancements can help communities achieve compliance and triple-bottom-line objectives by

- reducing implementation time, cost, and risk;
- increasing infrastructure resiliency in a changing climate;
- providing performance data for stormwater management practices; and
- reducing the scope of major construction projects and limiting public inconvenience.

Private property example

With these benefits in mind, PWD awarded grant funding through its Stormwater Management Incentives Program to enable the private owner of an existing retention basin to retrofit the facility by installing CMAC technology. The retrofit was needed because the retention basin was not meeting PWD's current stormwater management standards. Since the retrofit, the retention basin has achieved the project goals of complying with the standard, further reducing wet weather flows to the city's combined sewer, and increasing treatment of detained runoff.

The retention basin collects runoff from 3.2 ha (8 ac) on private property. According to PWD's stormwater management standards, for all areas served by a combined sewer and where infiltration is infeasible, 100% of the runoff from 38 mm (1.5 in.) of rainfall must be routed through an acceptable pollutant-reducing practice and detained for no more than 72 hours. Furthermore, any detained runoff may not be released from the site at a rate that exceeds 0.001 m³/s (0.05 ft³/s) per impervious acre. If all areas draining to the combined sewer system comply with this limit, the sewer system and

Figure 1. Depiction of continuous monitoring and adaptive control technology

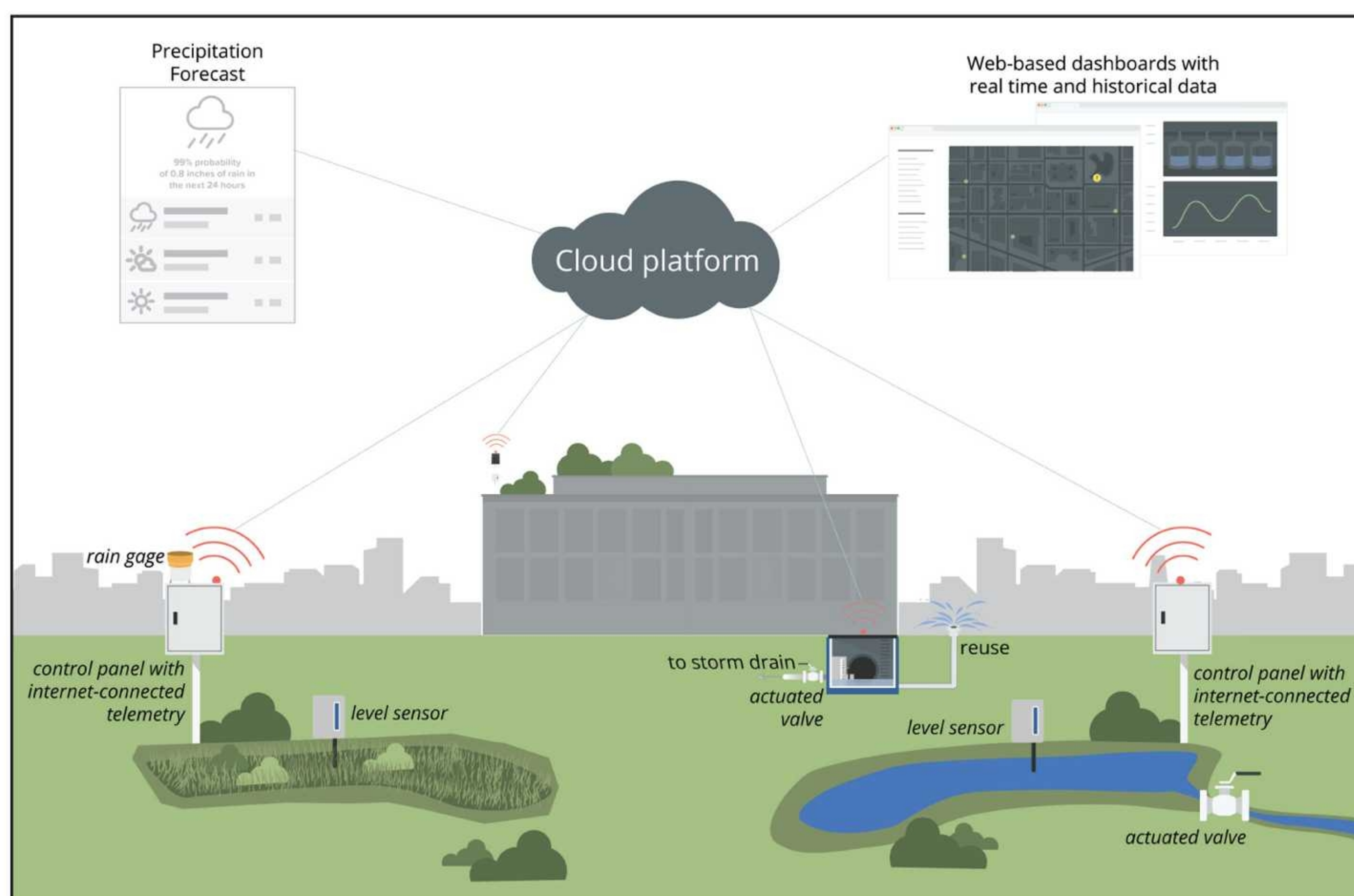
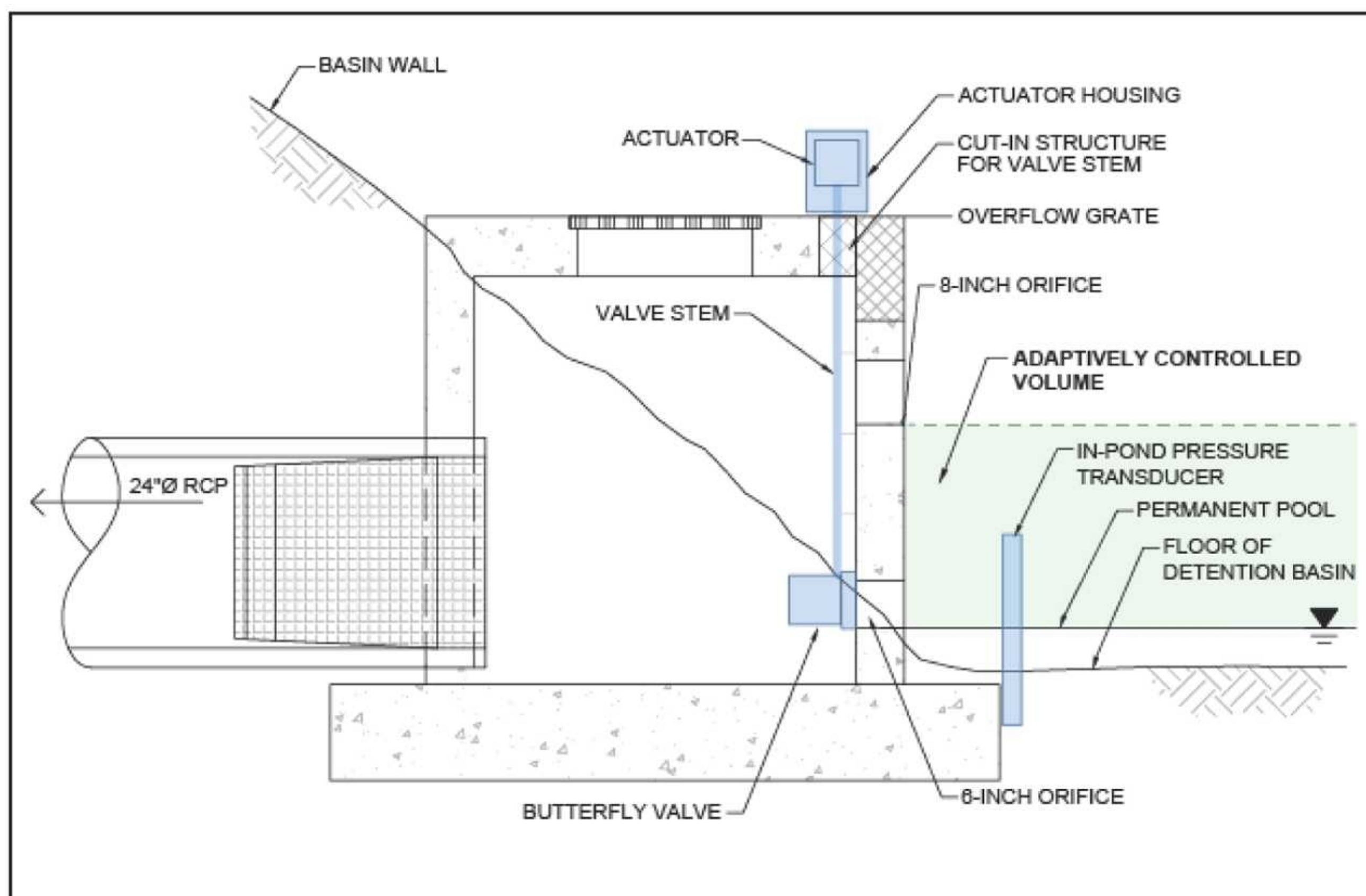


Figure 2. Retention basin outlet structure



the downstream water resource recovery facility can accommodate the incoming flows, thereby avoiding CSOs. Because 2.1 ha (5.2 ac) of impervious area drain to the retention basin, its maximum discharge rate equates to 0.007 m³/s (0.26 ft³/s).

Although originally designed as an infiltration basin, the existing basin does not infiltrate sufficiently. Rather than attempting to conduct an expensive reconstruction of the basin, PWD funded a much more cost-effective approach – installation of CMAC technology on the existing outlet control structure of the basin. The system includes a water level sensor, actuated valve, and integrated, cloud-based software that provide dynamic control of stormwater storage and discharge of flows in excess of the permanent pool of water in the existing basin.

Configuring the retrofit

The stormwater pond contains a permanent pool of 637 m³ (22,500 ft³) maintained by an outlet structure with a 150-mm-diameter (6-in.-diameter) orifice. A second 200-mm-diameter (8-in.-diameter) orifice is positioned approximately 0.6 m (2 ft) above the invert of the lower orifice, and an overflow weir is approximately 0.6 m (2 ft) above the upper orifice. (See Figure 2, above.)

The retrofit involved installing a 150-mm-diameter (6-in.-diameter) actuated valve on the existing orifice of the same size and a water level sensor, both of which are wired to a control panel to connect these items to the cloud-based control software. The software uses the water-level data along with storm forecasts provided by the U.S. National Weather Service to determine the optimal percentage that the valve should be open to minimize storm flows to the combined sewer.

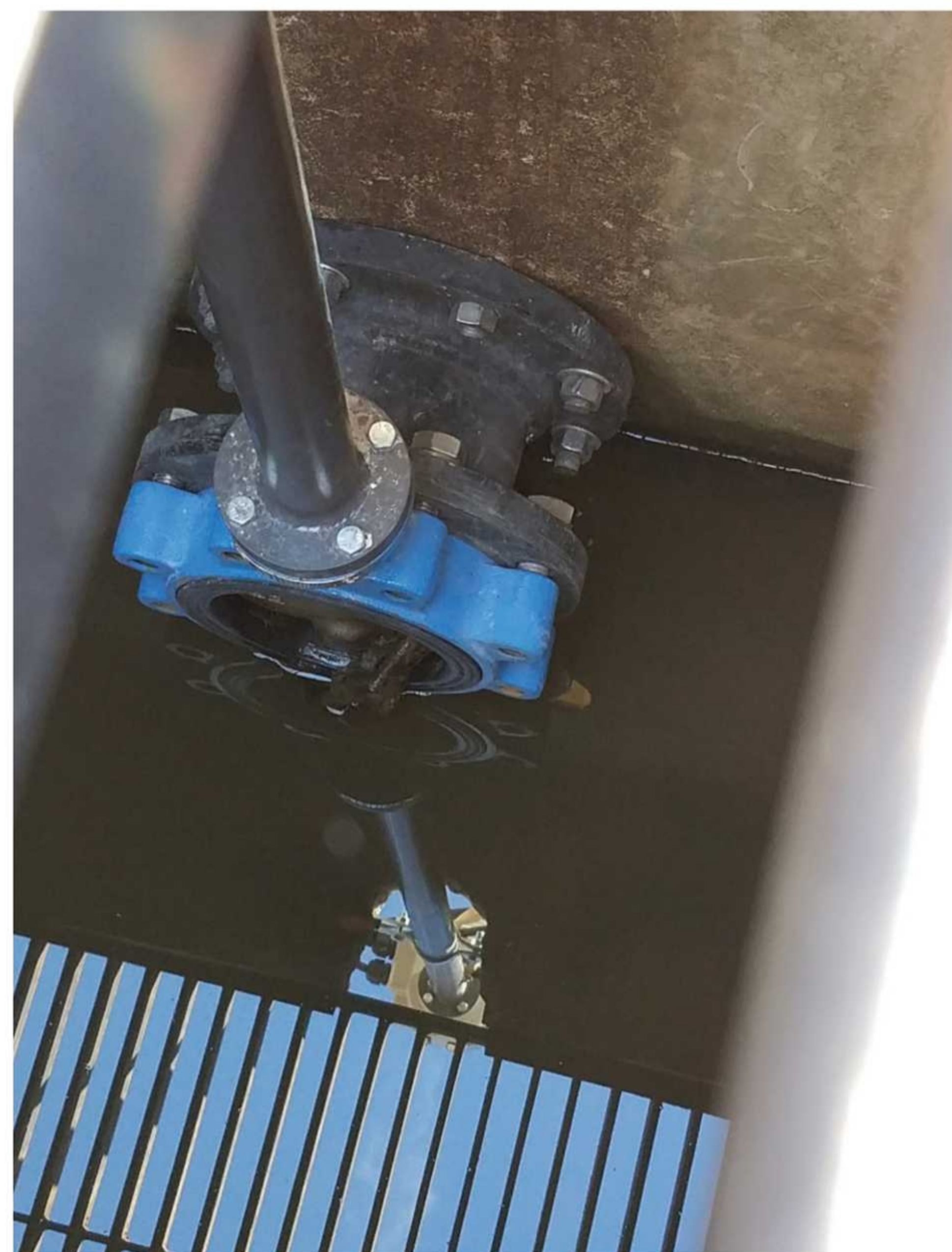
For this basin, the software was configured to achieve the following logic.

- When the anticipated runoff from a forecasted storm can be fully captured within the basin storage between the permanent pool and the 200-mm-diameter (8-in.-diameter) orifice, close the actuated valve to eliminate wet weather flow.
- After the event, open the valve to release the captured runoff within the 72-hour retention period without exceeding the maximum discharge of 0.007 m³/s (0.26 ft³/s).

- When the forecast indicates that runoff from an upcoming storm cannot be fully captured, release water from the basin at the lowest possible rate to avoid overflowing the riser structure. This logic ensures that the target of 0.007 m³/s (0.26 ft³/s) is only exceeded during large events to mitigate high water levels and flow rates. Following the event, release any captured storm runoff within the 72-hour retention period without exceeding the target.

The storage volume available above the permanent pool of water and below the invert of the larger orifice is 1076 m³ (38,000 ft³). This volume is larger than the runoff generated by a 50-mm (2-in.) storm event, which corresponds to 963 m³ (34,000 ft³). Therefore, for all rainfall

events up to 50 mm (2 in.), the retrofitted basin is able to fully capture the runoff with no discharge to the combined sewer during the wet weather event. After the event, the valve will slowly but continuously adjust, by opening further as the driving head drops, to match the target release rate until the basin returns to its permanent pool elevation.



The continuous monitoring and adaptive control system uses the water-level data along with storm forecasts to determine the optimal percentage that the outlet's discharge valve should be open to minimize flows to the combined sewer. OptiRTC



The retrofit involved installing a 150-mm-diameter (6-in.-diameter) actuated valve on the existing orifice of the same size, a water level sensor, and a continuous monitoring and adaptive control panel to connect these items to a cloud-based control software. OptiRTC

Safely accommodating large events

Along with meeting the requirements for stormwater retention credits, the retrofit facility still safely accommodates flows associated with larger storm events. The pond bathymetry and outlet structure configuration were not changed as part of the retrofit. To avoid overtopping the outlet structure, the CMAC system's software logic will open the valve as far as is needed, up to fully open for very large events. When the valve is fully open, the retrofitted facility has the same peak flow and maximum water surface elevation as the original basin. If the CMAC system were to fail to function properly and the 150-mm-diameter (6-in.-diameter) valve was closed during a large event, modeling shows that the basin will safely convey all runoff associated with the 100-year event and will not contribute to local flooding.

The CMAC system includes the following fail-safe features that protect the infrastructure in the event of failures related to connectivity or physical hardware.

- Locally programmed fail-safe logic at the on-site controller will control the valve if cellular data connectivity is lost.
- Battery backup enables the fail-safe to actuate the valve in the event of a power failure.
- Remote manual controls allow any authorized user to control the valve manually from any Web browser.

- On-site manual controls allow maintenance staff to control the valve electronically or with a hand crank.
- E-mail alerts are sent when cellular connectivity is lost, the pond reaches the overflow elevation, or any data needed by the software to make a control decision is unavailable.

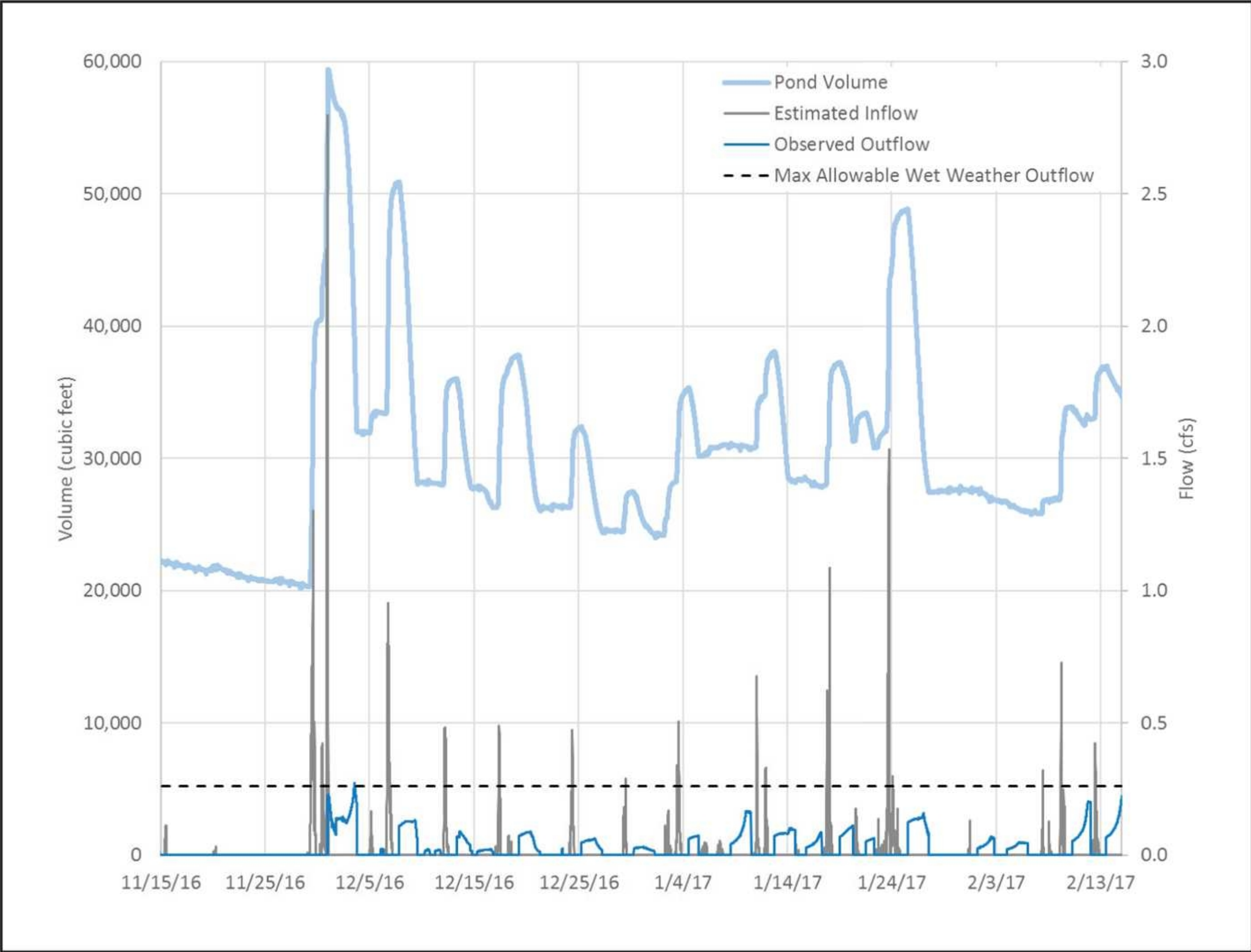
Comparing the retrofitted and original systems

Installed in November 2016, the CMAC retrofit has been collecting hydraulic data continuously while adaptively managing the pond discharge. To analyze system performance, the control software collected continuous real-time sensor data from November 2016 to February 2017. The data used for this performance analysis included minute-by-minute records of

- water elevation,
- pond volume,
- wet and dry weather, as indicated by the National Weather Service forecast information, and
- the percent to which the valve was open.

The data analysis involved calculating the outflow rate, based on water level and valve state, and estimating the inflow rate, based on the wet/dry weather indicator and a system volume mass balance. The outflow calculations were calibrated to match the observed pond

Figure 3. Observed pond volume and flows with continuous monitoring and adaptive control system



drawdown. The estimated inflow time series was validated against nearby rainfall records for the same period.

The data indicate that 187 mm (7.35 in.) of rain fell at the site between Nov. 14, 2016, and Feb. 17, 2017. For the purposes of comparison, 197 mm (7.77 in.) of rainfall were recorded at Philadelphia International Airport, which is located 11.6 km (7.2 mi) south of the site. Inflows to the retention basin were estimated based on an effective impervious cover of 20,537 m² (221,066 ft²) at the site. The estimated inflow was used as input to a hydraulic model of the pre-retrofit, passive pond for the same time period. The model of the pre-retrofit, passive system used the inflow time series and hydraulic equations to produce a pre-retrofit condition outflow rate time series, facilitating direct comparison with the post-retrofit, observed outflow rate time series. Figures 3 and 4 (above and right, respectively) show the time series of observed, calculated, and modeled flow rates and pond volumes for the retrofitted basin equipped with the CMAC system to control the outlet and the original basin with passive outlet control.

During the 95-day analysis period, 14 rainfall events were observed. An “event” is defined as a period of precipitation occurring at

least 24 hours after the previous one and resulting in measurable runoff – that is, greater than 2.5 mm (0.1 in.) of precipitation. The estimated size of these precipitation events ranged from 2.5 to 53 mm (0.1 to 2.1 in.). The table on p. 51 lists the events along with the estimated precipitation depth, peak inflow rate, peak observed outflow rate during wet weather, peak observed outflow rate observed during dry weather after the event, and peak passive outflow rate during wet weather (all peak passive outflows occur during wet weather).

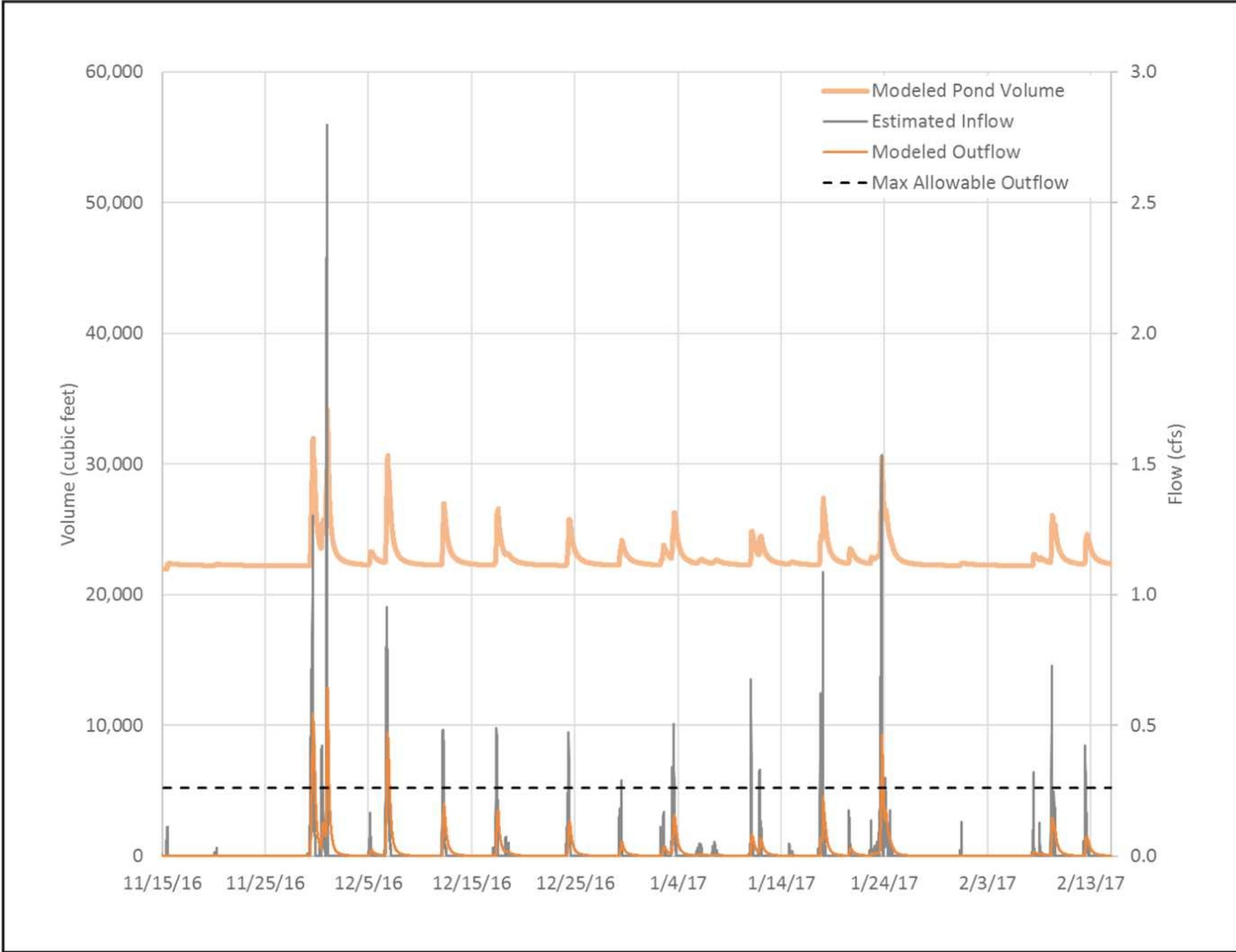
Performance results

The CMAC system prevented wet weather outflow rates from exceeding the maximum allowable release rate of 0.007 m³/s (0.26 ft³/s) in all events. By comparison, the model results

indicate that the pre-retrofit pond would have released flows above this threshold during 3 of the 14 storm events.

The CMAC system is designed to maintain flows below the wet weather flow threshold, even in dry weather, for events up to 50 mm (2 in.) per impervious acre. The Nov. 29 event involved 53 mm (2.1 in.) of precipitation. Following this event, the system discharged outflows at a peak rate slightly above

Figure 4. Modeled pond volume and flows with passive outlet control



Rainfall events and system performance with and without the continuous monitoring and adaptive control (CMAC) system

Start date	Precipitation, mm (in.)	Peak uncontrolled flow, m³/s (ft³/s)	With CMAC		Without CMAC
			Peak observed wet weather outflow, m³/s (ft³/s)	Peak observed dry weather outflow after event, m³/s (ft³/s)	Peak modeled passive wet weather outflow, m³/s (ft³/s)
2016					
Nov. 29	53 (2.1)	0.08 (2.80)	0.007 (0.23)	0.008 (0.28)	0.018 (0.65)
Dec. 5	2.5 (0.1)	0.005 (0.16)	0.00	0.001 (0.02)	0.001 (0.02)
Dec. 6	23 (0.9)	0.03 (0.95)	0.00	0.004 (0.13)	0.013 (0.47)
Dec. 12	10 (0.4)	0.014 (0.48)	0.00	0.003 (0.09)	0.006 (0.2)
Dec. 17	10 (0.4)	0.014 (0.49)	0.00	0.003 (0.09)	0.005 (0.18)
Dec. 24	7.6 (0.3)	0.014 (0.47)	0.00	0.002 (0.06)	0.004 (0.13)
Dec. 29	2.5 (0.1)	0.008 (0.29)	0.00	0.001 (0.03)	0.001 (0.05)
2017					
Jan. 2	10 (0.4)	0.014 (0.51)	0.00	0.002 (0.07)	0.005 (0.16)
Jan. 10	7.6 (0.3)	0.019 (0.68)	0.00	0.003 (0.10)	0.002 (0.08)
Jan. 17	13 (0.5)	0.030 (1.09)	0.00	0.003 (0.11)	0.007 (0.23)
Jan. 20	2.5 (0.1)	0.005 (0.18)	0.00	0.002 (0.06)	0.001 (0.03)
Jan. 22	25 (1.0)	0.043 (1.53)	0.00	0.005 (0.16)	0.013 (0.47)
Feb. 7	10 (0.4)	0.020 (0.73)	0.00	0.006 (0.20)	0.005 (0.15)
Feb. 12	5.1 (0.2)	0.012 (0.42)	0.00	0.006 (0.22)	0.002 (0.07)

Note: Precipitation recorded at Philadelphia International Airport. Highlighted cells show flow rates that violate the Philadelphia Water Department's wet weather discharge criteria for this site of 0.007 m³/s (0.26 ft³/s).

the limit of 0.007 m³/s (0.26 ft³/s). This outcome occurred because the pond was not draining as quickly as expected, and so had more volume to drain in a shorter period of time as the 72-hour retention period expired. Notably, this higher discharge occurred in *dry* weather, meaning that it most likely did not contribute to any CSO event. The CMAC system's software settings were adjusted to prevent this outcome from recurring. This adjustment exemplifies the ability to optimize system performance after installation, based on the actual observed behavior of a system in the field.

During its first 90 days of operation, the CMAC system exceeded PWD's criteria for wet weather site discharges, completely avoiding wet weather outflows during nearly all rain events.

All told, the 14 storm events occurring during the first 90 days of the retrofitted system's operation generated approximately 3820 m³ (1.01 million gal) of runoff. Of this amount, the dynamically controlled system prevented 3670 m³ (970,000 gal) from entering Philadelphia's combined sewer during wet weather. Moreover, the system also maintained a very low release rate during dry weather, averaging 0.003 m³/s (0.10 ft³/s). In fact, 90% of the time, the system discharged water during dry weather at a rate of 0.0001 m³/s (0.004 ft³/s) or lower, helping to avoid dry weather overflows and unwanted flow volatility at the water resource recovery facility.

Multiple benefits

As the first use of CMAC technology on a stormwater project in Philadelphia's combined sewer area, the retrofitted retention basin illustrates the advantages associated with dynamically controlled stormwater management systems. Ultimately, the incorporation of the system within the basin is expected to confer multiple benefits for PWD, both in terms of cost savings and environmental improvement.

With an estimated price tag of \$131,000 per greened ha (\$53,000 per greened ac), the retrofit project cost significantly less than typical green infrastructure projects conducted by PWD within the public right of way.

Along with minimizing wet weather discharges from the site for storm events generating as much as 50 mm (2 in.) of precipitation, the system extends the residence time for water in the retention basin. The longer residence times enhance gravitational settling and nutrient uptake through biological processes, improving water quality of inflows to the water resource recovery facility. Finally, the integrated nature of the CMAC system enables improved system monitoring, adaptability, and reporting capabilities to PWD.

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