Digitalizing Stormwater Infrastructure

Focus on Below-Ground Systems

by

Christopher M. Foley, PhD, PE, FASCE
President

Nicholas J. Hornyak, PhD, PE
Vice President – Construction & Sensor Technology

P4 Infrastructure, Inc. White Paper Report 2026-01

May 18, 2026

P4 Infrastructure, Inc.
9090 N. 51st Street
Brown Deer, WI 53223

414-446-4145
www.p4i.io

Introduction

Stormwater infrastructure spending in the United States is increasing at significant rates. It is estimated that the total addressable market for below-ground stormwater infrastructure systems is in the range $800 million to $1.5 billion annually in the mid-2020's[1]. The Compound Annual Growth Rate (CAGR) for spending on these types of systems is projected to be 7-10% and potentially 10-14%[2]. It is projected that the market in 2030 could rise to $1.3-$2.5 billion[3].

Below-ground detention and infiltration stormwater infrastructure systems come in a variety of materials from several manufacturers. These systems are made from high-density polymer materials and reinforced concrete. A very popularly employed system is modular precast concrete. A snapshot of the manufacturers of these systems and their products is shown in Figure 1.

Figure 1. Below-Ground Infiltration and Detention Systems and Manufacturers

The main drivers for use of these systems are urbanization, climate variability, space constraints, aging infrastructure, and stricter regulations for flood control and water quality. These, and other, systems are often referred to as stormwater runoff Best Management Practices (BMPs). While used in the past primarily as flood control BMPs, below-ground systems are quickly evolving into water quality BMPs through addition of pre-treatment devices upstream and sediment capture systems within them (*e.g.* specialized devices, sediment

[1] www.finance.yahoo.com
[2] https://www.linkedin.com/pulse/market-revenue-forecast-north-america-underground-stormwater-uihne/
[3] https://www.marknteladvisors.com/research-library/us-stormwater-infrastructure-market.html

collection bays). Below-ground systems generally have lower on-going costs when compared to surface systems due to minimal need to maintain vegetation and perform landscape maintenance. It is safe to say that below-ground stormwater management infrastructure systems are an important tool in the stormwater manager's toolkit and their installation and on-going use will continue.

Performance Documentation and O&M Expenses

Stormwater management practice is maturing very rapidly. The number of companies providing stormwater infrastructure systems and components grows annually. The sheer variety of systems and their systematic deployment throughout watersheds renders management and performance documentation of the individual infrastructure component and its contribution within the watershed network of systems a challenge.

The Wisconsin Department of Natural Resources (WI DNR) establishes requirements for managing stormwater runoff[4] and issues stormwater discharge permits[5]. Private owners of stormwater infrastructure systems must submit Storm Water Management Program Plans (SWMPPs) consistent with NR 151/NR 216 requirements. The State of Wisconsin issues Municipal Separate Storm Sewer System (MS4) permits to municipalities, villages, university campuses, and consortia using NR 151/NR 216 as the basis for permitting. MS4 permits are reviewed and renewed on a regular basis. Integration of privately owned BMPs into MS4 permittee's management plans has historically been a challenge. If an MS4 permittee plans to utilize privately owned stormwater infrastructure in their MS4, they will require a stormwater infrastructure management agreement signed by the private owner. If the privately owned stormwater infrastructure is transferred to a new owner, the management plan is transferred as well.

The SWMPP's developed by municipalities to meet the requirements of NR 216 require long-term maintenance of the stormwater infrastructure systems. This maintenance has commensurate long-term expenses. There are several drivers of long-term maintenance expenditures:

- Private owners typically handle regular inspections of their stormwater infrastructure and must demonstrate performance.
- Municipalities often enforce long-term maintenance through recorded maintenance agreements, which may mandate annual (or more frequent) inspections, documentation, and repairs.
- Quarterly inspections are sometimes referenced, but annual inspections are commonly required to demonstrate on-going performance.

Inspections of below-ground stormwater infrastructure systems are relatively unique when compared to other stormwater infrastructure (e.g. surface ponds, permeable pavement, biofiltration) systems. These inspections are

[4] Wisconsin Administrative Code, Chapter NR 151, Runoff Management
[5] Wisconsin Administrative Code, Chapter NR 216, Stormwater Discharge Permits

typically of two types: typical and those that require confined space entry. A high-level description of these types of inspections is described below.

Typical Inspection

- Visual checks of inlets/outlets
- Evaluation of sediment accumulation
- Condition of access points and/or manholes
- Structural integrity of the system
- Signs of clogging or failure to infiltrate or changes in infiltration rates (for an infiltration system)
- Signs of changes in discharge duration
- Post-event performance (e.g. infiltration rate, drawdown)
- Documentation and reporting (possibly involving PE stamp for compliance)
- Process and Cost
  - Site Visit
  - Assessment
  - Reporting
  - Estimated Cost: $500 to $1,500 per inspection

Confined Space Entry Inspection

The need for confined space entry depends upon the system being considered. One could argue that entry into the below-ground system is not required annually but is required on a regular basis. If confined space entry is required, it has several additional requirements that are outlined below.

- <u>Crew and Training</u>: at least one authorized entrant, an attendant, and often a supervisor is required to enter the confined space (i.e. the below-ground system).
- <u>Equipment</u>: atmospheric monitoring devices are required, ventilation systems may be needed, harnesses/lifelines/retrieval systems are required, Personnel Protective Equipment (PPE), communication devices, and possibly lighting and/or dewatering pumps.
- <u>Procedures</u>: Pre-entry atmospheric testing, permitting, ventilation setup, continuous monitoring, and emergency rescue plans/notifications. There is additional equipment set-up and tear-down required and this generally adds 2-3 hours per inspection. Local emergency response personnel (e.g. local police and fire) notifications are required on date of entry.
- <u>Access Challenges</u>: Manhole vault openings are typically 24-inches in diameter and create challenges for entry. There is the potential for standing water in the below-ground system that may require removal prior to entry.
- Process and Cost
  - Labor (2-4 person crew)

➢ Equipment
➢ Time on Site (3-6 hours)
➢ Reporting
➢ Estimated Cost: $2,000 to $4,000 per inspection

It is apparent that inspection of below-ground stormwater infrastructure systems poses unique challenges to meet the regulatory requirements for long-term performance and these challenges present commensurate costs. From the owner's perspective (municipal, university campus, private) the long-term maintenance documentation and reporting have a cash flow cycle and amortization of these long-term costs annually facilitates annual budgeting. Capital expenditures for a below-ground system can range from $150,000 to $10,000,000 depending upon the volume required. A schematic of the owner's cash-flow cycle for a below-ground system is provided in Figure 2.

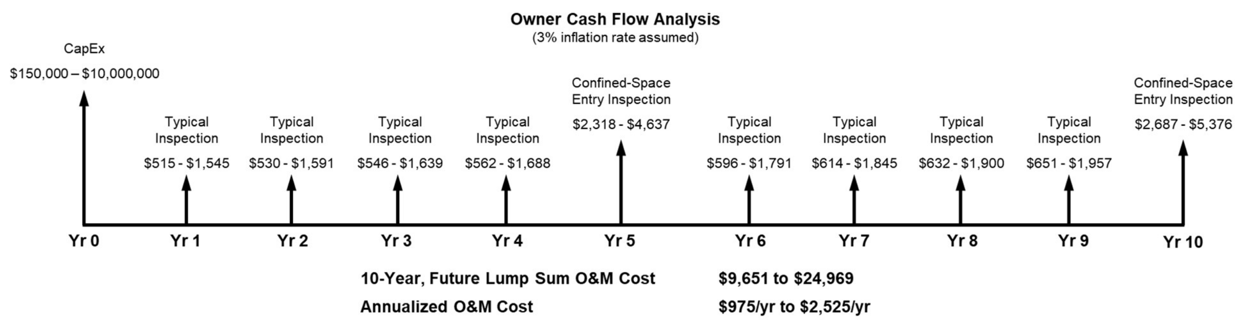

Figure 2. Long-Term Maintenance Cash-Flow and Annual Cost Estimate

Aside from the pure "cost" of long-term maintenance and performance documentation, there are several higher-level considerations to manual inspections of below-ground stormwater infrastructure. Manual inspections are labor intensive and in the case of confined space entry personnel safety is of paramount importance. Manual inspections tend to be infrequent (unless mandated and enforced) leading to gaps in performance documentation. Manual inspections are subjective, leading to variations in interpretation that can lead to inadequate assessment of actual performance of the system. Finally, manual inspections are limited in that they do not document actual performance of the system.

Digitalizing a below-ground system with tools to acquire real-time performance data in response to real rainfall events is valuable. Digitalization offers the following advantages to traditional manual inspections:

✓ Continuous, real-time monitoring of rainfall demand and system response with remote and autonomous documentation
✓ Low to zero maintenance of the digitalization system for years of service
✓ Actionable insights related to performance and more importantly, documented changes in performance over time leading to data-driven maintenance interventions rather than reactive maintenance

- ✓ Bullet-proof regulatory compliance documentation
- ✓ Verifiable asset performance that is very valuable for a private owner intending to turn-over properties
- ✓ Data-driven watershed-level performance documentation for MS4 regulatory compliance.

Digitalization of below-ground systems presents the opportunity to move in an innovative direction for stormwater management and jump a regulatory compliance gap that is present in the management of stormwater infrastructure systems. This is schematically shown in Figure 3.

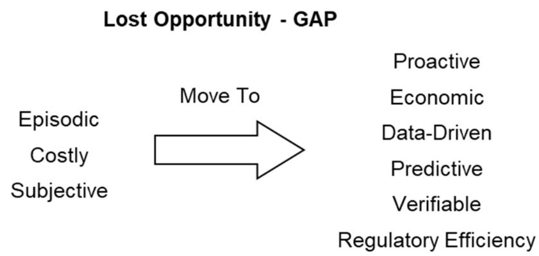

Figure 3. Lost Opportunity and Gap Achieved via Digitalization in Stormwater Infrastructure

P4 Infrastructure, Inc. Digitalization Kits and Cloud-Compute Platform

P4 Infrastructure, Inc. in Brown Deer, WI has developed a suite of digitalization kits and a cloud-based data platform with wireless transmission that sets the stage for digitalization of stormwater infrastructure systems including below-ground detention and infiltration. A schematic illustration of P4's products and services is shown in Figure 4.

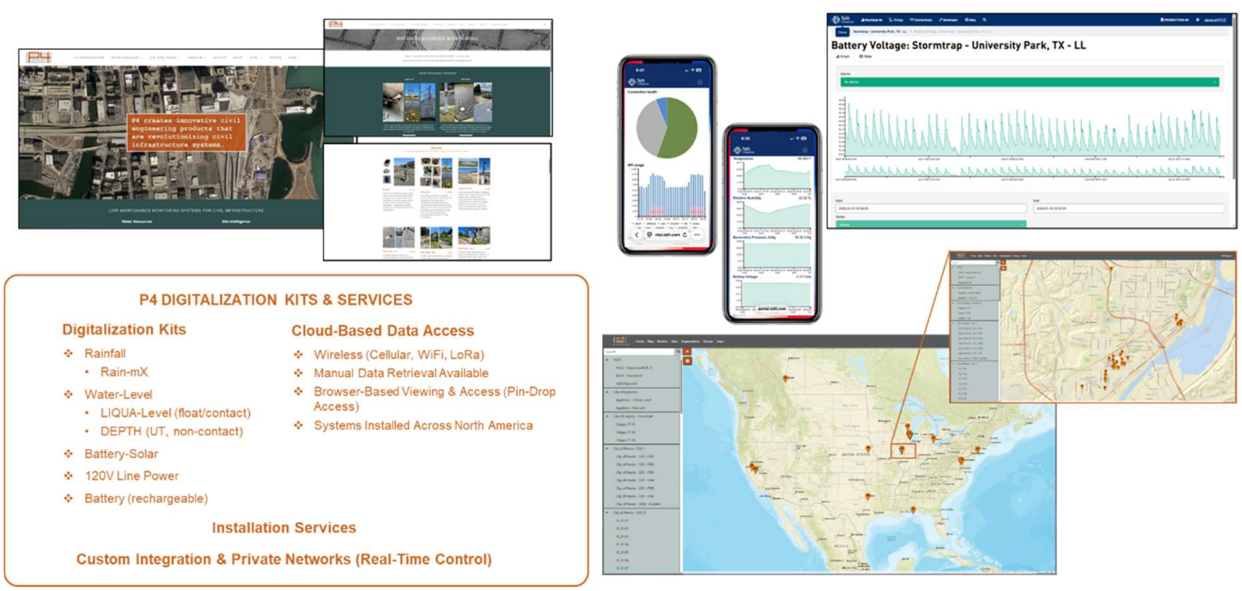

Figure 4. Digitalization Kits, Cloud-Based Wireless Data Platform and Services Provided by P4.

There are several P4 digitalization kits applicable to below-ground stormwater infrastructure. The first is the rainfall and environmental monitoring system: Rain-mX. This is a stand-alone system that can be mounted to vertical poles or flat roofs in the catchment watershed. The Rain-mX kit has a data acquisition rate of 10-minutes for rainfall, barometric pressure, temperature, and relative humidity. The system includes wireless cellular data transmission to P4's browser-based viewing and data access platform.

The second set of systems measure water level. The two systems are fundamentally different in the following manner: in-contact with the water and NOT in contact with the water. These systems contain several options described below:

LIQUA-Level

This digitalization kits is a contact Hall Effect float-based sensor with measurement ranging from 0" to 120" with 0.25-inch resolution. The 120-inch maximum length is defined because of shipping considerations. Longer lengths can be accommodated via multiple LIQUA-Level sensors (*e.g.* 140 inches of measuring range can be accommodated with 80-inch and 60-inch sensors mounted in tandem). Mounting of the sensor inside the below-ground system is most often done within an observation well or against the tank wall. If cellular connectivity is to be used, and cellular signal strength is reliable, a composite manhole rim and cover should be used to facilitate cellular data transmission from the manhole riser.

DEPTH

The DEPTH kit is a non-contact ultrasonic (UT) sensor with measuring ranges from 0" to 168" with 0.10-inch resolution. The DEPTH sensor system is conveniently mounted inside the manhole access risers typically found in below-ground systems. If cellular connectivity is to be used, and cellular signal strength is reliable, a composite manhole rim and cover should be used to facilitate cellular data transmission from the manhole riser.

The LIQUA-Level and DEPTH digitalization kits have several power supply options. The sensor and computer systems are all low-voltage (12 VDC) systems. The unique scenarios at a specific location will drive the system selection.

Battery Power

The battery-powered versions include two rechargeable battery packs with 6-month to 1-year service life. The battery version is equipped with USB data access. Users will be required to download data via the USB interface (CSV format). The visit that includes USB data download is also convenient for rechargeable battery exchange. P4 products are plug-and-play. The depleted battery pack will then be recharged and exchanged at the next data download.

Battery – Solar Power

The battery-solar powered version requires sunlight access to the solar panels that continuously recharge the battery powering the system. This is easily accomplished via P4's stand-alone pole mounting kit. If the stand-alone pole mount for the computer system is utilized, there will need to be a conduit run from the sensor location to the stand-alone pole. The sensor wire will then be run from the sensor location to the stand-alone pole through the conduit. P4 also provides a direct-bury sensor wire option that will not require conduit. The system is low-voltage (12 VDC) and is analogous to landscape lighting systems. Therefore, burial depth is nominal.

120V Line Power

The LIQUA-Level and DEPTH digitalization kits will utilize cellular data transmission if the site allows for reliable cellular connectivity. If cellular data transmission is possible the data is transmitted on 10-minute intervals and stored in the P4 cloud-compute platform for viewing and access. If cellular transmission is not possible, P4 kits with USB data access is recommended. Data can be accessed via USB download when battery pack exchange occurs. If data is desired in the P4 cloud-compute platform, the user will transfer data to P4 for inclusion. Users can also manually view the downloaded data in their own platform.

The selection of the appropriate P4 digitalization kit for water level can seem daunting. However, the P4 systems have a very simple selection process. The flowchart in Figure 5 schematically describes the selection of the water-level and rainfall monitoring kits.

The P4 cloud-compute platform is map-centric. In other words, data is accessed via pin drops and downloaded into CSV format. This allows watershed-level digitalization to be viewed. It also allows watershed-wide stormwater infrastructure data to be easily aggregated for regulatory compliance considerations. The P4 cloud-compute platform is felt to be the ideal venue for MS4 permittees to record performance data for all stormwater infrastructure in the watershed they manage. It also facilitates incorporation of privately owned stormwater best management practices to be included and recorded by the MS4 permittee(s).

It should be noted that digitalization kits can be purchased and used by firms that offer services for stormwater infrastructure inspection and documentation of performance.

Below-Ground System Digitalization Examples

P4 digitalization kits have been deployed and are operational throughout North America. Permeable pavement systems have been digitalized, biofiltration systems have been digitalized, surface infiltration systems have been digitalized, below-ground systems have been digitalized, and rooftop detention systems have been digitalized. The following will outline digitalization of major below-ground systems in Appleton, Wisconsin, University Park, Texas, and Naperville, Illinois. The examples will outline performance of below-ground detention systems and an example where a private owner will employ a digitalization kit to meet the requirements of a municipal stormwater management plan.

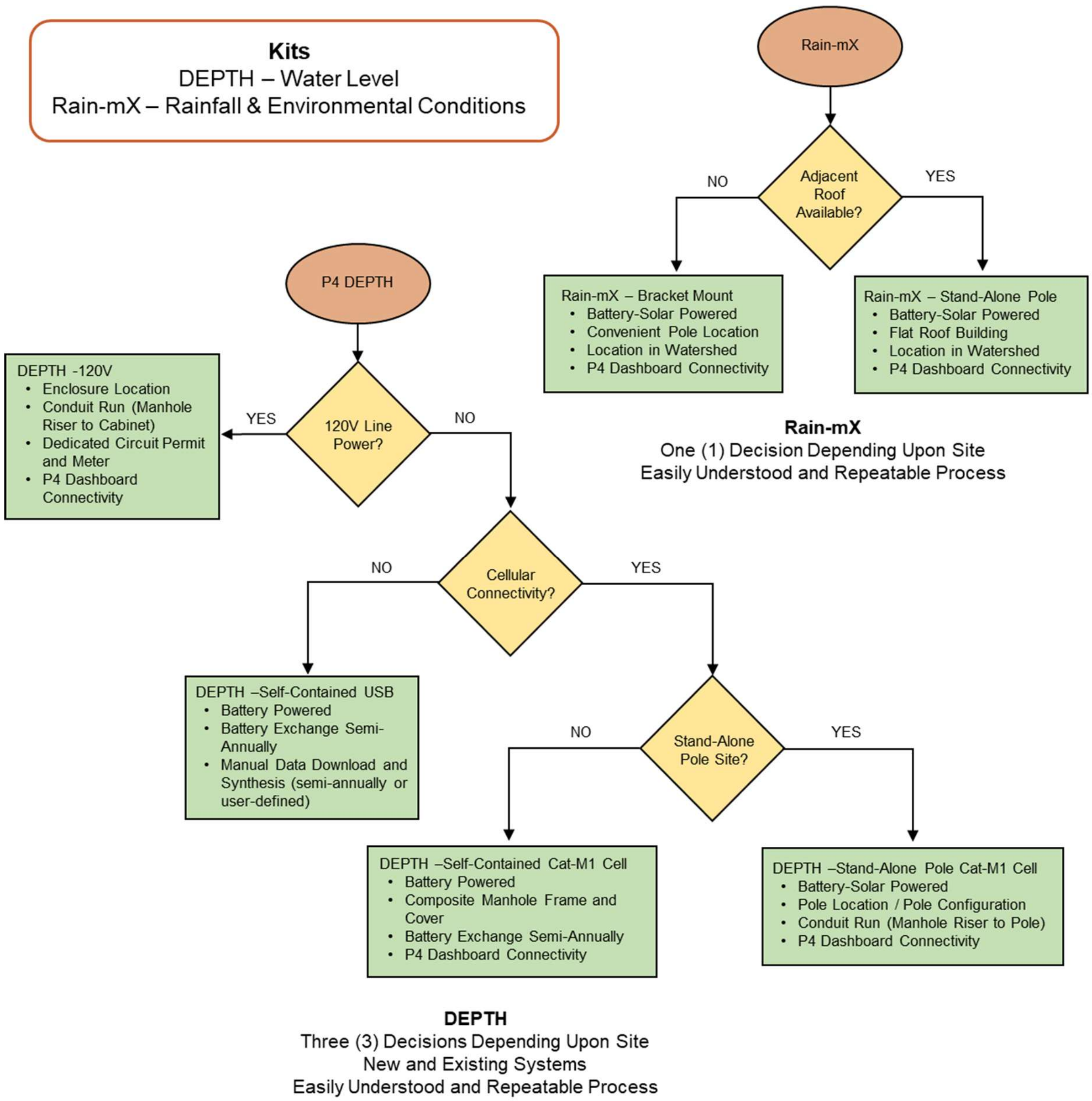

Figure 5. Selection Flowchart for P4 Rain-mX, LIQUA-Level and DEPTH Digitalization Kits.

Appleton, Wisconsin – StormTrap Detention System

The first below-ground stormwater infrastructure system considered is a detention basin beneath the parking lot at Appleton East High School in Appleton, Wisconsin. This system serves a highly-urbanized watershed and its focus was flood mitigation due to surface runoff. A schematic description of the basin, the motivation for digitalization, and the digitalization kits employed are shown in Figure 6. The main motivating factors for digitalizing the detention basin were understanding the impact (if any) on the groundwater at the site (the below-ground system invert is located well below the groundwater table); and to understand system performance during significant rainfall events historically resulting in flooding from stormwater runoff. The storage volume of the basin is roughly 424,122 cubic-feet (9.7365 acre-feet). The basin is roughly 7'-6" high and the precast concrete modules were configured to fit within the plan area of the school parking lot.

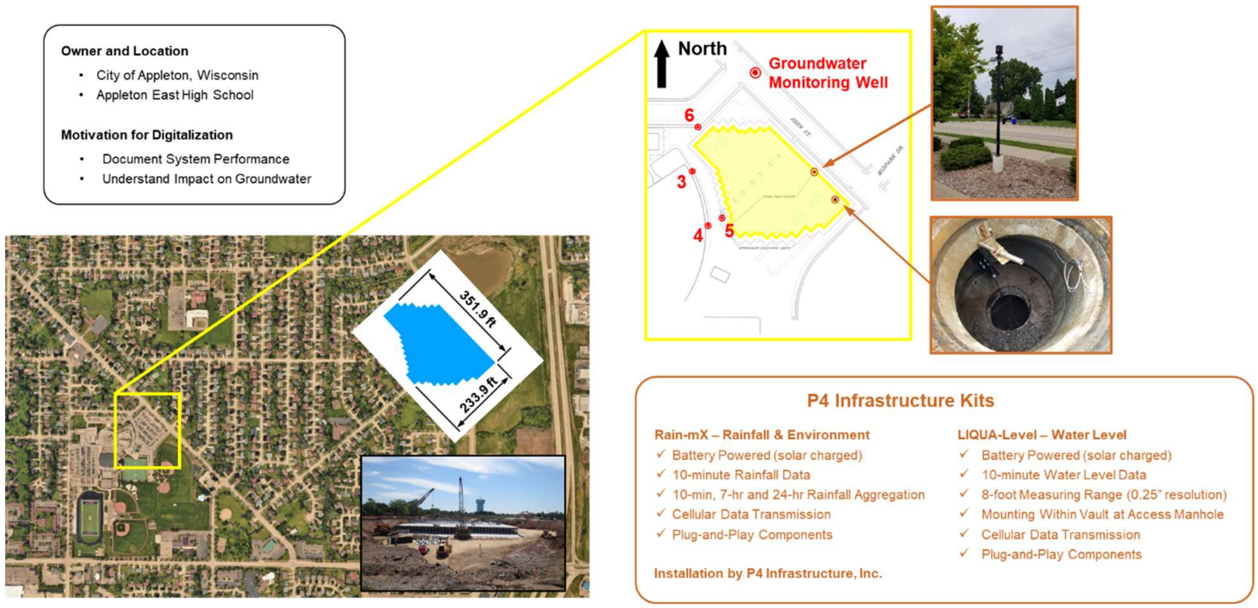

Figure 6. Below-Ground Detention Basin – Appleton East High-School, Appleton, Wisconsin.

The P4 Rain-mX (rainfall monitoring) system and P4 LIQUA-Level (water level monitoring) system were deployed for this installation. Both systems were battery powered and solar recharged. The digitalization kits were located on a stand-alone pole adjacent to the basin (installed by P4 Infrastructure, Inc.). Both systems utilize cellular data transmission to the P4 cloud-compute platform.

The City of Appleton maintains a groundwater-level monitoring program. The process includes manual measurement of groundwater levels on a regular basis using monitoring wells located within the City. There are four groundwater monitoring wells located in the near vicinity of the StormTrap vault. The P4 LIQUA-Level kit measures water level within the detention basin and the Rain-mX kit measures rainfall and environmental conditions within the local watershed. Digitalization of the detention basin afforded the ability for the City to monitor the impact of the below-ground basin on the groundwater level over time. P4 and Appleton synthesized manual groundwater monitoring data with rainfall and water level from 2019 to 2024. The results of this synthesis are shown in Figure 7.

The below-ground detention vault was digitalized in December 2019. Rainfall and water level is measured in 10-minute intervals. This has resulted in over 680,000 contiguous data points linking rainfall demands in the local watershed to below-ground detention system response to that demand. Figure 7 illustrates the expected variability of groundwater levels near the high school. However, there is relatively consistent ground water levels from December 2019 through December 2024 and the water levels in the detention basin have been essentially zero during this five-year period (one event with around 11 inches of water level response occurred in May 2024). This confirms that the below-ground detention basin does NOT affect ground water levels as the ground water levels have the expected consistency with time and the water levels in the tank are not rising indicating entry of groundwater into the below-ground basin. Therefore, the sealing system employed for the modular precast concrete system is working beautifully and as expected.

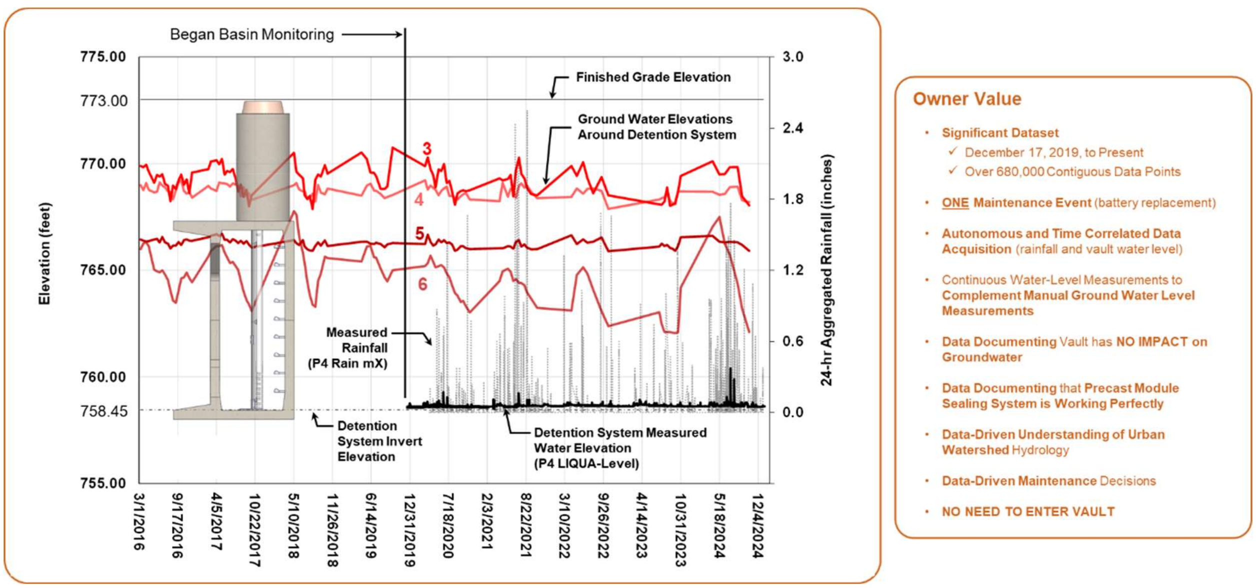

Figure 7. Groundwater, Rainfall, and Water Level Monitoring at Below-Ground Detention Basin in Appleton, Wisconsin.

The digitalization kits also afford documentation of the performance of the stormwater infrastructure component over time. The Appleton, Wisconsin below-ground system was not "activated" until April 13-14, 2026. The term "activation" here indicates significant water level rise resulting from a significant rainfall event. It should be emphasized that when there is a large-catchment area contributing to a below-ground detention basin like that in Appleton, Wisconsin, it is a perfect vehicle for calibration of hydrologic models for rainfall demand and system response including time of concentration, response lag time, surface runoff coefficients, etc.

On April 13-14, 2026, Appleton, Wisconsin had a significant rainfall event. The below-ground detention basin "activated" during/after this event. Figure 8 illustrates the water level response in the basin. The Rain-mX system was not regularly maintained after December 2024 and therefore, did not operate correctly (really unfortunate). The detention basin filled to over 63 inches in the early morning hours of April 14, 2026. It is estimated that over 2.2 million gallons of stormwater were detained during this event. The detention basin employed a “duck bill” release system that controls discharge of stormwater runoff from the basin. The discharge curve from the basin follows a very nice nonlinear trajectory expected from discharge controlled by head pressure. The basin discharged in just less than 24 hours. It also filled up to the 63-inch level very quickly (approximately 2 hrs) giving an indication of the lag-time from start of event or time of concentration for runoff in the watershed to reach the below-ground basin.

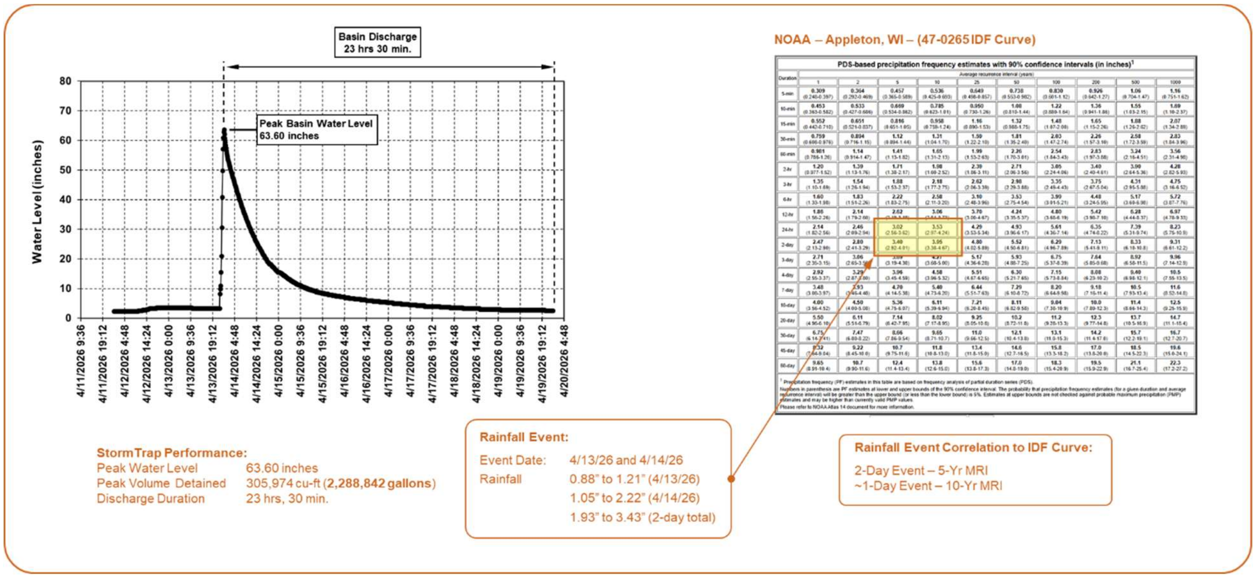

Figure 8. Below-Ground Detention System Response to Rainfall Event April 13-14, 2026 in Appleton, Wisconsin.

The total rainfall demand for the 1- to 2-day event ranged between 2 to 3.5 inches. The intensity of the rainfall event could not be measured because the Rain-mX system was not operating. However, the total rainfall demand can be qualified within the context of NOAA ATLAS-14 IDF curves for Appleton, WI. The rainfall event could be classified in the range of a 1-day, 10-yr MRI to a 2-day, 5-yr MRI event expected for Appleton. This is a a significant event and the response of the below-ground system was captured very well by the digitalization system.

The benefits of digitalization for the City of Appleton and their stormwater management team are significant. First, they can easily document that the below-ground system has no effect on the groundwater table. No ground water is infiltrating into the below-ground system. Secondly, there is the ability to document performance of the system within the context of NOAA ATLAS-14 IDF curves to correlate with original design intent. Finally, there is the ability to utilize the data-documented response to calibrate the hydrologic model used in the design of the system. This is very valuable as Appleton conceptualizes, designs, and constructs additions to their stormwater infrastructure network to mitigate flooding and comply with regulations for their MS4 permit. Perhaps the most valuable aspect to digitalization of the below-ground system is that this documentation is autonomous and can be done from their desk without having to manually visit and measure response. Furthermore, the data can be used to make stormwater infrastructure investment and benefit transparent to stakeholders (*i.e.* taxpayers).

University Park, Texas – StormTrap Detention System

A second below-ground detention system in University Park, Texas was digitalized. University Park's Department of Public works is charged with managing stormwater in a highly urbanized watershed near Dallas. A below-ground detention system was designed and constructed as part of a multi-year stormwater management effort. The first below-ground detention system designed and constructed as part of this plan was in Caruth Park. Figure 9 schematically illustrates the below-ground system, the motivation for digitalization, and the P4 digitalization kits employed.

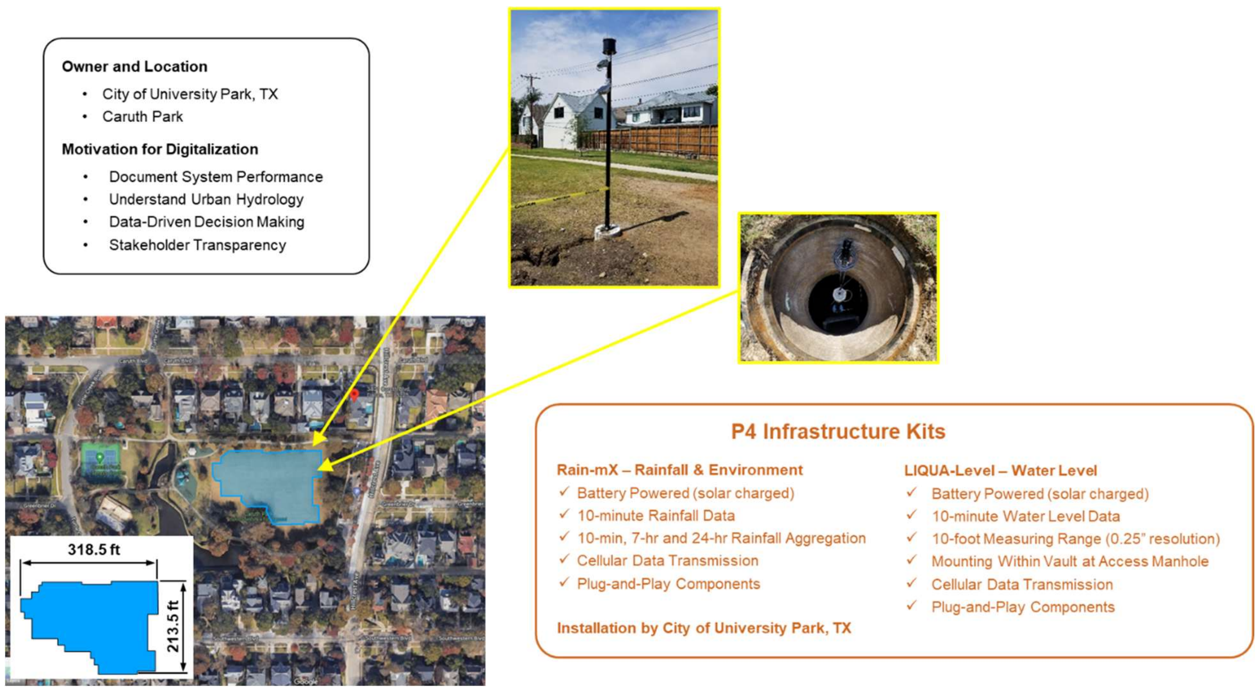

Figure 9. Below-Ground Detention Basin – Caruth Park, University Park, Texas.

University Park employed two P4 digitalization kits: Rain-mX and LIQUA-Level. The motivation for digitalization was to document below-ground system performance; document their understanding of urban hydrologic modeling using SWMM; provide a foundation for data-driven decision making for future below-ground system investments; and provide transparency to stakeholders. The LIQUA-Level system had a measuring range from 0" to 120" and was mounted within one of the access manholes. The City of University Park installed the digitalization kits. Both kits used cellular data transmission to the P4 cloud-compute platform.

The system has been operating since the Fall of 2024 providing continuous 10-minute measurements of rainfall, temperature, barometric pressure, relative humidity and water level within the below-ground detention basin. The value of digitalization in meeting University Park's goals can be illustrated through synthesizing the performance during any given year. Figures 10 and 11 illustrate quarterly performance of the below-ground system to rainfall events measured.

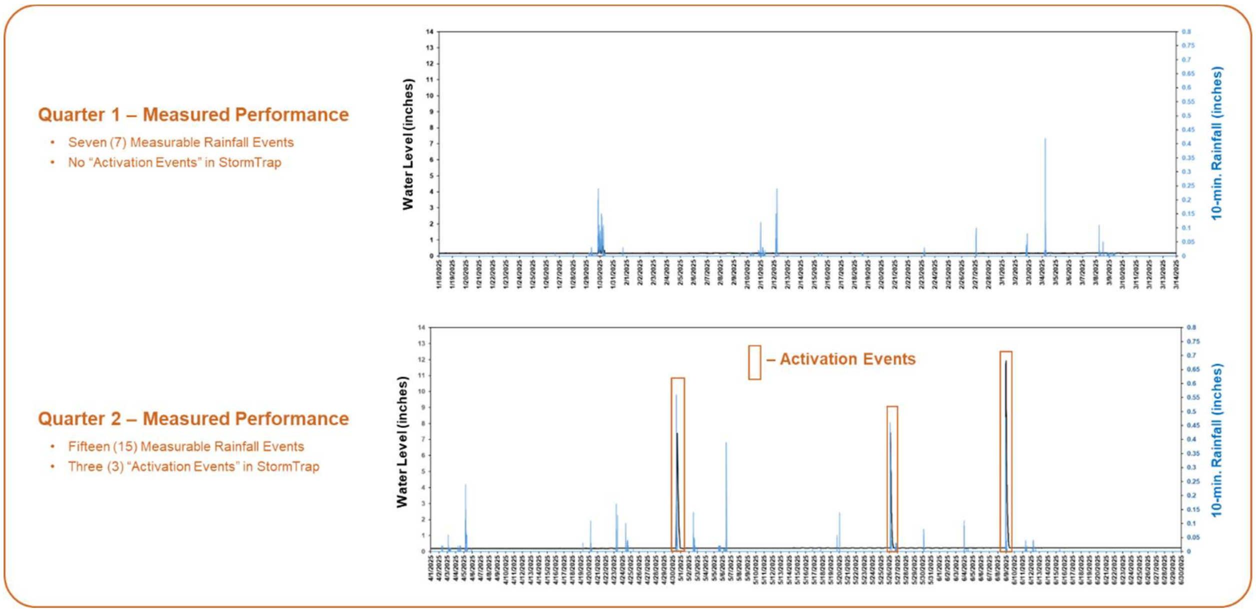

Figure 10. Measured Data for Quarters 1 and 2, 2025 for Caruth Park Below-Ground Detention System.

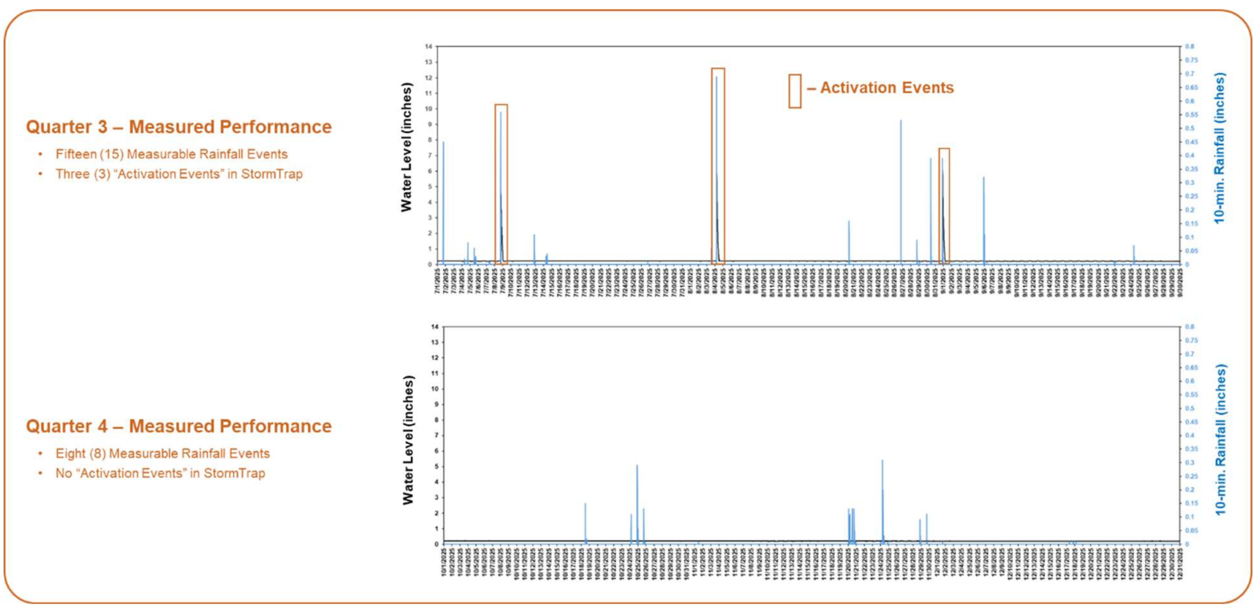

Figure 11. Measured Data for Quarters 3 and 4, 2025 for Caruth Park Below-Ground Detention System.

Activation events during 2025 are defined as rainfall events that result in significant water level rise in the below-ground detention basin. There were three (3) activation events in Quarter 2 and three (3) activation events in Quarter 3. This is expected as these quarters correspond to the "rainy season" in Dallas, Texas. Each activation event can be studied further by looking at the data recorded for rainfall and water level in the below-ground detention system. The six (6) activation events documented in 2025 for the below-ground detention basin are shown in Figures 12 through 17. A tabulated summary of the events is shown in Figure 18.

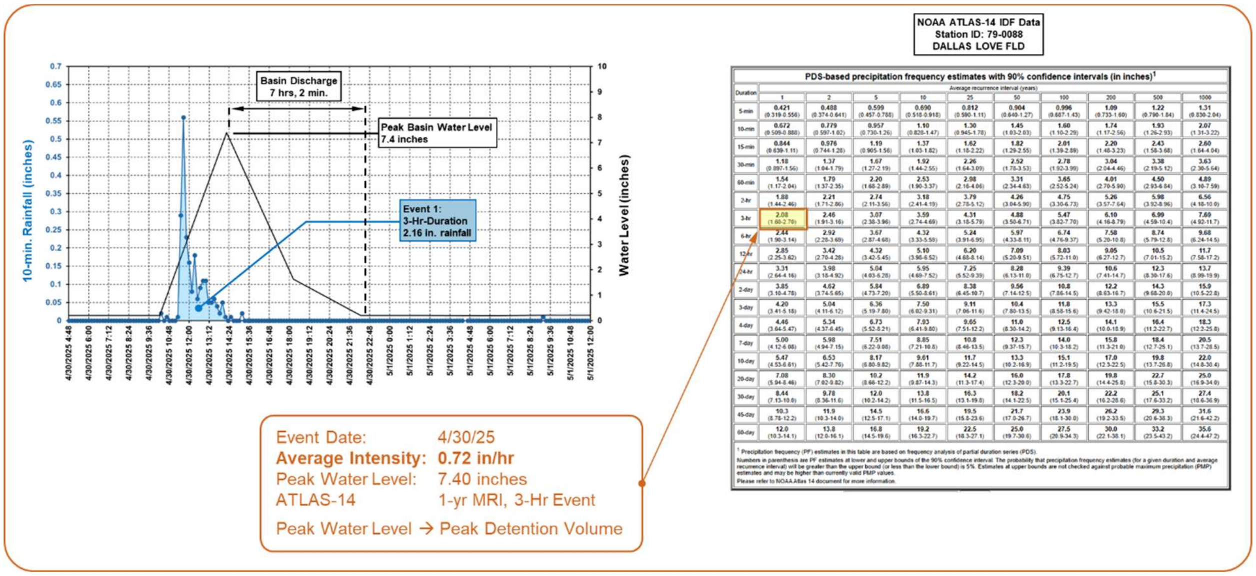

Figure 12. Below-Ground System Response and Rainfall Demand for Activation Event 1 for Caruth Park Below-Ground Detention System.

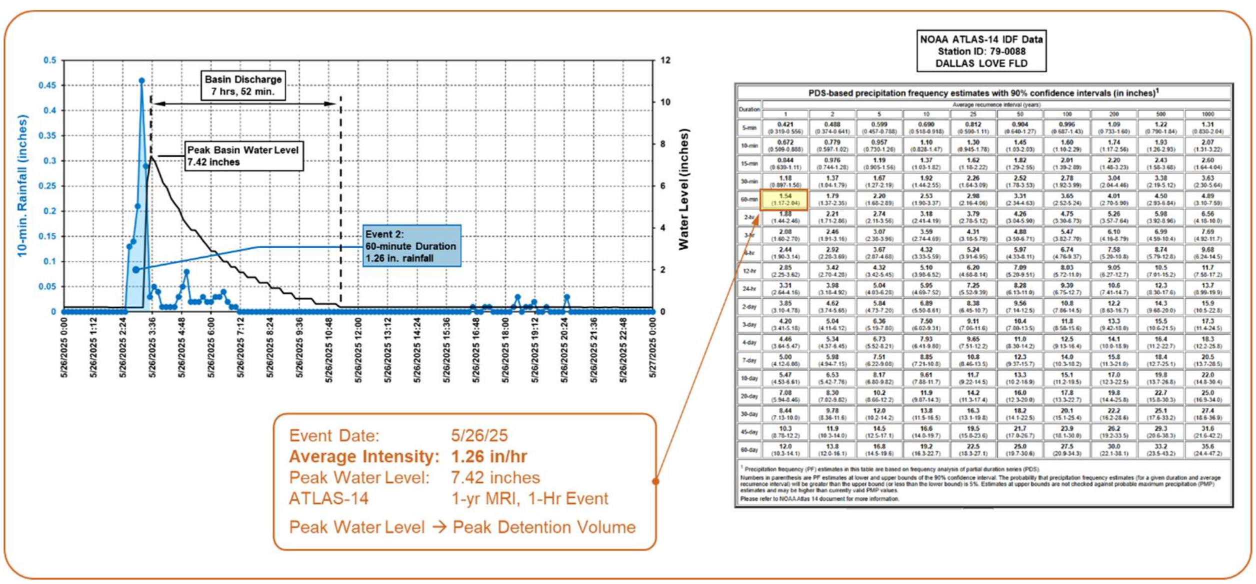

Figure 13. Below-Ground System Response and Rainfall Demand for Activation Event 2 for Caruth Park Below-Ground Detention System.

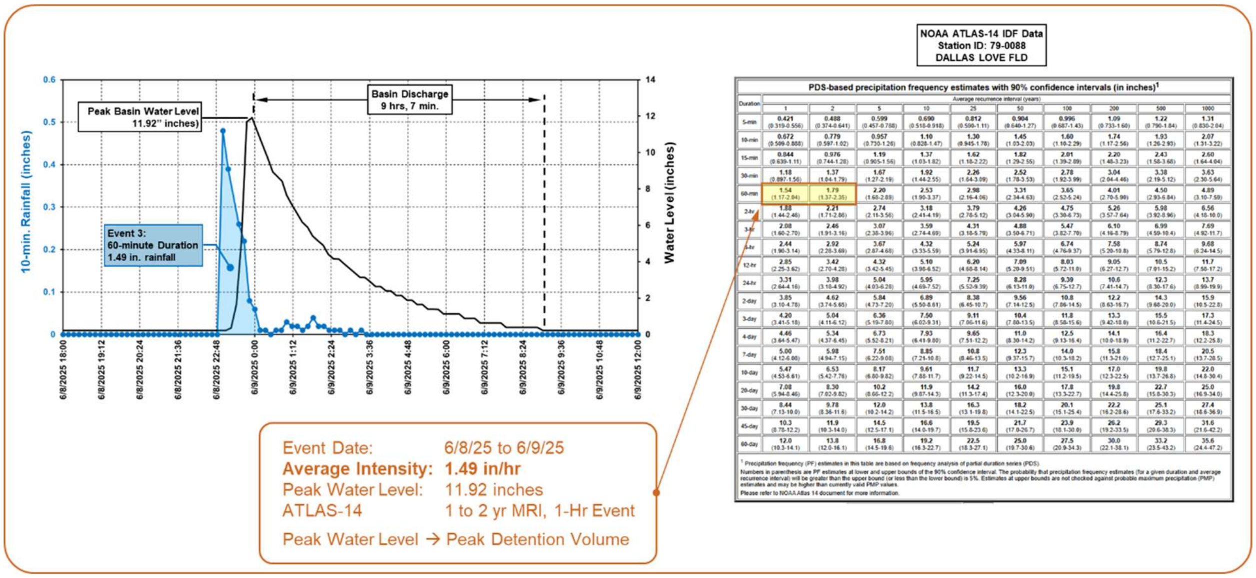

Figure 14. Below-Ground System Response and Rainfall Demand for Activation Event 3 for Caruth Park Below-Ground Detention System.

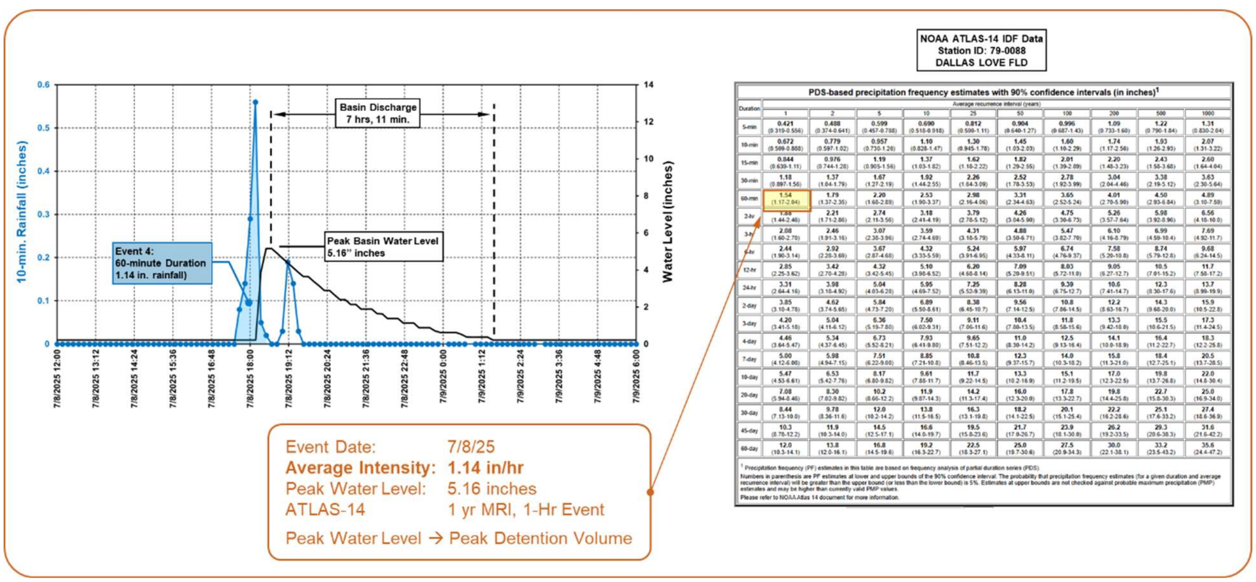

Figure 15. Below-Ground System Response and Rainfall Demand for Activation Event 4 for Caruth Park Below-Ground Detention System.

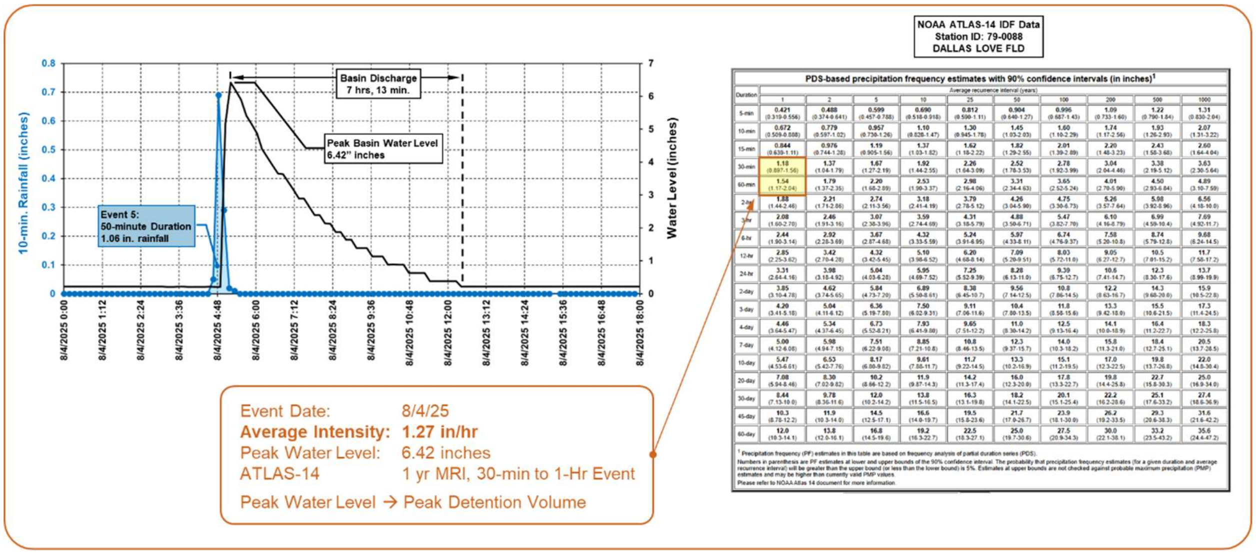

Figure 16. Below-Ground System Response and Rainfall Demand for Activation Event 5 for Caruth Park Below-Ground Detention System.

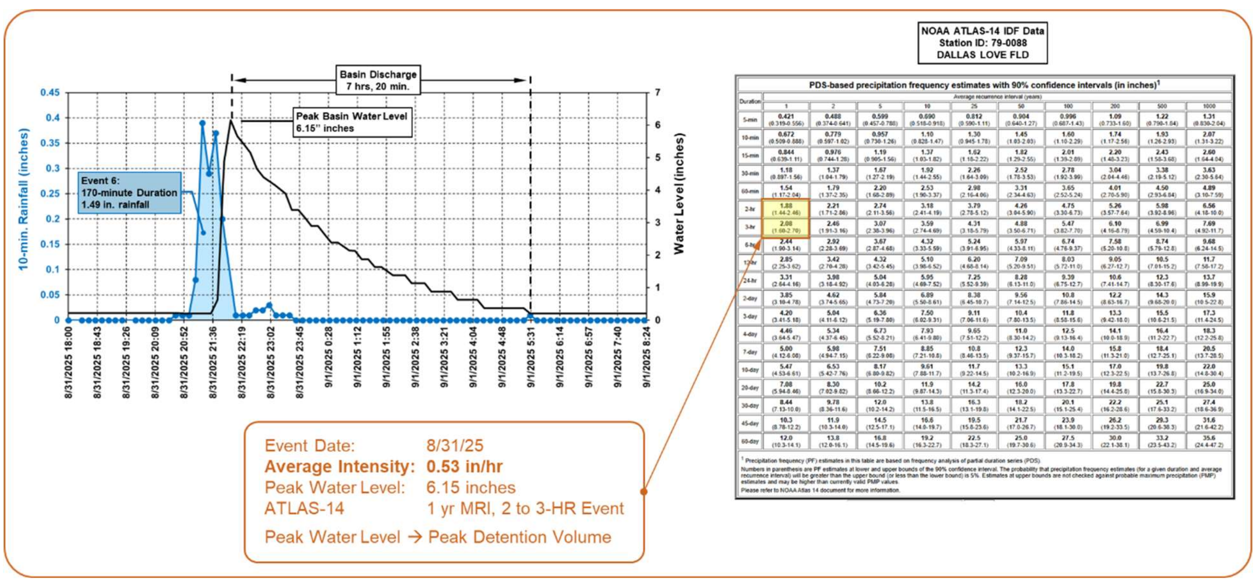

Figure 17. Below-Ground System Response and Rainfall Demand for Activation Event 6 for Caruth Park Below-Ground Detention System.

Event Date	Rainfall				StormTrap Response		
	Rainfall Amount (in)	Rainfall Duration (min, hr)	Rainfall Avg. Intensity (in/hr)	ATLAS IDF Correlation (Avg. Recurrence Interval, Duration)	Peak Water Level (in)	Peak Volume (cu-ft)	Discharge Duration
4/30/25	2.16	180, 3	0.72	1-Yr, 3-Hr	7.40	28,587	7 hrs, 2 min.
5/26/25	1.26	60, 1	1.26	1-Yr, 1-Hr	7.42	28,665	7 hrs, 52 min.
6/8/25	1.49	60, 1	1.49	1-Yr to 2-Yr, 1-Hr	11.92	46,049	9 hrs, 7 min.
7/8/25	1.14	60, 1	1.14	1-Yr, 1-Hr	5.16	19,934	7 hrs, 11 min.
8/4/25	1.06	50, 0.83	1.27	1-Yr, 30-min to 1-Hr	6.42	24,801	7 hrs, 13 min.
8/31/25	1.49	170, 2.83	0.53	1-Yr, 2-Hr to 3-Hr	6.15	23,758	7 hrs, 20 min.

Annual Observations and Summary

- Six (6) measurable rainfall events that "activated" the StormTrap detention basin
- 8.6 inches of total rainfall during these events
- 171, 794 cu-ft (1,285,108 gallons) of stormwater runoff detained in StormTrap basin
- Rainfall events that "activate" StormTrap detention basin are roughly 1-Yr events of varying duration defined by ATLAS-14 IDF curves for Love Field in Dallas, TX
- Average rainfall intensity that activates the basin are roughly > 0.7 inches/hour
- Consistent and correlated peak water level and discharge durations – StormTrap detention basin performing as expected – **NO SITE VISITS REQUIRED as System Operating as Expected**
- Smaller rainfall event with intensity of 0.53 inches/hour "activates" the StormTrap detention basin – requires a more detailed examination

Figure 18. Summary of Below-Ground System Response and Rainfall Demand for Activation Events for Caruth Park Below-Ground Detention System 2025.

The average rainfall intensities for events that activated the detention basin in 2025 range from 0.53 in/hr to 1.48 in/hr. Peak water levels for these events ranged from 6.15 inches to 11.92 inches. Discharge durations ranged from 7 hrs 2 min to 9 hrs 7 min and are consistent with the peak water levels reached in the basin. During 2025, there is consistency in rainfall intensity for the events as well as peak water levels reached and discharge durations. Therefore, for the year considered (2025) there is no need to consider any maintenance intervention for the below-ground system. If changes in peak water levels for comparable rainfall events would have changed during the year, this would be a trigger for a site visit and/or maintenance considerations.

It is interesting to note that the rainfall event on 8/31/25 activated the detention basin. The average rainfall intensity for this event was 0.53 in/hr and its duration was nearly 2 hrs. This event is significantly different than the other events that caused activation in the basin. This triggered a second look at the event. Event 6 during the year considered (2025) was preceded by a nearly equal event 9 hours earlier. Figure 19 illustrates the basin response along with the measured rainfall for Event 6 and the preceding event (Event 6a). Event 6a had an average intensity of 0.49 in/hr and Event 6 had an average intensity of 0.53 in/hr. This antecedent event was closely spaced with the follow-on event. Therefore, it appears that these two events acted together to create a basin response that is consistent with the summation average intensity of both events (0.49 + 0.53 in/hr) and were "additive". It also appears that the average runoff coefficient in the catchment watershed changed because of the potential saturation of the pervious surfaces in the catchment watershed area. Digitalization of the system affords documentation of this phenomenon and this is very important to the understanding of urban hydrology and modeling.

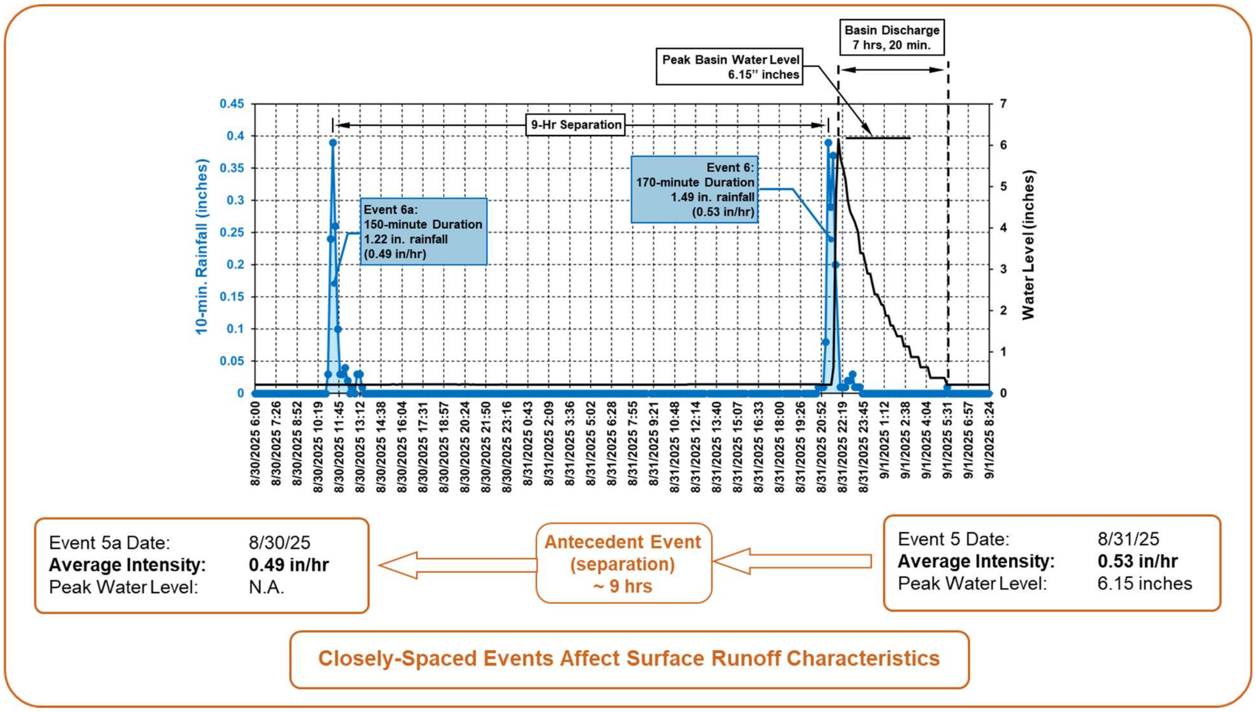

Figure 19. Effective of Antecedent Event on Activation and Response of the Below-Ground Detention Basin for Caruth Park Below-Ground Detention System 2025.

The value of digitalization to University Park is significant. First, they have annual data-documented performance of their below-ground system at Caruth Park. The past year's quarterly performance with synthesized rainfall demand in the local watershed and response of the system to that demand is bullet-proof documentation of performance without the requirement for site visits. Any change in this (e.g. year over year) is a trigger to conduct a site visit. In this way, University Park can eliminate arbitrarily scheduled visits and focus their fiscal resources only when necessary. University Park can also correlate the measured rainfall events to ATLAS-14 IDF curves to relate rainfall events and performance to that assumed during design. University Park can also use the measured demand and response to calibrate hydrologic models (e.g. SWMM) as part of their planning, design, and construction of additional stormwater infrastructure systems used as part of their stormwater management plan in their local watershed. Perhaps the greatest benefit is that digitalization provides transparency for stakeholders. Measured data can be brought to city council meetings to demonstrate the effectiveness of fiscal resources designed to mitigate flooding in University Park in a manner that the taxpayer can easily digest. This transparency extends to all members of the department of public works team. Those charged with planning have demonstrated performance of their stormwater infrastructure systems, and those charged with maintenance of stormwater infrastructure have data to drive their maintenance interventions. Perhaps most importantly, all of these entities have a common data platform as a foundation for their activities. In other words, they are all on the same page.

Naperville, Illinois – StormTrap Infiltration System

A private developer is building townhomes and STEM school in the City of Naperville, Illinois. This project will implement a 14-foot deep below-ground infiltration basin as part of their stormwater management system. This project is under construction. A schematic of the development is shown in Figure 20.

Owner and Location

- Private Developer (Townhomes and STEM School)
- City of Naperville, Illinois

Motivation for Digitalization

- Satisfy City of Naperville Requirements
- Master Association Mandate
- Prepare Annual Reports on Hydraulic Function and Operational Integrity of the Stormwater Management System

Figure 20. Townhome and STEM School Development Schematic in Naperville, Illinois.

The City of Naperville required a stormwater management plan as part of the approval for the development. This plan included a large below-ground infiltration basin. The city required that year-over-year documentation of this system as part of this plan. This requirement was put in place because of "infiltration" being the primary mechanism for managing stormwater runoff and the size of the below-ground system. The developer's consultant recommended digitalization of the below-ground system to document performance. The city of Naperville approved the use of digitalization, and this was included as part of the stormwater management plan for the development.

The digitalization kits that will be installed are an ultrasonic depth sensor (P4 DEPTH) located in a manhole riser with the sensor wire being run via conduit to a city-owned electrical enclosure where 120V power and dedicated/metered circuit will reside. The computer for the digitalization kit will be in this enclosure and a wireless (cellular) data transmission "puck" will be installed on the cabinet. A description of the kits that will be employed in shown in Figure 21. The below-ground infiltration basin will provide over 6 acre-feet of stormwater runoff storage and infiltration. The below-ground basin occupies the plan area of the plaza in the middle of the townhomes.

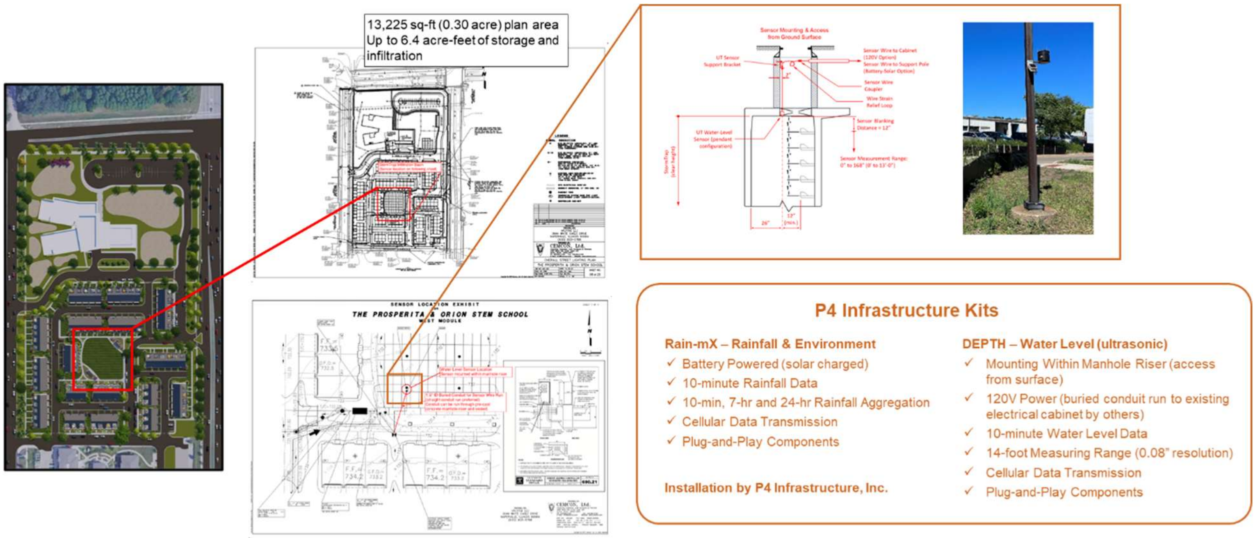

Figure 21. Townhome and STEM School Development Schematic in Naperville, Illinois.

Staged storage and infiltration volumes will be documented using information provided by the manufacturer (StormTrap). There is two infiltration basins within the plan area that are "equalized" in water level, and three storm sewer outflows exist should water level exceed the storage/infiltration capacity of the basin. Water level readings will indicate when infiltration occurs, the duration of infiltration when it occurs, and if bypasses to the storm sewer outflows occurs. This process is schematically indicated in Figure 22.

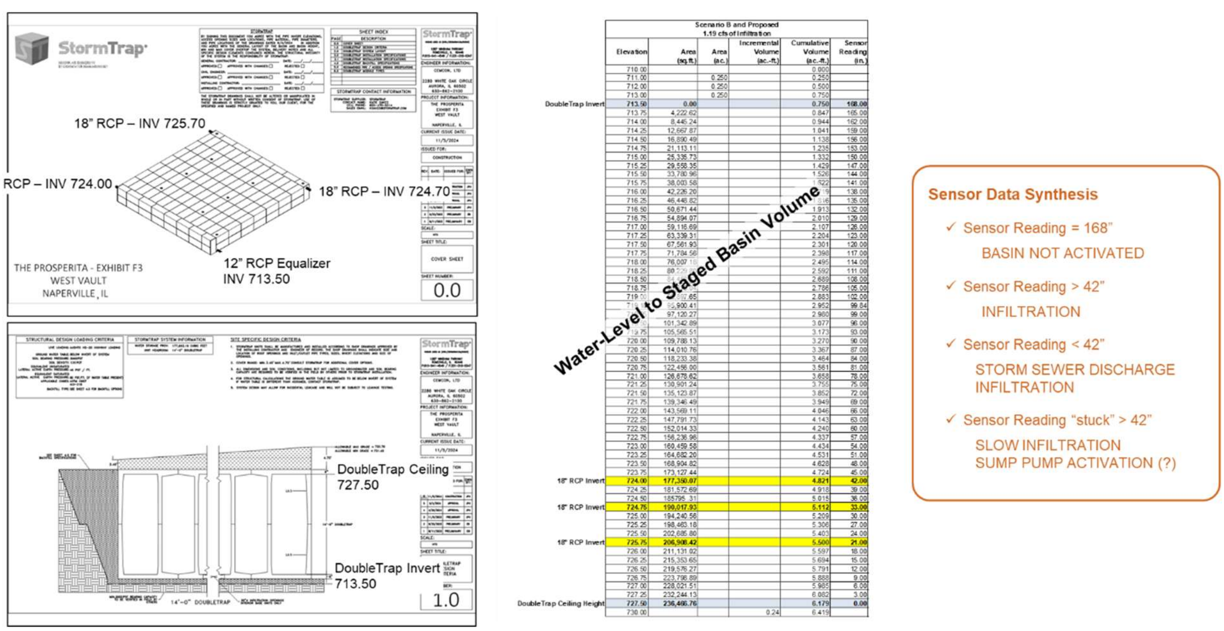

Figure 22. High-Level Characterization of Below-Ground Infiltration System Performance.

This system will be installed in late spring or summer 2026 and there is no measured data (yet) to document in-service performance. However, past data from detention systems allows projection of how the system's performance will be characterized using the digitalization kits. This is shown schematically in Figure 23.

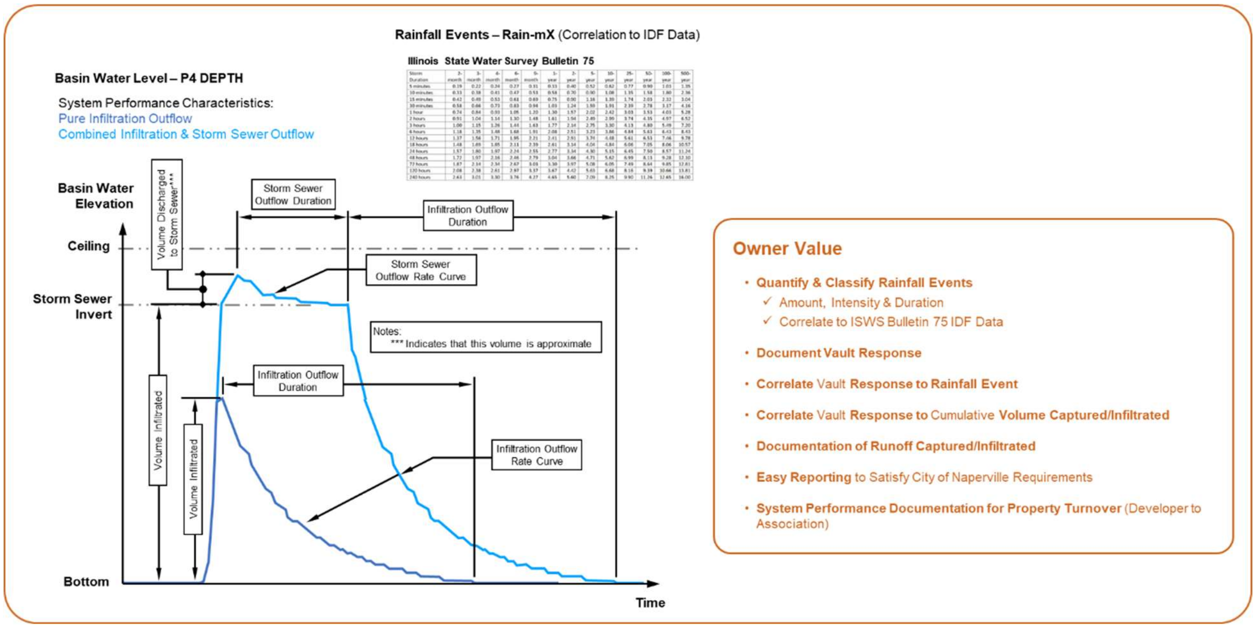

Figure 23. Detailed Characterization of Below-Ground Infiltration System Performance and Owner/City Value Obtained through Digitalization.

The fundamental performance characteristics of the below-ground system can be broken down into two phases: (a) when infiltration occurs; and (b) when storm sewer discharge occurs. When infiltration occurs, the volume of water captured and infiltrated for rain events is documented. The duration and rate of infiltration will be documented. Water level and rainfall data will be acquired in 10-minute intervals and correlated by giving rainfall demand as well as system response. Should the infiltration rate change year-over-year, the owner will have a trigger for site visits and/or maintenance intervention. The city will have confidence that the system is performing as intended as well as having data-driven and owner-notified response of changes in performance and follow-on maintenance activity. If infiltration rates are not sufficient to keep up with stormwater runoff demand, the water level measured will document that this bypass occurred and the duration for the bypass. The system should then return to discharge via infiltration. Area-Flow-Velocity digitalization was not included within the storm sewer bypass system and therefore, volumes and rates of discharge to storm sewer will not be recorded (although it could have been).   Rainfall demand will be correlated with Illinois State Water Survey Bulletin 75 IDF curves for correlation with original design parameters of the system. The city will have complete understanding of the system within the IDF context.

There is significant value to the owner obtained through digitalization. The owner will have bullet-proof documentation of system performance over time that satisfies the requirements of the stormwater management plan approved. The design consultants will also receive significant value through their ability to use the data to enhance their stormwater consulting practice and design models for watersheds like that contributing to the infiltration basin.

It is interesting to point out the likely overlooked value digitalization provides to the private developer. They, of course, receive bullet-proof documentation that the stormwater management system functions as intended to meet the regulatory requirements provided by the city. Private developers often "turn over" the development to homeowner or condominium associations after defined periods of time. The digitalization system gives the owner a more valuable piece of property as the documentation of stormwater management system performance is data-based rather than based upon arbitrarily scheduled and subjective visual inspections that cannot document actual performance. When a homeowner's association or condominium association then receives the duty to carry on documentation of performance required by the city, the digitalization system is the easy button. Lastly, if another private entity would like to purchase a property or development, this buyer will have confidence that what they are buying is functioning property, maintenance has been done, and the City is on board. This is analogous to keeping service records for your vehicle when you want to transfer ownership.

Value of Digitalization in Dollars & to Stormwater Management Practice

The value of digitalization in relation to performance documentation of below-ground systems has been demonstrated previously. It is also prudent to look at the value of the system in relation to long-term and annual costs to owners and managers of these systems as well as examine the potential future value of digitalization impacting and improving stormwater management practice.

Reducing Annualized O&M Costs and Easing Budgeting Complexity

Examining cash flow diagrams for below-ground infrastructure systems with and without digitalization illustrates the value of digitalization in dollars. Two typical cashflow diagrams for long-term expenditures for a below-ground stormwater infrastructure system are shown in Figure 24. The owner's cash flow for a typical below-ground detention or infiltration basin without digitalization consists of the following components mentioned earlier in Figure 2. The capital expenditure for the below-ground system depends upon storage volume required. These can range from $150,000 on the low end to $10,000,000 on the high end. There are two types of inspections considered. The first is a routine visual inspection with reporting. The second is a more detailed inspection that includes confined space entry. If we assume an inflation rate on labor and equipment costs, the annual expenditures for a 10-year period are illustrated. Therefore, if a typical system is managed without digitalization, the total expenditure after 10 years is expected to range from $9,651 to $24,959. The annualized long-term O&M costs range from $975/year to $2,525/year.

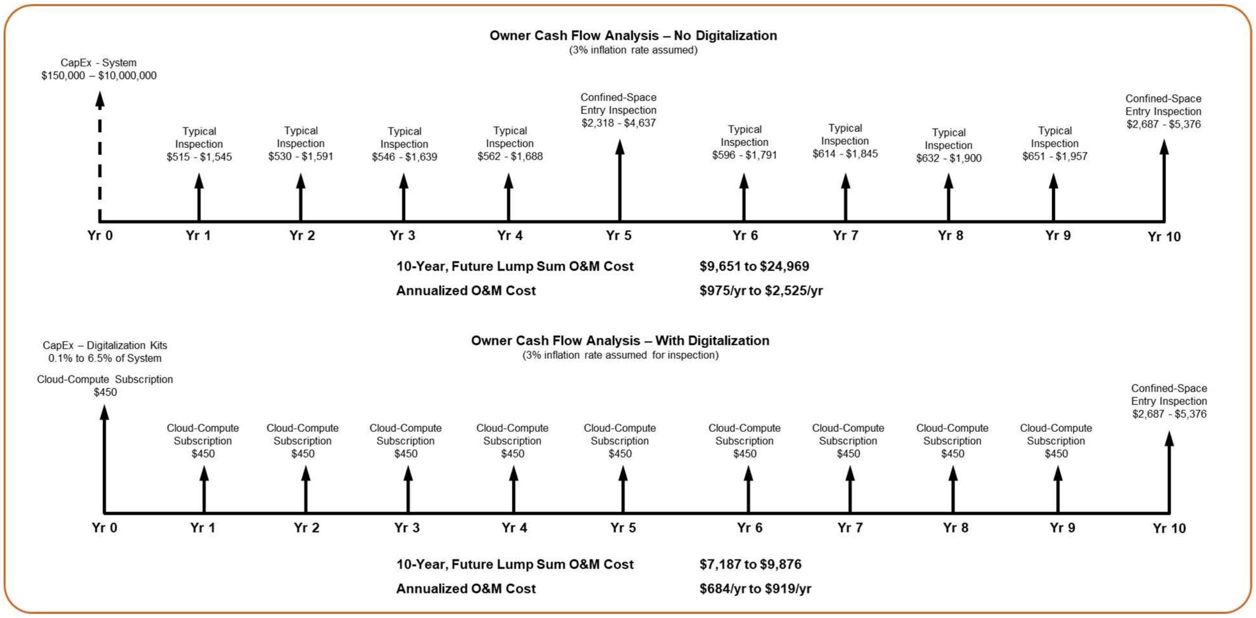

Figure 24. Long-Term and Annualized Costs of Digitalization (Cash Flow Analysis)

The long-term O&M costs for a system with digitalization is significantly different. The typical digitalization kits that may be employed involve a rainfall monitoring system and a water-level monitoring system. The capital expenditure for these kits range from 0.1% to 6.5% of the capital expenditure of the below-ground system. In an ideal world, the capital expenditure for the digitalization system would be built-in to the capital expenditure of the below ground system. This is assumed in the cash flow analysis. The digitalization kits (rainfall + water level) range from $8,752 to $9,801 for systems typically employed in below-ground detention and infiltration basins.

The annual expenditures for the digitalization system are for the cloud-compute platform. This is basically a wireless cellular data subscription plan to cloud-compute and cloud-storage of data. It includes viewing and downloading of data. Subscriptions for two digitalization kits is $450/year. There is no inflation to these subscriptions, and this makes budgeting simplified. It is assumed that only one confined space entry is required as the system's performance is continuously documented. One confined space entry inspection is performed at 10-year's of system service. The 10-year total for O&M spending for the digitized system ranges from $7,187 to $9,876. This range is considerably tighter when compared to the non-digitized below-ground system. The reason for this is the fixed subscription cost for remote monitoring and documentation when compared to the range of annual costs possible for the typical on-site inspection with manual reporting. The annualized O&M cost ranges from $684/year to $919/year. On the low end, the annual O&M costs for the digitized system are 70% that of the non-digitalized system. On the high end, the annual O&M costs for the digitalized system are 36% of the non-digitalized system. The tighter range of O&M costs indicates that the digitalized system will be better for budgeting purposes resulting from the constant cloud-compute subscription plan cost that is not affected by inflationary effects of equipment and labor costs. Raw dollars are not the only measure of value for a digitalized system. The following section outlines additional value to stormwater management practice.

Opportunity Capture for Stormwater Management Practice

Figure 3 outlined the opportunities for stormwater management practice to move from episodic, costly, and subjective practice to proactive, economic, data-driven, predictive, verifiable practice that will yield regulatory compliance efficiency and improved design leading to a better surface and ground water environment.

Digitalizing the local watershed to measure rainfall events, barometric pressure, relative humidity, and temperature presents very interesting opportunities that can impact hydrologic modeling, pollutant capture, and flood mitigation. A digitalization kit that documents rainfall in 10-minute intervals with cloud-based storage and retrieval allows input files (rainfall) for commonly used hydrologic modeling software (*e.g.* SWMM, WinSLAMM). This can be automatically done after a CSV file is downloaded from the cloud-storage platform. Figure 25 illustrates the fundamentals of this process and the value in doing so.

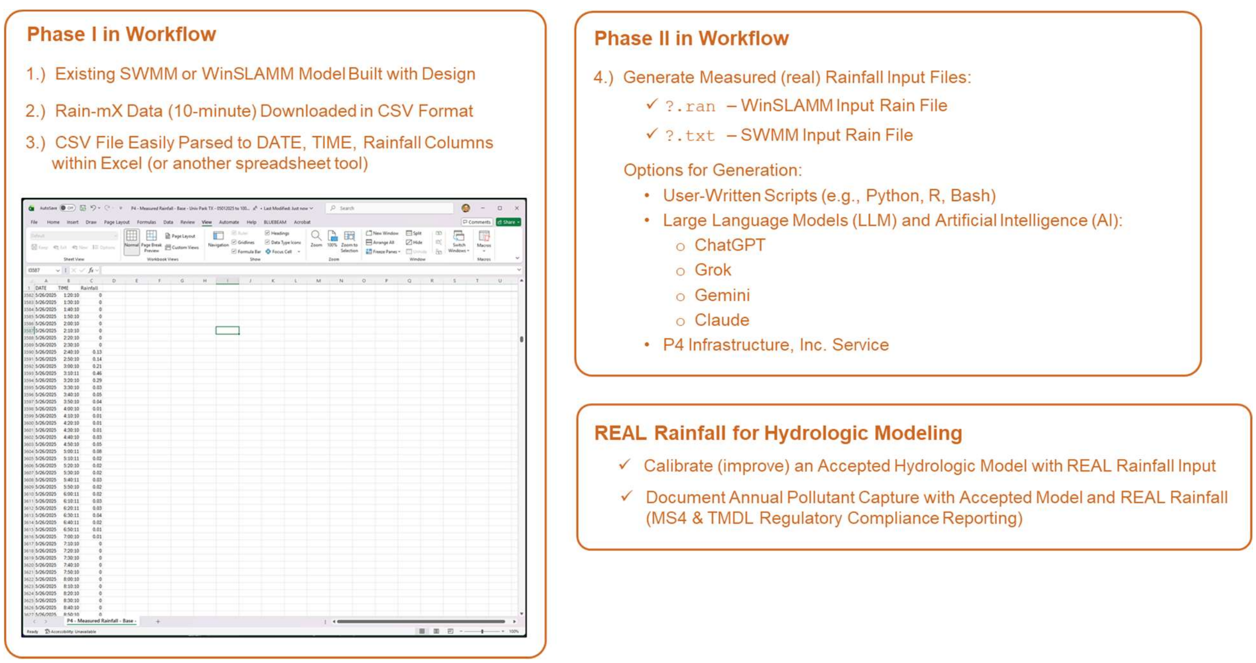

Figure 25. Workflow for Use of Measured Rainfall in 10-minute Intervals as Part of Hydrologic Modeling Software (*e.g.* SWMM, WinSLAMM).

The slightly modified workflow for the stormwater engineer is to download measured rainfall histories in 10-minute intervals for a defined period (*e.g.* one year) in a CSV file for that measured rainfall history. This CSV file can be easily cast into input files for SWMM or WinSLAMM software. AI agents (*e.g.* Grok, ChatGPT, Gemini, Claude) can cast these CSV files into suitable "txt" or "ran" files for input. One can easily imagine having multiple rainfall monitoring kits with 10-minute acquisition rates located strategically throughout a managed watershed. All these rainfall monitoring "stations" can then be used to feed measured rainfall into modeling software.

This has tremendous impact on the field of stormwater management. First, these measured rainfall histories can be used in conjunction with other digitalization kits located in stormwater infrastructure like below-ground detention and infiltration systems. These models seeded with measured rainfall can be used to calibrate the hydrologic models through better modeling of runoff coefficients, times of concentration, lag time, etc. Second, the model used for the original design most likely has been approved by the regulatory agency and the consulting engineer to carry out the original design of the system. A measured annual rainfall history fed into this approved model can be used to document annual pollutant removal quantities contributed by the below-ground BMP. This is very useful documentation of annual pollutant removal that occurred during the previous year. Doing this year-over-year documents long-term pollutant removal performance using the "best" calibrated model as well as real (measured) rainfall histories. This can have a large impact on MS4 regulations and TMDL restrictions being met and exceeded. The calibrated models employing measured rainfall data can be integrated into graphical methods for displaying progress toward regulatory compliance[6,7] using all forms of stormwater infrastructure systems.

There are far-reaching opportunities to move stormwater management in innovative directions through digitalization technologies. It is important to highlight these within the context of the previous discussion. The following outlines these opportunities. Figure 26 illustrates these within the context of regional and watershed-level stormwater management using cloud-based data viewing and retrieval platforms.

Enhanced Accessibility and Efficiency: Regulators can view performance data (water levels, infiltration rates, storage status, precipitation correlation) from any internet-connected device without special software or site visits. This reduces travel, fieldwork, and administrative burden while enabling quick checks across many sites.

Spatial Visualization and Contextual Insights: A map-based interface (GIS-integrated) displays all assets geographically, revealing watershed-scale patterns, clustering of issues, proximity to sensitive waters, or cumulative impacts. This supports better prioritization of inspections, enforcement, or interventions.

Real-Time Monitoring and Rapid Response: Continuous data allows immediate detection of problems like reduced infiltration, unexpected overflows, or underperformance during/after storms—far superior to infrequent manual inspections. This enables proactive compliance enforcement and faster mitigation of risks to water quality or flooding.

---

[6]Diekfuss, Foley, Weik (2020) "Technology for Increasing Efficiency and Monitoring of Stormwater BMPs and Graphical Method for Management of Stormwater BMPs", Presentation to Wisconsin Department of Natural Resources, July 10, 2020, P4 Infrastructure, Inc.

[7] Diekfuss and Foley (2020) "Technology for Increasing Efficiency and Monitoring of Stormwater BMPs and Graphical Method for Management of Stormwater BMPs", Research Report 2020-01, P4 Infrastructure, Inc., July 10, 2020.

Improved Compliance, Reporting, and Accountability: Easy verification of system performance against permit requirements (e.g., MS4 annual reports for Wisconsin). Automated or one-click report generation, audit trails, and historical trends strengthen documentation, reduces disputes, and supports defensible regulatory decisions.

Data-Driven Decision Making and Resource Optimization: Trend analysis, performance metrics, and predictive insights help agencies allocate limited resources effectively, justify funding, model long-term outcomes, and refine policies or technical standards.

Transparency, Collaboration, and Stakeholder Engagement: Secure sharing with permittees, municipalities, consultants, or the public (where appropriate) fosters better communication, consistency across jurisdictions, and public trust in stormwater management efforts.

Cost Savings and Scalability: Fewer physical inspections, reduced paperwork, and streamlined workflows lower operational costs. The platform scales to handle growing numbers of regulated sites as development continues.

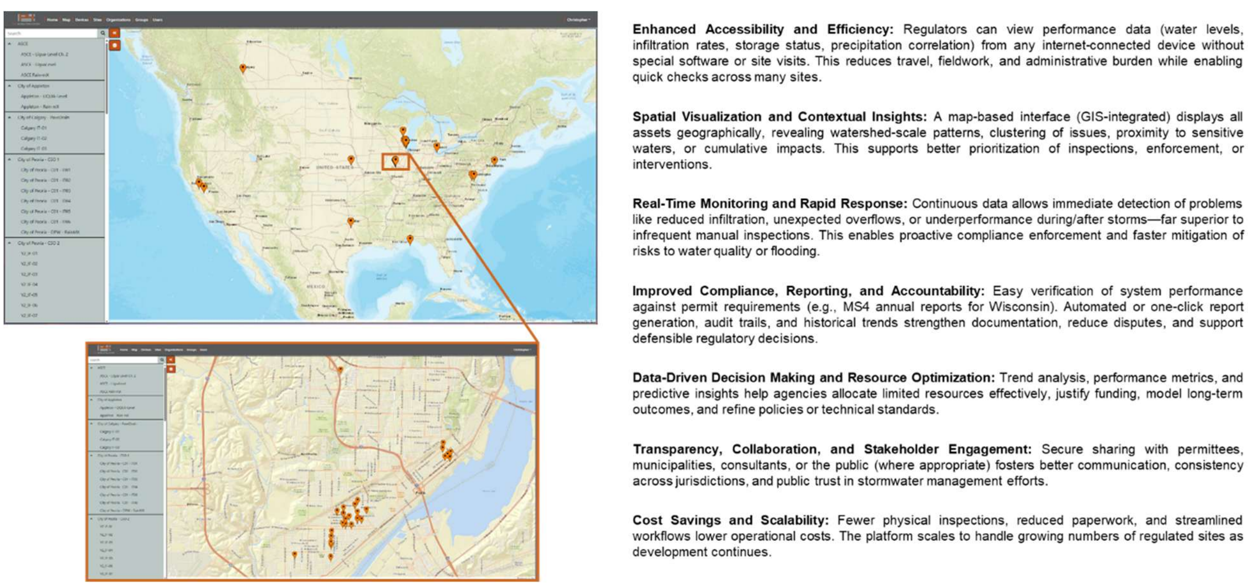

Figure 26. High-Level Opportunities in Stormwater Management Using Digitalization Technologies for Stormwater Infrastructure Systems at the Watershed Level.

Readiness of Profession for Digitalization Technology

A natural question to consider is if the profession is ready for applications of digitalization in stormwater infrastructure systems. The authors made a presentation at a recent conference that attempted to get answers to this question[8]. This presentation was a follow-up to a presentation at this same conference 4 years previously. Four years ago, there were 10 in-person attendees. The follow-presentation made in 2026 had 64 in-person attendees and 10 on-line attendees (74 total). This anecdotal evidence suggests a significant interest in digitalization technologies for performance documentation and maintenance.

The presentation made in 2026 was focused on below-ground detention and infiltration systems and it included a pre-presentation survey that will be outlined here. Figure 27 outlines responses to the first question: "What is your organization's primary challenge when managing below-ground detention and infiltration systems?".

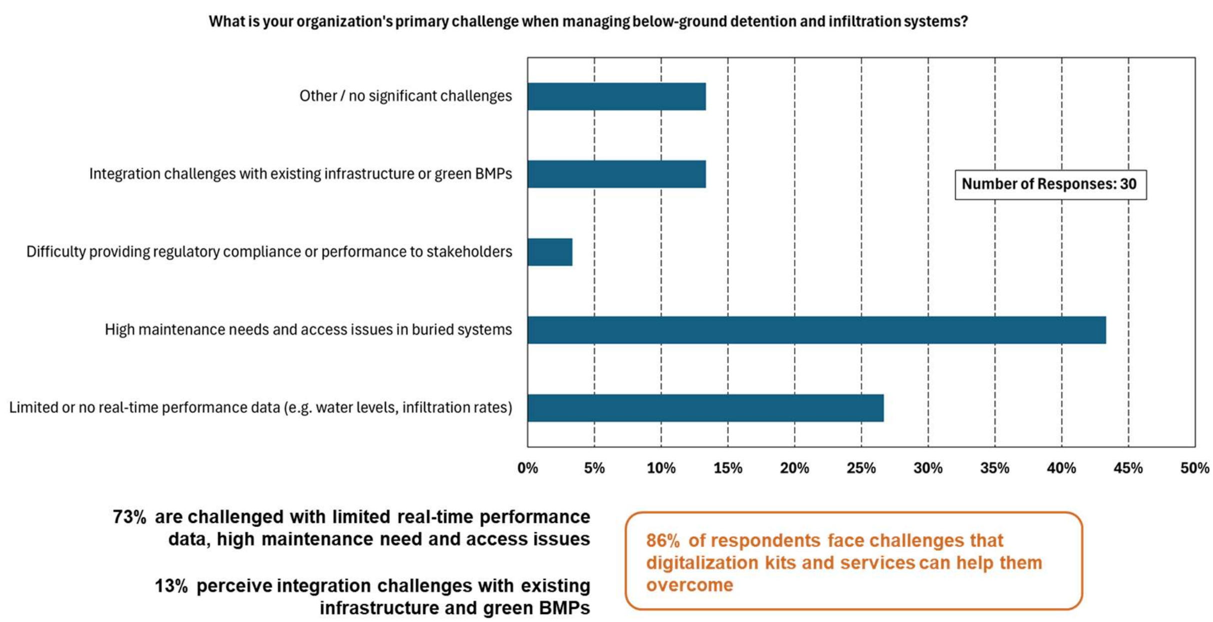

Figure 27. Responses to Pre-Presentation Survey Question 1: "What is your organization's primary challenge when managing below-ground detention and infiltration systems?" (30 respondents).

Eight-six (86) percent of respondents were found to have challenges that can be addressed through digitalization. Three areas where digitalization was thought to have the greatest value or benefit are:

- Integration challenges with existing infrastructure or green BMPs
- High maintenance needs and access issues in buried systems
- Limited or no real-time performance data (*e.g.* water levels, infiltration rates)

The opportunities for digitalization to satisfy the needs of the stormwater management profession are documented. A cloud-based platform meets the integration challenges of stormwater infrastructure systems across watersheds being managed. Digitalization also addresses the perception of high maintenance need for below-

[8] Foley and Hornyak (2026). "Digitalizing Below-Ground Stormwater Infrastructure", Fox-Wolf Watershed Alliance Annual Watershed Conference, Lambeau Field, Green Bay, WI, March 4, 2026.

ground systems by providing autonomous real-time performance data without the need for arbitrarily scheduled site visits. The documentation of performance through real-time measured performance data is also incredibly valuable.

The second question posed at the conference was: "What factor most raises questions regarding performance or reliability of your below-ground detention/infiltration systems?". Figure 28 illustrates the response to this question.

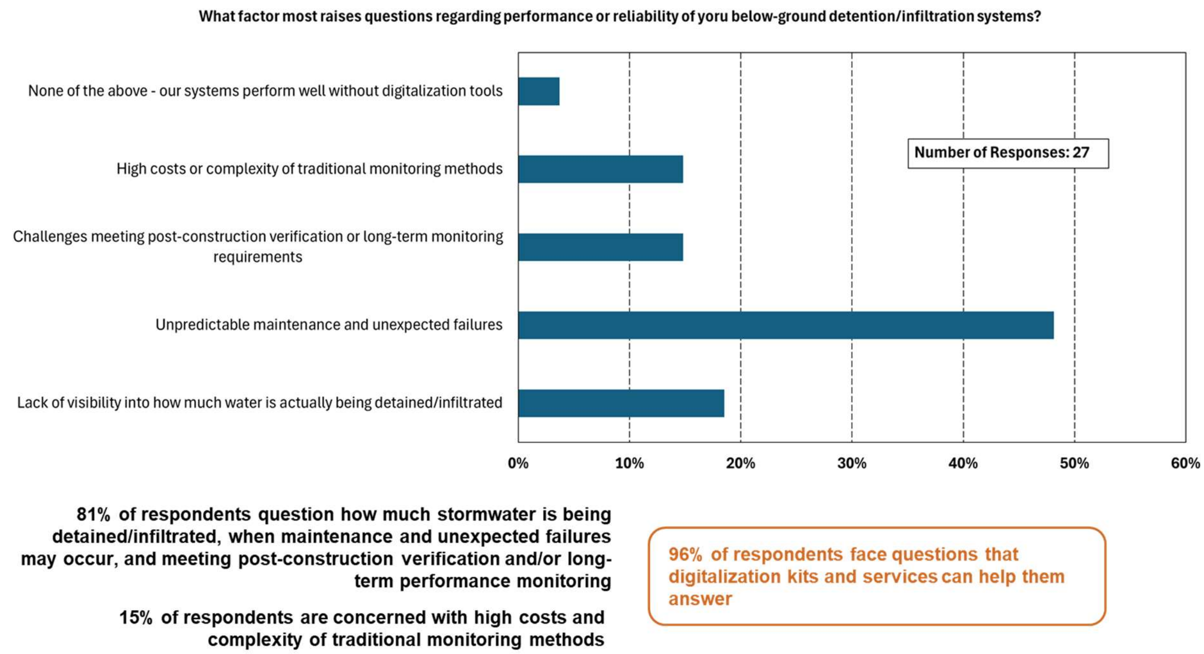

Figure 28. Responses to Pre-Presentation Survey Question 2: "What factor most raises questions regarding performance or reliability of your below-ground detention/infiltration systems?" (27 respondents).

Ninety-six (96) percent of respondents felt that there were four areas where digitalization technology could help them answer questions regarding management of below-ground stormwater infrastructure:

- High costs or complexity of traditional monitoring methods
- Challenges meeting post-construction verification or long-term performance monitoring requirements
- Unpredictable maintenance and unexpected failures
- Lack of visibility into how much water is actually being detained/infiltrated

Digitalization technologies provide direct support to answer these questions. Digitalization systems have been shown here to be incredibly economical when compared to traditional methods to answer these questions. In many cases, traditional methods simply cannot address these questions. The survey results illustrate that less than five (5) percent of respondents feel their systems perform well without digitalization. Digitalization tools are uniquely position to address concerns in meeting post-construction verification and long-term monitoring requirements of MS4 regulations and TMDL requirements. Digitalization tools are also in a unique position to definitively answer the question related to unpredictable maintenance and unexpected failures. These tools provide data-driven insights with regard to maintenance need and the continuous real-time data streams remove the risk of "unexpected failures". Finally, digitalization tools provide data-documented visibility into how much stormwater runoff is being detained and/or infiltrated. Digitalization tools will have significant impact on stormwater management practice meeting the needs of owners of below-ground stormwater infrastructure systems.

The third question posed at the conference was: "What is your current level of experience with digitalization tools for monitoring below-ground stormwater BMPs (*e.g.* sensors for water level, infiltration or storage)?". Figure 29 illustrates responses to this question.

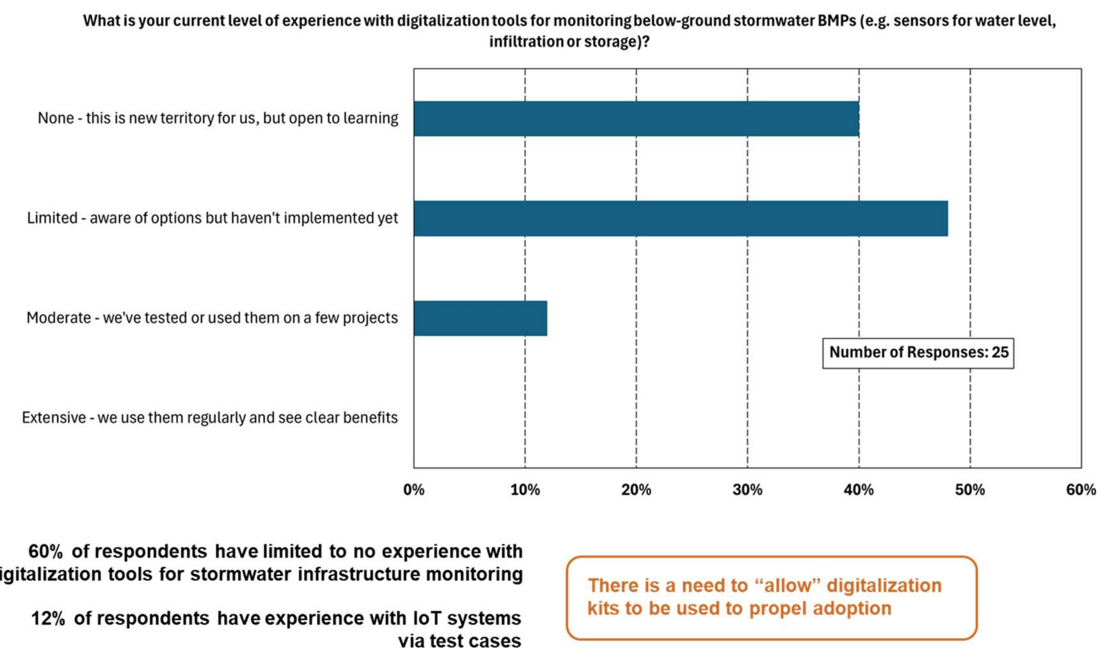

Figure 29. Responses to Pre-Presentation Survey Question 3: "What is your current level of experience with digitalization tools for monitoring below-ground stormwater BMPs (*e.g.* sensors for water level, infiltration or storage)?" (25 respondents).

One hundred (100%) percent of respondents admit that digitalization tools are new territory for which they have limited to moderate knowledge. It is the authors' opinion that limited use of digitalization tools is a result of two factors: (a) there is a perception that these tools are expensive; and (b) there is no clear acceptance or approval of use of these systems as part of stormwater management plans. The earlier discussion related to the Naperville, Illinois below-ground infiltration system was the first time a regulatory body was integrally involved in the requirement and acceptance of digitalization tools as part of a stormwater management plan. The acceptance of using these tools by regulatory bodies is integral to garnering widespread use of these systems in stormwater management practice.

Concluding Remarks

This white paper outlined an introduction to the below-ground stormwater infrastructure market, current methods to document performance, and managed operations and maintenance expenses experienced by owners of below-ground detention and infiltration systems. An outline of digitalization kits provided by P4 Infrastructure, Inc. was provided. The goal of this white paper was not to imply that P4 tools are the only tools available. The goal was to provide clear examples of the tools that are available to address the challenges found with below-ground detention and infiltration systems.

Three examples of digitalization kit deployment were outlined. These involved below-ground detention and infiltration systems throughout the United States. The value of these deployments to owners of these systems was clearly demonstrated. The value of digitalization tools in dollars to owners of these systems was also provided. Paths to reducing annualized operation and management costs and easing budgeting complexity through use of digitalization tools were also outlined. Paths toward moving stormwater management practice from episodic, costly, and subjective practices to proactive, economic, data-driven, predictive, verifiable, and efficient regulatory compliance practice through innovative and reliable technology were also provided.

Digitalization tools provide significant value to owners of below-ground systems and the stormwater management profession. The stormwater management and design profession are ready to implement these tools, but there is no clearly defined acceptance by regulatory agencies for using these tools as part of stormwater management.

It is hoped that this white paper provides the Wisconsin Department of Natural Resources confidence in allowing the use of digitalization technology and its integration into stormwater management practice. The impacts of integration of these tools will be far reaching in the DNR’s goals to preserve our natural groundwater and surface water resources.