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Water Level Loggers as a Low-Cost Tool for Monitoring of Stormwater Control Measures

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Abstract: Stormwater control measures (SCMs) are a key component of watershed health in urbanized areas. SCMs are used to increase infiltration and reduce discharge to streams or storm sewer systems during rain events. Monitoring is important for the evaluation of design and causes of failure in SCMs. However, the expense of monitoring means it is not always included in stormwater control planning. This study shows how low-cost water level loggers can be used to answer certain questions about SCM performance. Five case studies are presented that use water level loggers to evaluate the overflow of basins, compare a traditional stormpipe trench with an infiltration trench, monitor timing of blue roof storage, show the effects of retrofitting a basin, and provide long term performance data. Water level loggers can be used to answer questions about the timing and location of stormwater overflows, which helps to evaluate the effectiveness of SCMs. More expensive monitoring and modeling can be used as a follow up if needed to more thoroughly assess a site. Nonetheless, low-cost monitoring can be a first step in identifying sites that need improvement or additional monitoring.

Keywords: urban hydrology; stormwater control measures; monitoring; retention basin; infiltration trench; blue roof; infiltration chamber

1. Introduction

Controlling stormwater runoff is critical to watershed health. Increased infiltration can help to reduce both the volume of water and contaminant loads that threaten streams due to increased impervious surface area [1]. As urban centers expand or renovate, sustainable design typically depends on including stormwater controls to infiltrate water more efficiently in less space than natural systems [2].

A variety of stormwater control measures (SCMs) are used to increase infiltration during rain events and reduce discharge to streams or storm sewer systems [2,3]. Stormwater basins are one of the most common methods for capturing stormwater, and there are several different designs used [4–6]. Some basins include a subsurface retention chamber with perforated piping and gravel to store water, while some use natural soil or fill. Some basins include wetland plants to help retain water and some are dry between storms, while many have mowed grass. These basins vary in size, depending on the intended capture area; for example, a survey of 100 basins in the Valley Creek Watershed outside Philadelphia found sizes of 2.6×10^{-3} km^2 to 11 km^2 [7]. There is typically an inlet pipe and an outlet pipe or multiple inlets to take water from paved areas to the basin and then delay release to urban drainages. In addition to capturing land surface drainage, SCMs are needed for roof drainage. Although roof drainage can be piped to stormwater basins, sometimes green or blue roofs are used to reduce stormwater discharge from buildings. Green roofs use plants to help store water on the roof. Design considerations include low-cost plant maintenance and roof stability. Blue roofs store water on a waterproof membrane without plants, using instead check valves to slow the rate of discharge on the roof top [8]. Flat roofs with good stability are required. When space is more limited, smaller stormwater trenches are used instead [5,9]. These are designed with storage pipes surrounded by gravel, an inlet and outlet, but are smaller in size—typically a meter or two wide and 2–10 m long. Trenches can be used between buildings, along roadways, and in parking lot berms.

Although use of SCMs has increased since the 1990's, when stormwater control ordinances became more common, monitoring their effectiveness is not typically part of the design [2,10,11]. It is unfortunate that such monitoring is not standard, because stormwater control measures can fail for a variety of reasons. The systems can release water too rapidly due to design malfunction [12], fail to infiltrate due to clogging or reduced infiltration over time [7,9], and allow the release of chemicals of concern [13,14]. If these failures could be prevented by repair or improved designs, then the dollars spent on stormwater control would be more effective.

Monitoring is important for the evaluation of design problems and causes for failure in SCMs. Instrumentation is added to SCMs to evaluate the capacity for storing stormwater and to monitor inflows and outflows to calculate a water budget [15–17]. Rain gauges are needed to characterize storms at the site scale. Flowmeters, water level loggers, and soil moisture sensors are typically used to track water flow [11]. Instrumentation may need to be built into the initial design if weirs to focus outflow are needed or if sensors to measure soil moisture or water levels need to be buried within the SCM [9,15,17]. Long-term monitoring is conducted to evaluate potential clogging infiltration basins—a common problem [9,12,14]. In some cases, stream monitoring is implemented to evaluate the impact of SCM on catchments [18,19]. Both models and runoff capture calculations require careful assessment of land use and design specifications. However, monitoring tends not to be included because of the additional cost. Costs include changes in construction to include monitoring and additional site characterization, such as soil properties [9,15]. Often, multiple outlets and inlets or multiple structures in a treatment train [11,15,16] need to be monitored, which adds to the cost. Although models can be used to assess catchment hydrology, stream gauging stations are needed to calibrate the models. If gauging stations are not already in place, the cost to install is beyond the budget for a single project. Among the most expensive components of SCM monitoring is water quality assessment. A wide variety of chemicals may need to be analyzed [11], which can be expensive, and sample collection requires either automatic samplers or labor-intensive monitoring. Water quality monitoring typically depends on concurrent flow monitoring to assess loads.

Some stormwater control issues related to physical performance (rather than water quality) can be addressed by low-cost monitoring techniques. Although low-cost monitoring does not provide as much quantitative information about performance, it can be an initial screening tool, and more projects can be monitored. When necessary, follow-up using higher-cost, more detailed monitoring can be conducted. This paper reviews the types of projects and questions that lend themselves to low-cost monitoring.

2. Materials and Methods

Monitoring was conducted with water level loggers to answer questions about the effectiveness of various SCMs. Onset HOBO pressure transducers (4 m range, 0.3 cm accuracy) were used to measure water level. One to three water level loggers were installed, and data were collected at 15 min intervals. Water level loggers were installed in pairs to evaluate the timing and size of storm responses. An additional barometric logger was also needed to correct water level data for changes in barometric pressure. Rain data were obtained from nearby weather stations that report online or a rain gauge was installed on site. A monitoring system that included three loggers, software, computer connectors, and a rain gauge cost only $1,750 using the Onset HOBO water level logger ($300 each) and rain gauge ($420 each). Nearby sites could share rain gauges and barometric loggers. The water level loggers also include a temperature sensor, which sometimes provided additional information on stormflow. Labor costs were not included in the monitoring budget, and they can be highly variable depending on the number of sites, location, and frequency and duration of downloading data. However, relatively little training is needed to download and process the data (undergraduate students performed the field work in most of the projects described here.)

The five sites selected for this project were all in Philadelphia or its suburbs, in urban settings where stormwater impairs the local streams. In the city proper, stormwater creates combined sewer outfall overflows, and the city is implementing a large green infrastructure implementation program to reduce overflows. In the suburbs, impervious surface cover leads to the majority of stream reaches being impaired. In the studies summarized here, three vegetated basins, one parking lot infiltration trench, one parking lot infiltration chamber, and one blue roof were monitored. Two SCMs were inside the city and three sites with SCMs were outside the city. The specific locations of loggers, duration of monitoring, and questions addressed are described below for each case history. The site descriptions do not include a detailed diagram of capture areas or SCM design. One of the points of low-cost monitoring is not to include capture area analysis or design capacity calculations, but to instead use hydrographs to supplement anecdotal information about how stormwater is moving through the system.

3. Results

3.1. Comparison of Overflow in Two Stormwater Retention Basins

Site one contains two adjacent stormwater basins installed on the suburban campus of Temple University. One basin received water from a roof and surface runoff from nearby pavement. This 7.5 m diameter basin had standing water and wetland plants. Water was observed to overflow the wetland, and a small gully formed. A water level logger was installed in the gully to record the frequency with which water overflowed the wetland, and storm events were monitored for a year. The second basin received surface runoff from paved areas, then diverted it through a 35 m long meandering channel to a small depression (approximately 7.5 by 10 m) planted with trees and grass. This depression could pond, but was typically dry. Again, a gully formed at one end of the basin that diverted overflow, and a water level logger was placed in the overflow gully and monitored for a year.

The wetland overflowed for all but one of the nine storms with daily rain greater than 0.1 cm in the Fall (Figure 1). For the basin with a meandering channel, only five storms overflowed the basin, and the responses were smaller (Figure 1). The berm on one side of the wetland was not elevated enough, resulting in overflow, even for small storms. The wetland design was not sufficient to store the stormwater captured. In contrast, infiltration along the meandering channel and in the vegetated depression may have reduced overflow in this basin. Placement of rocks in the channel was observed to slow the flow of stormwater during storms. A similar contrast in response was observed for the Summer and Spring, but Winter data did not account for snow events, so it was more difficult to relate overflow to storm events.

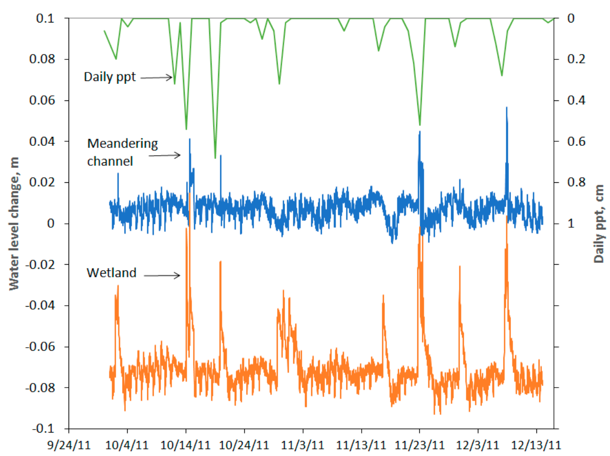

Figure 1. Comparison of stormwater overflow shown as spikes in water level in two retention basins: one with a meandering channel and one with a wetland. The baseline for the wetland was shifted down 0.08 m to show responses on the same plot.

This example showed that low-cost monitoring could quantify how often overflow occurred in an observed gully. Monitoring also contrasted differences in design between two sites, which led to increased basin overflow at a site with less infiltration.

3.2. Monitoring before and after Retrofit of a Basin

Stormwater basins often fail to infiltrate because mowing compacts the soil, or because the inlet and outlet are well-connected and water is not given enough storage time. Both issues decreased basin effectiveness at site two on the property of the Warrington Township Building. The basin was mowed, and a concrete track ran from the inlet structure to the outlet structure (Figure 2a). To improve infiltration, the basin was retrofitted by removing the concrete track, deepening about 0.3 m to reach a shallow water table, and planting with wetland vegetation that did not require mowing (Figure 2b).

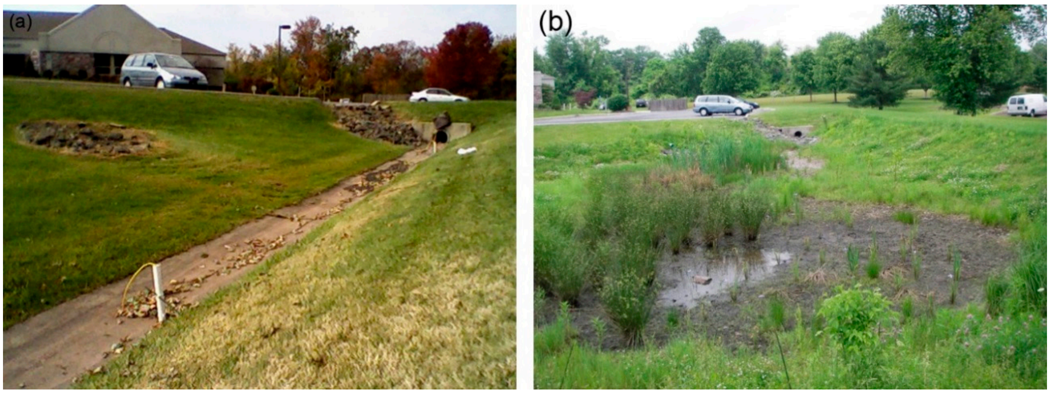

Figure 2. Photograph of a basin (**a**) before and (**b**) after retrofitting.

Water level loggers were placed in the inlet and outlet structures before and after retrofitting. The inlet and outlet were monitored for three months (August–October) before the retrofit. Monitoring resumed after the retrofit for eight months (from May to December). The shortened pre-monitoring period was due to the limited time before the anticipated construction schedule. A longer monitoring period post-construction was used to overlap seasons with the pre-monitoring period and to confirm the observed change in response over multiple seasons. Typically, 1 cm of daily rain was needed for an observed increase in water level. Pre-construction, 20 storms greater than 1 cm of daily rain were observed; post-construction, 30 storms greater than 1 cm were observed.

Before the retrofit, runoff from every storm reached the outlet, and the timing and water level indicated that no significant infiltration occurred. For example, for two rain events, one with daily rain of 2 cm and one with a cumulative rain of 1.9 cm spread over 3 days showed water level peaks with identical timing (Figure 3a). The water level in the outlet was 0.03 m higher for the first storm and 0.03 m lower for the second storm. There was no rain the week before the first rain event shown. In some cases, the water level was higher at the outlet due to the capture of additional water from inlets on the other side of the basin. After retrofitting, there was little to no water level increase at the outlet for similar storm input (Figure 3b). For the rain events in post-retrofit, a daily rain of 2.4 cm was observed for the first storm, then 1.9 cm cumulative over 3 days. The antecedent conditions were 0.2 cm of rain 3 days before, otherwise no rain for 6 days. The first storm showed only a small water level response in the outlet compared to the inlet, and the second storm showed no response in the outlet. Of the 30 storms recorded post-retrofit, 25 storms showed no response. Only three storms showed a small increase in water level of 0.05 m at the outlet (similar to Figure 3b), with another three 0.02 cm or lower, and the inlet showed at least five times higher response for each of these storms. Thus, even for an extended monitoring period, the outlet showed little or no response after the retrofit. This example provided quantitative measures of improvement in stormwater retention after retrofitting.

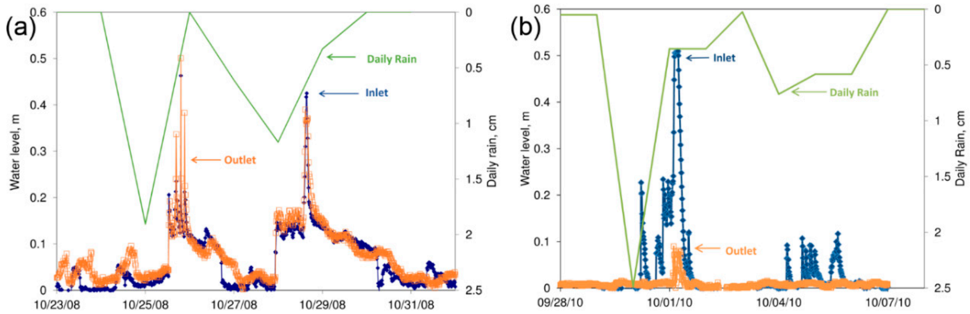

Figure 3. Water level response to storm events (**a**) before and (**b**) after retrofitting.

3.3. Blue Roof for Stormwater Storage Control

Site three is located at Paseo Verde, an apartment complex next to the Temple University campus, which is the first platinum Leadership in Energy and Environmental Design (LEED)-certified neighborhood development project in the U.S. One aspect of the LEED certification is a combination of green and blue roofs to provide stormwater control and energy insulation. The roof has a series of "bars" or corridors that alternate between blue and green roofs. Low-cost monitoring included water level loggers on two of the blue roofs. An additional logger was placed in the concrete manhole accessing the pipes leading from the roof bar to the street. A nearby rain gauge 500 m away was used to monitor the rain events.

Low-cost monitoring with water level loggers was used to evaluate the size of a rain event that creates a response on the roof, the length of time water was stored on the roof, and how often the street level pipes receive water compared to the roof. Only 5 mm of rain (per 15 min interval) produced a measureable response on the roof (Figure 4). This response was consistent across seasons for a year of monitoring and consistent between the two blue roofs monitored. For small storms (an hour or less) there was no storage, and the roofs immediately drained after the storm event ended. For longer storms lasting 6 to 12 h, the roofs stored water while the storm intensity declined, then drained about an hour after the end of the precipitation event. Snow depth was not recorded and not accounted for as storage. Longer storage was observed in the manhole going to the street (Figure 4). The outflow pipe in the manhole constricted flow, leading to slower drainage. A water level increase was recorded for every storm, both on the roof and in the street manhole. While the low-cost monitoring does not provide a water balance to indicate how much of the precipitation reached the storm pipe at the street, the close timing of the roof and street response suggests water flows rapidly from the roof with little opportunity for evaporation. One way to increase the travel time would be to decrease the size of the roof outlets, but care must be taken not to allow the water level to exceed the roof capacity.

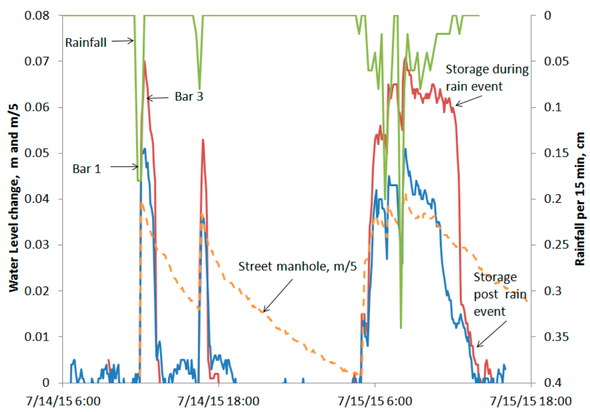

Figure 4. Water level responses on two blue roofs (Bar 1 and Bar 3) and a street manhole. The street manhole water level is divided by five to show on the same plot as the roof loggers.

3.4. Comparison of an Infiltration Trench and a Traditional Stormpipe in a Parking Lot

Site four is a stormwater trench installed next to a traditional stormwater collection pipe in a parking lot on the Temple University campus. The stormwater trench had 1 m of gravel surrounding a perforated pipe under a grass berm; the traditional storm pipe was in the paved section of the parking lot, had no external storage, and drained directly to the municipal combined sewer outfall in the street. This side-by-side installation allowed for comparison of storm response in two different systems to the same storm events. A water level logger was emplaced in the storm drain in the paved section, and another in the storm trench designed as green infrastructure.

The traditional stormpipe under pavement showed a water level rise for every storm event (Figure 5). Water rose between 0.05 and 1.5 m. In the inlet connected to the infiltration trench, the water level rose only for storm events with daily rain of 1 cm or greater, showing that for smaller storms the water was stored in the gravel surrounding the perforated pipe. Runoff across the parking lot would reach the gravel infiltration trench before the paved stormpipe inlet based on the slope, so there would not have been by-passing of this inlet. The water level rise was typically higher in the pipe with the gravel stormwater trench, but exceptions where the water level was higher in the traditional paved pipe also occurred.

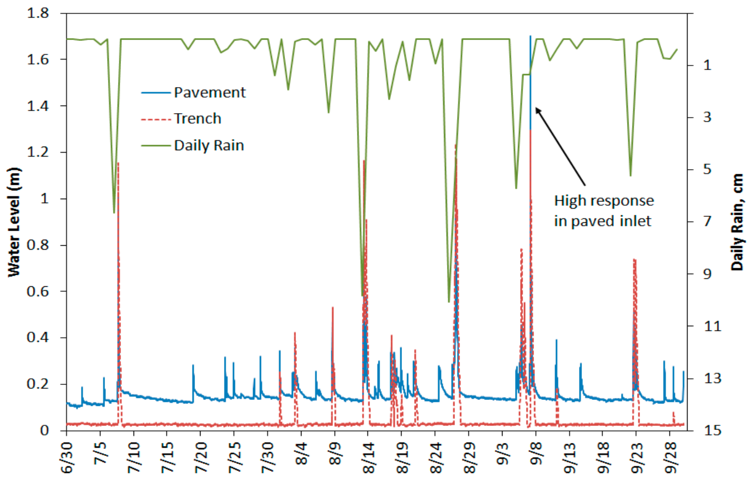

Figure 5. Water level response in parking lot infiltration trench and traditional storm pipe with a paved inlet. On 8 September 2011, the paved pipe had a higher response (see detail in Figure 6).

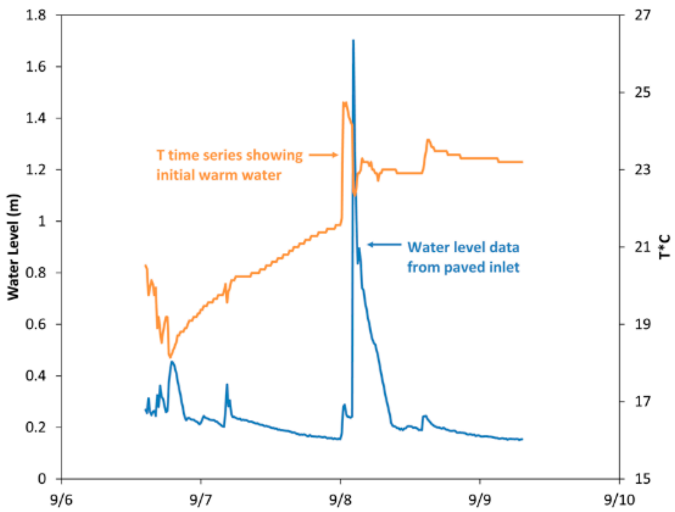

Figure 6. Water level and temperature for storm on 8 September 2011.

Higher response in the pipe beneath the pavement was linked to flow reversals. The water showed a temperature increase when the water level response was higher. For a storm on 8 September 2011, the warmer water appeared at 1:00 A.M.; however, warmer water is not expected for a night time rain event (Figure 6). Stormwater stored in the street stormpipe may have been warmed and entered the parking lot during this and similar storm events. Higher-cost monitoring using a flowmeter was used to follow up this observation. This flowmeter monitoring confirmed that flow sometimes reverses direction, moving water from the street to the parking lot.

3.5. Long-Term Monitoring of Infiltration Chamber Performance

Site five is an infiltration chamber installed beneath a parking lot at the Pennypack Ecological Restoration Trust (PERT). The infiltration chamber has five corrugated pipes surrounded by crushed stone that was washed to remove fines, and underlies an 8 × 13 m parking lot. Water enters the chamber by a drop inlet equipped with sediment filtration fabric as well as by entering through porous pavement on part of the parking lot. The system was designed to capture storms for the 2-year 24-h event, or approximately 8 cm of precipitation. The drainage area was estimated to be about 1.8 hectares (4.5 acres), with forest and residential development.

The PERT infiltration gallery was monitored for 2.7 years to evaluate its effectiveness and longevity. A monitoring well installed in the trench instrumented with a water level logger recorded the height of water and the recession. The logger data were compared to the rain gage recording events on the PERT site.

For most storms, there was no water level response. This lack of response demonstrates that rapid infiltration occurred. There was no response for any storm with daily rain less than 3 cm. Since 65% of annual precipitation occurs in storms less than 3 cm [20], the data indicate effective infiltration of the majority of stormwater. For storms with daily rain 3 cm and over, 50% had a measureable water level response, but 50% showed rapid infiltration and no response (Table 1). In 2007, there were five storms recorded with 3 cm or more of precipitation, and two had a water level response showing storage in the gallery. In 2008, there were six storms recorded with high precipitation, and three had a water level response. In the portion of 2009 that was monitored, there were two storms with high precipitation, and one had a water level response. Thus, there was no evidence of decline in effectiveness based on stormwater response. The water level peaks varied from 0.1 to 0.5 m, although some storms produced multiple peaks, so peak height was not always related to storm volume. The highest peak was for a 2.3 cm/h intensity storm.

Table 1. Summary of storm responses in parking lot infiltration chamber for events greater than 3 cm for 2.7 years of monitoring.

dd/mm/yyyy	Daily Rain, cm	Intensity, cm/h	Storm Peak, m	Recession, h
2/3/2007	4	0.2	0.25	3.5
16/4/2007	10	0.3	0.25	3
27/4/2007	3.6	0.4	0	
9/10/2007	3.2	1.3	0	
27/10/2007	3.7	0.2	0	
1/2/2008	3.3	0.2	0	
13/2/2008	5	0.4	0.1	6
8/3/2008	3.5	0.7	0.2	3
28/10/2008	3	0.2	0	
12/12/2008	5	0.5	0.08	7
13/6/2009	3.4	0.8	0	
2/8/2009	5	2.3	0.5	5

The recession times were short, 7 h or less with an average of 4.5 h. This recovery is considerably less than the 72 h required by the Pennsylvania Department of Environmental Protection stormwater manual [20], so there was no evidence for clogging during the monitoring period. The recovery times were somewhat longer in the last two years, but there was overlap with the early data. There was only one storm as large as the designed 2-year, 24-h storm event (Table 1, 16/4/2007), but it showed a similar water level rise to other storm events and similar rapid infiltration. Thus, the infiltration gallery had sufficient capacity to handle the designed event.

In summary, the infiltration gallery effectively captured and infiltrated the largest storms observed. Furthermore, the trench did not show signs of degradation after 2.7 years of monitoring, based on small storms showing no response both at the beginning and end of the period, and based on similar recession over time for larger storms. A typical trench can show signs of degradation at this point in time if clogging is an issue [7,9]. An appropriately-sized trench with a sediment filtration system improved the effectiveness and longevity of the PERT parking lot infiltration gallery.

4. Discussion

Low-cost monitoring can be an effective way to answer certain types of questions related to SCM design. It does not provide quantitative assessment of performance or capture volume or water quality issues. Instead, low-cost monitoring is suggested to provide a level of assessment that supplements observations and anecdotal evidence of SCM functioning. Low-cost water level loggers can be used to evaluate how often stormflow reaches an overflow monitoring point and for which storm events. The hydrograph also provides timing to indicate how fast stormwater is moving through the system. Green infrastructure can also be assessed before and after retrofitting.

The design of a low-cost monitoring system typically involves monitoring two points in a system, such as the inlet and outlet. Selection of monitoring points sometimes involves observing a system during wet weather to identify overflow points. The water level logger can be dry in between rain events, but it helps to have a collection point where water pools to record a water level rise in response to storms. Local precipitation data are also needed to relate the size of the storm event to the response. The time period for monitoring should be sufficient to capture a variety of storm events, and long-term monitoring (a year or more) requires little maintenance with low-cost water level loggers.

There are some limitations when relying on water level loggers to assess SCMs. Water quality assessment is not provided, although water level data can complement water quality sampling. It can be difficult to assess Winter performance, because snow melt can release water unrelated to a precipitation event and because frozen ground can change infiltration characteristics. Placing loggers in stormpipes can make them susceptible to movement, and the data record can be disrupted if the logger is knocked over or displaced from the pipe. Monthly data downloads can help keep the data record from getting disrupted, but that adds to labor costs. With a limited number of loggers, not all sources of inflow to a system can be monitored, and the sources can change depending on the season and storm intensity. Uneven distribution of rainfall can make it difficult to tie data directly to rain events. Despite such uncertainties, low-cost monitoring can help overcome resistance to making quantitative assessments of SCM performance.

In the examples presented here, there were several types of assessment provided by the low-cost monitoring. At site one, monitoring the inlet and outlet of two retention basins revealed differences in design that influenced how often the basin overflowed. At site two, monitoring showed that retrofitting reduced the number of storms that overflowed to the outlet structure. On a blue roof (site three), the timing of retention and overflow to the street pipe were recorded, which showed that water storage on the roof was short. Comparison of storm response in a traditional storm pipe and an infiltration trench (site four) showed improved storage in the trench, as expected. Stormpipe monitoring also showed warm water entering during storms, which may indicate overflow from street stormpipes. Because of the low-cost of the sensors, long-term monitoring can easily be implemented, and for an infiltration chamber beneath a parking lot (site five), showed little change in storage capacity in a 2.7-year study.

Observations of hydrographs using low-cost monitoring can help to evaluate the effectiveness of SCMs. Stormflow reduction is not always achieved, but monitoring can suggest improved designs that slow the flow of water and increase infiltration. Sites that need improvement or additional monitoring can be identified with low-cost monitoring.

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