Case Study

Application of a Monitoring Plan for Storm-Water Control Measures in the Philadelphia Region

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Abstract: Storm-water control measures (SCMs), also known as storm-water best management practices (BMPs), are increasingly being used to mitigate the impacts of development and restore the hydrologic cycle. This paper presents a three-tiered monitoring plan that can be used to determine the effectiveness of structural, nonproprietary SCMs in the Northeast United States. The monitoring plan offers three levels of monitoring: high, medium, and low. This 1-2-3 approach is common in environmental monitoring. The monitoring protocol integrates hydrologic, water quality, and ecological factors and recommendations for equipment with the level of monitoring. The monitoring plan is then applied to a rain garden on Villanova University's campus in Villanova, Pennsylvania, and a cost analysis of the different monitoring levels is provided. **DOI: 10.1061/(ASCE)EE.1943-7870.0000714.** *© 2013 American Society of Civil Engineers.*

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Introduction and Background

Awareness of the deleterious effects of a disrupted hydrologic cycle has increased dramatically over the past decade. Development decreases pervious surfaces and plant cover, thus increasing the amount of runoff while decreasing infiltration and evapotranspiration. The runoff from developed areas entering nearby streams moves more quickly, is hotter, and carries more pollutants than runoff from undeveloped areas. The damage from this runoff not only affects the area of development but also extends to the remainder of the watershed [e.g., National Research Council (NRC) 2008; Wang et al. 2001; Schueler 1994; Traver and Chadderton 1983]. Storm-water control measures (SCMs), also known as storm-water best management practices (BMPs), are increasingly being used to restore the hydrologic cycle and, as such, are a key component of low-impact development (LIDs) plans. Storm-water control measures are designed to serve three main purposes: (1) control the volume of runoff, (2) control the peak flow rates, and (3) reduce pollutants while restoring the natural hydrologic cycle [Pennsylvania Dept. of Environmental Protection (PADEP) 2007].

This paper presents a three-tiered monitoring plan that can be used to determine the effectiveness of structural, nonproprietary SCMs in the Northeast United States, depending on practicality and budgetary issues. Monitoring is broken into three levels: high, medium, and low. Depending on the desired level of monitoring, recommendations are provided on the equipment and frequency of monitoring. The proposed plan combines traditional monitoring activities to assess storm-water volume and quality, with ecological criteria recognizing the increasing trend to implement SCMs that have been designed to mimic natural systems.

The cost-effective inspection and monitoring of SCMs has garnered attention recently as township engineers are faced with increasingly stringent regulations. The monitoring plan presented in this paper seeks to fill a void by creating a succinct, multilevel approach to monitoring that can be applied to different types of SCMs by using data obtained during rain events. The recommended protocol incorporates the results and monitoring protocols used in long-term monitoring studies (e.g., Wadzuk et al. 2010; Emerson et al. 2010; Kwiatkowski et al. 2007) and other assessment protocols (e.g., Greising 2011; Asleson et al. 2009; Hankins et al. 2008; Gulliver et al. 2010; Lindsey et al. 1992).

This three-tiered monitoring plan is then applied to a rain garden on Villanova University's campus in Villanova, Pennsylvania, which is located approximately 24 km west of Philadelphia. The rain garden is part of the SCM demonstration park that has been constructed on campus over the past decade.

Types of Storm-Water Control Measures

Each SCM can be evaluated by considering five storm-water management goals: (1) control the volume of runoff, (2) control peak runoff rates, (3) reduce pollutants, (4) promote evapotranspiration, and (5) establish wetland structure and function. Goals 1–4 are traditional runoff control goals whereas Goal 5 is a relatively recent goal associated with the increasing use of SCMs designed to mimic natural systems such as wetlands. Although many SCMs integrate more than one goal into their design, they are grouped according to their primary goal in Table 1.

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Table 1. Storm-Water Control Measure Types and Goals

Type of SCM	Storm-water control measure goals[a]				
	Control runoff volume	Control peak runoff rates	Reduce pollutants	Promote evapotranspiration	Establish wetland structure and function
Infiltration: Infiltration trench/bed, pervious pavement	**Yes**	**Yes**	**Yes**	No	No
Bioinfiltration: rain garden, swales	**Yes**	**Yes**	**Yes**	Yes	No
Evapotranspiration: green roof	**Yes**	**Yes**	Yes	**Yes**	No
Constructed wetland, wet pond	**Yes**	**Yes**	Yes	Yes	**Yes**

[a]Primary goals are in bold, and secondary goals are in plain text.

Monitoring Methods and Equipment

Hydrologic

Hydrologic monitoring can range from a visual inspection to continuous monitoring. The equipment used to monitor the hydrologic performance of a SCM are rain gauges, staff gauges, ultrasonic level detectors, pressure transducers, area/velocity bubblers, weirs, and soil moisture meters. These instruments enable the monitoring of precipitation, infiltration rates, inflow and outflow, and volumetric water content.

Precipitation

Precipitation is monitored at the site by using either a standard (e.g., graduated cylinder) or electronic (e.g., tipping bucket) rain gauge. It is important to have site-specific rainfall information because rainfall amounts can vary significantly over short distances. If that is not possible, however, data from nearby weather stations can be assessed to determine the storms that have a more-uniform distribution and can be used to estimate the uncertainties involved in using this off-site data. If one wishes to perform hydrologic modeling of the site, a calculation of antecedent dry time can be determined by examining the precipitation data.

Infiltration Rates

Staff gauges, ultrasonic level detectors, and pressure transducers can be used to measure the water surface elevation or ponded depth. The ponded depth over time is used to determine the infiltration rate and the total volume of water retained by the SCM. The infiltration rate, which can be determined by drawing a regression curve of ponded depth against time and finding the slope (Emerson and Traver 2008), is a key performance parameter for infiltration SCMs, such as permeable pavements, bioinfiltration bed/trenches, and rain gardens. To account for viscosity changes caused by temperature changes, the infiltration rate should be normed to 20°C by multiplying the infiltration rate by the ratio of the viscosity of water at the given temperature to the viscosity of water at 20°C (Braga et al. 2007).

Runoff Inflow and Outflow

At the lowest level, a visual inspection can determine if runoff is entering a SCM. A pressure transducer in conjunction with a weir can be used to determine the volume of water entering or exiting the site. The pressure transducer is used to determine the height of the water behind the weir. Once the dimensions of the weir are known, the flow over the weir can be determined.

Volumetric Water Content

Moisture meters or reflectometers, which provide the volumetric water content, can be placed in the soil below the SCM. These probes must be calibrated to the site-specific soils to provide accurate measurements. There are many soil moisture meters available on the market, and the calibration must be performed in accordance with the manufacturer's guidelines. Moisture meters can help determine the capacity of soil pores to collect water and provide information on the infiltration rate as the moisture front moves through the soil. They can be used to determine the antecedent moisture content to create more-accurate mathematical models for infiltration rates and evapotranspiration.

Water Quality

The pollutants found in storm water vary widely from site to site. Proper siting and design of SCMs are needed to ensure that contaminants are not introduced to the groundwater system. Pretreatment may be required if significant contaminants are present. The concept of applying a treatment train approach to SCMs is gaining in popularity, as this approach has the potential to reduce maintenance costs and increase longevity (Brown et al. 2012; Wadzuk and Traver 2012; Greenway 2007). Suspended solids are a storm-water contaminant in part because other contaminants often stick to sediment or fines suspended in runoff. Thus, determination of total suspended solids (TSS) and total dissolved solids (TDS) may be useful at some sites (Emerson et al. 2010; Kwiatkowski et al. 2007). In addition, pH, nutrients, metals, and hydrocarbons may be of concern, depending on the sources of runoff (McNett et al. 2011; Gulliver et al. 2010; Soller et al. 2005; Deletic 1998). Temperature, which is important to maintain the health of fish and amphibian populations in receiving waters, can be measured with separate sensors or as part of the pressure transducer readings (Jones and Hunt 2009).

Runoff Samples

Runoff is sampled to determine the pollutant levels of the water entering the SCM. First-flush samplers, autosamplers, and grab samples can be used to obtain samples of runoff. First-flush samplers are placed at the edge of the SCM and are designed to capture the runoff from the early part of the storm. Depending on the antecedent conditions, this portion of the runoff can have significantly higher contaminants than runoff generated during later parts of the storm (Batroney et al. 2010; Kang et al. 2008; Soller et al. 2005; Deletic 1998). Samples of water ponded in the SCM may be obtained by an autosampler or by grabbing samples by hand.

Subsurface Samples

Lysimeters, also known as pore-water samplers, are used to collect water from the vadose zone and can be placed at several locations beneath the SCM to obtain subsurface water samples (Komlos and Traver 2012; Welker et al. 2012; Kwiatkowski et al. 2007). To obtain samples, a vacuum is created within the ceramic cup of the lysimeter that exceeds that of the soil suction within capillary spaces, causing water to flow into the sampler. These samples can then be used to determine changes in water quality as a function of depth. Subsurface samples are only used for the highest levels of monitoring.

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Ecological

Ecological monitoring, which includes evaluating plant diversity and coverage, nutrient uptake by plants, insect and animal utilization, and soil conditions, is used to assess the effectiveness of vegetated SCMs, such as green roofs, rain gardens, wet ponds, and constructed wetlands.

Plant Diversity and Coverage

The health of the plantings in a vegetated SCM is critical because the plants help to stabilize the soil in the SCM and increase evapotranspiration, thus reducing peak runoff and, in some cases, uptaking nutrients. For all vegetated SCMs, a planting diagram should be developed at the time of planting. Plant diversity and coverage is evaluated by inspection (Gulliver et al. 2010).

Nutrient Uptake

Wetlands, wet ponds, and rain gardens are planted with native plant species, many of which have proven phytoremediation capabilities and can be sampled for nutrient uptake to determine the amount of nutrients being absorbed (Tanner 1996). Nutrient uptake monitoring involves collecting vegetation samples, separating the shoots from the stems, weighing the mass of each sample, and then assessing the amount of nitrogen and phosphorus in the two types of plant tissue per species (Hoagland et al. 2001). Nutrient uptake analysis is only recommended at the highest level of monitoring.

Insect and Animal Utilization

Some SCMs, such as constructed wetlands, wet ponds, and, to a lesser extent, rain gardens, can provide habitat to vertebrate and invertebrates. The utilization of these SCMs by insects, fish, frogs, birds, and mammals can provide insight into the established habitat value of the SCM. Biological assessments are important to evaluate the contribution of wet-pond and wetland SCMs to regional habitat and biological diversity (Hayes et al. 2000). These assessments are only recommended at the highest level of monitoring.

Soil Conditions

Monitoring the soil conditions of wet-pond and wetland SCMs is important to assess pollutant and nutrient retention and to provide measures of wetland function. Soil samples are obtained and analyzed for organic content, texture, particle size, and hydric state. Sediment traps can be used to monitor how well a wet-pond or wetland SCM is retaining sediments (Hayes et al. 2000).

Monitoring Recommendations by Type of SCM

When developing a monitoring plan for SCMs, there are several factors that need to be considered. The monitoring recommendations presented in this paper include traditional factors, such as the type and frequency of monitoring, but also account for the realities of budget and personnel constraints. Consequently, three levels of monitoring—low, medium, and high—are presented. The low level of monitoring assures that the SCM is functioning as designed. The medium level of monitoring provides more-detailed information to better define how the SCM is working hydrologically. Finally, the high level of monitoring includes detailed water-quality data collection and more-sophisticated ecological monitoring.

The frequency of monitoring can be broken into four groups:

1. Yearly—Monitoring is performed yearly, ideally at the same time each year. This is applicable to ecological monitoring.
2. Seasonal—Monitoring is performed in response to rain events once in each season. In the authors' experiences in the Northeast United States, at least 0.6 cm of rain in an 8-h period will provide measurable quantities of runoff. This is applicable to runoff inflow and outflow and infiltration monitoring at infiltration and bioinfiltration SCMs and precipitation monitoring at infiltration, bioinfiltration, and evaporation SCMs.
3. Event—Monitoring is performed approximately monthly. This is applicable to water-quality monitoring at all four SCMs. Similar to the seasonal monitoring, a rain event that produces at least 0.6 cm of rain in 8 h should provide measurable quantities of runoff.
4. Continuous—Monitoring is performed continuously for all rain events that produce measurable quantities of runoff. This is applicable to hydrologic and water-quality instrumentation that is self–data logging. The data can then be downloaded and evaluated after the rain event is completed.

Infiltration SCMs

Fig. 1 shows a site that utilizes pervious concrete and porous asphalt to transmit water to an infiltration basin. The recommended monitoring activities for infiltration SCMs will provide data to assess the performance of the SCM with respect to its three design goals: reduce runoff volume, control peak runoff, and reduce pollutants (Horst et al. 2011; Emerson et al. 2010; Maniquiz et al. 2010; Kwiatkowski et al. 2007; Gilbert and Clausen 2006; Barrett et al. 1995). The type and frequency of monitoring for infiltration SCMs across the three levels is presented in Table 2. The visual inspection checklist for monitoring infiltration SCMs includes the following items:

1. Ponded water present for more than 48 h after rainfall event (infiltration rate);
2. Movement of water;
   - Sediment accumulation in basin area;
   - Clogged inlet structures; and
   - Clogged outlet structures.

A "yes" to any of the items in the above list indicates that maintenance or repair is required. At the medium level of monitoring, the infiltration rate can be obtained by measuring the depth of water in the trench or infiltration basin at 1-h intervals for approximately 8 h after a storm event or until the water is gone.

Fig. 1. Porous asphalt/pervious concrete comparison site (photograph courtesy of Patrick Jeffers)

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Table 2. Recommended Monitoring for Infiltration SCMs

Monitoring criteria	Low	Medium	High
Hydrologic			
Precipitation		Seasonal: standard rain gauge	Continuous: electronic rain gauge
Infiltration rate		Seasonal: staff gauge Infiltration rate of pavements [ASTM 1701 (ASTM 2009)]	Continuous
Inflow and outflow	Seasonal: visual inspection	Seasonal: visual inspection	Continuous
Volumetric water content			Continuous: sensors (optional)
Water quality			
Surface water samples			Event: first flush and autosampler or grab Continuous: temperature sensors (optional)
Subsurface water samples			Event: pore-water samplers

Note: Not applicable to ecological monitoring.

Bioinfiltration SCMs

A rain garden, which is a type of bioinfiltration SCM, is shown in Fig. 2. The recommended monitoring activities will provide the data to assess the performance of the SCM with respect to its three main design goals: reduce runoff volume, control peak runoff, and reduce pollutants. The type and frequency of monitoring for bioinfiltration SCMs across the three levels is presented in Table 3 (Asleson et al. 2009; Davis 2008; Heasom et al. 2006), and the visual inspection checklist for bioinfiltration and pond and wetland SCMs is presented as follows:

Fig. 2. Rain garden when full (photograph courtesy of Laura Lord)

1. Ponded water present for more than 48 h after rainfall event (infiltration rate);
2. Movement of water;
   - Sediment accumulation in basin area;
   - Clogged inlet structures;
   - Clogged outlet structures; and
   - Excessive erosion.
3. Plant diversity and coverage;
   - Presence of invasives;
   - Percent vegetative cover;
   - Presence of wetlands plants such as cattails, arrowheads, and marsh smartweeds;
   - Color, quality, and size of leaves, stems, and flowers.

Bioinfiltration SCMs are typically designed to drain within 48–72 h of filling (Environmental Services Div. 2007; PADEP 2007); therefore, the presence of wetland plants or water several days after a rain event would indicate that maintenance or repair is needed. At the medium level of monitoring, the infiltration rate in a rain garden can be obtained by measuring the depth of water at 1-h intervals for approximately 8 h after a storm event or until the water is gone. Emerging research on evapotranspiration from bioinfiltration SCMs indicates that evapotranspiration is likely to play a large role in volume reduction (Welker and Wadzuk 2011).

Evapotranspiration SCMs

The performance goals of evapotranspiration SCMs are to reduce runoff volume and pollutant discharge through evaporation and transpiration. An example of an evapotranspiration SCM is a

Table 3. Recommended Monitoring for Bioinfiltration SCMs

Monitoring criteria	Low	Medium	High
Hydrologic			
Precipitation		Seasonal: standard rain gauge	Continuous: electronic rain gauge
Infiltration rate	Seasonal: visual inspection	Seasonal: staff gauge	Continuous
Inflow and outflow	Seasonal: visual inspection	Seasonal: visual inspection	Continuous
Volumetric water content			Continuous: sensors (optional)
Water quality			
Surface water samples			Event: first flush and autosampler or grab Continuous: temperature sensors (optional)
Subsurface water samples			Event: pore-water samplers
Ecological			
Plant diversity and coverage	Seasonal: visual inspection Yearly: plant inventory	Seasonal: visual inspection Yearly: plant inventory	Seasonal: visual inspection
Nutrient uptake			Yearly: plant samples

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vegetated roof (Fig. 3). The monitoring plan for this type of SCM is presented in Table 4, and the visual inspection checklist for evapotranspiration SCMs is presented as follows:

1. Movement of water: clogged inlet structure;
2. Plant diversity and coverage;
   - Presence of invasives;
   - Percentage of vegetative cover; and
   - Color, quality, and size of leaves, stems, and flowers.

As with the bioinfiltration SCMs, the purpose of measuring ecological parameters is not to determine if the facility is functioning as a natural system but to ensure that vegetation has been established or to assess the uptake of nutrients by vegetation (high). At the time of writing this paper, the equipment for measuring evapotranspiration is not yet commercially available; however, research into quantifying evapotranspiration from SCMs is ongoing (Wadzuk et al. 2013).

Pond and Wetland SCMs

The performance goals of ponds and wetlands include reducing runoff volume, controlling peak runoff, reducing pollutants, and establishing habitat (Fig. 4). The recommended monitoring plan (Table 5) includes hydrologic, water quality, and ecological monitoring criteria. The visual inspection checklist for bioinfiltration SCMs can also be used for pond and wetland SCMs. However, for ponds and wetlands, the presence of wetland plants and the inability of water to drain 48 h after a storm event indicate that the SCM is functioning properly.

The monitoring protocol for the ecological parameters at the highest level of monitoring was based on wetland monitoring and success evaluation guidance developed by the U.S. Army Corps of Engineers (Hayes et al. 2000). Correspondingly, the recommended monitoring plan includes the collection, analysis, and reporting of soil conditions, sedimentation rate, vegetation, and biological diversity and abundance data essential to assessing the success of SCMs designed to function like wetland systems.

Monitoring of plant communities is essential to evaluating wetland function, as vegetation affects hydrology, sedimentation, and habitat suitability. Native plant species planted for soil and water erosion control around the pond and wetland SCMs should be evaluated for their establishment rates. General information about the vegetation should be obtained by sampling the site with a transect method. Transects are required when monitoring ecological parameters because ponds and wetlands tend to be much larger than other vegetated SCMs. Five permanent transects should be established through the wet ponds. Nested quadrants, which

Fig. 3. Green roof (photograph courtesy of Dominik Schneider)

Fig. 4. Constructed storm-water wetlands (photograph courtesy of Michael Rinker)

Table 4. Recommended Monitoring for Evapotranspiration SCMs

Monitoring criteria	Low	Medium	High
Hydrologic			
Precipitation		Seasonal: standard rain gauge	Continuous: electronic rain gauge
Outflow	Seasonal: visual inspection	Seasonal: visual inspection	Continuous
Volumetric water content			Continuous: sensors (optional)
Water quality			
Surface water samples			Event: autosampler or grab Continuous: temperature sensors (optional)
Ecological			
Plant diversity and coverage	Seasonal: visual inspection Yearly: plant inventory	Seasonal: visual inspection Yearly: plant inventory	Seasonal: visual inspection
Nutrient uptake			Yearly: plant samples

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Table 5. Recommended Monitoring for Wet Pond and Wetland SCMs

Monitoring criteria	Low	Medium	High
Hydrologic			
Precipitation		Seasonal: standard rain gauge	Continuous: electronic rain gauge
Inflow and outflow	Seasonal: visual inspection	Seasonal: visual inspection	Continuous
Water quality			
Surface water samples			Event: first flush and autosampler or grab Continuous: temperature sensors (optional)
Ecological			
Plant diversity and coverage	Seasonal: visual inspection Yearly: plant inventory	Seasonal: visual inspection Yearly: plant inventory	Seasonal: visual inspection
Nutrient uptake			Yearly: plant samples
Insect and animal utilization			Yearly: inspection
Soil conditions			Yearly: soil samples

include 5 × 5 m for sampling trees/shrubs and 0.5 × 0.5 m for sampling herbaceous plants, should be randomly located along the transects. The following vegetation properties should be recorded: total vegetation cover, species richness, relative dominance, and Shannon-Weaver diversity index. For each species, the survival rate should be tallied annually. Ten plants of each species should be tagged, and growth rates of elongating shoots and leaves should be measured monthly (Hayes et al. 2000).

Emergent species planted inside the wetland ponds can be evaluated for their growth. Survival rate should be tallied annually. Growth rate should be measured by using the method mentioned previously. Biomass should be sampled from a random set of 0.25-m^2 quadrants. Vegetation and litter in each quadrate should be clipped at ground level. Roots should be sampled by inserting a 6-cm diameter soil core 17 cm deep in the center of each quadrant. Roots should be separated out from the soil core. Plant materials should be sorted to species and weighted separately after drying monthly (Hayes et al. 2000).

Monitoring aquatic macroinvertebrates records the establishment of colonies essential in fostering vertebrate diversity. Macroinvertebrate samples should be collected from three replicate samples plus a leaf litter sample. The assessment should include the number of individuals, diversity of species, and tolerance of species. A sweep-net sampling procedure can be used to identify insects. Sweeps should be completed for each transect with identification and counts conducted for each species. A sweep should be completed at least once a year during the growing season and more frequently if resources permit. A correlation can possibly be drawn up between the insects and pollination of various plant species per transect. At this time, bird counts through inspection can also be completed [U.S. Environmental Protection Agency (USEPA) 2002a]. Bio-assessments for the birds and mammals should occur regularly and include a survey for migrating birds during breeding (Taylor and Currier 1999). Invertebrates should be identified to the lowest taxonomy, abundance, habitat, and functional feeding group (USEPA 2002b; Carter 2005).

Monitoring the soil conditions of pond and wetland SCMs is important to assess pollutant and nutrient retention and to provide measures of wetland function. Five soil core samples should be collected randomly throughout the site to obtain representative samples. These samples should be analyzed for organic content, texture, particle size, and hydric state. Monitoring a wetland system's sediment retention provides information on wetland function. Sediment traps should be placed in each plot's inlet area. Trap data should be collected annually and should include field measurement of the depth of sediment followed by dried weight and volume of sediments collected (Hayes et al. 2000).

Case Study

To demonstrate the appropriateness of the three levels of monitoring, a case study was performed using representative data collected in 2007 and 2008 from a rain garden. The hydrologic and water-quality factors were monitored at a high level; however, the nutrient uptake of the plants was not determined. A cost comparison of the different levels of monitoring performed for this case study is also presented.

Site Description and Background

In 2001, a conventional traffic island in a parking lot was converted into a rain garden (Fig. 2). It was designed to reduce peak flows, reduce runoff volume, control pollutants, and promote evapotranspiration by capturing the runoff from smaller storms. This SCM has a drainage area of 0.5 ha, of which 54% is impervious. The rain garden retains approximately 70% of the annual runoff from the area and was designed to capture the rainfall from smaller storms of 3.8 cm or less (Machusick et al. 2011; Heasom et al. 2006). Overflow from the SCM flows into the Darby Creek, a tributary of the Delaware River. The rain garden has been minimally maintained since its construction to permit studies on the life cycle of rain gardens (Gilbert et al. 2010).

The site has been extensively instrumented (Fig. 5). The hydrologic and water quality equipment installed at the site is

- Precipitation: Standard and electronic (tipping bucket) rain gauges
- Infiltration: Staff gauge, ultrasonic level detector, V-notch weir with pressure transducer (also used for outflow)
- Water quality: First-flush samplers and autosamplers in basin and lysimeters for pore-water samples

Low-Level Monitoring Results

The goal of this level of monitoring is to assess the performance of the SCM to determine if it is meeting its design goals. Low-level monitoring of bioinfiltration SCMs includes seasonal visual inspections of the infiltration rate and inflow and outflow and vegetation (Table 6). The visual inspection of infiltration and inflow and outflow revealed that the SCM was performing well and meeting its goals. Water was entering and exiting the SCM as designed, and the basin was draining within 48 h of rainfall events. A more-thorough plant inventory (Table 7) was performed in the summer, which revealed that a number of plants have died off, such as American beach grass, coastal panic grass, and marsh elder. In addition, a large number of plants have been introduced to the system; however, all of these plants are native species.

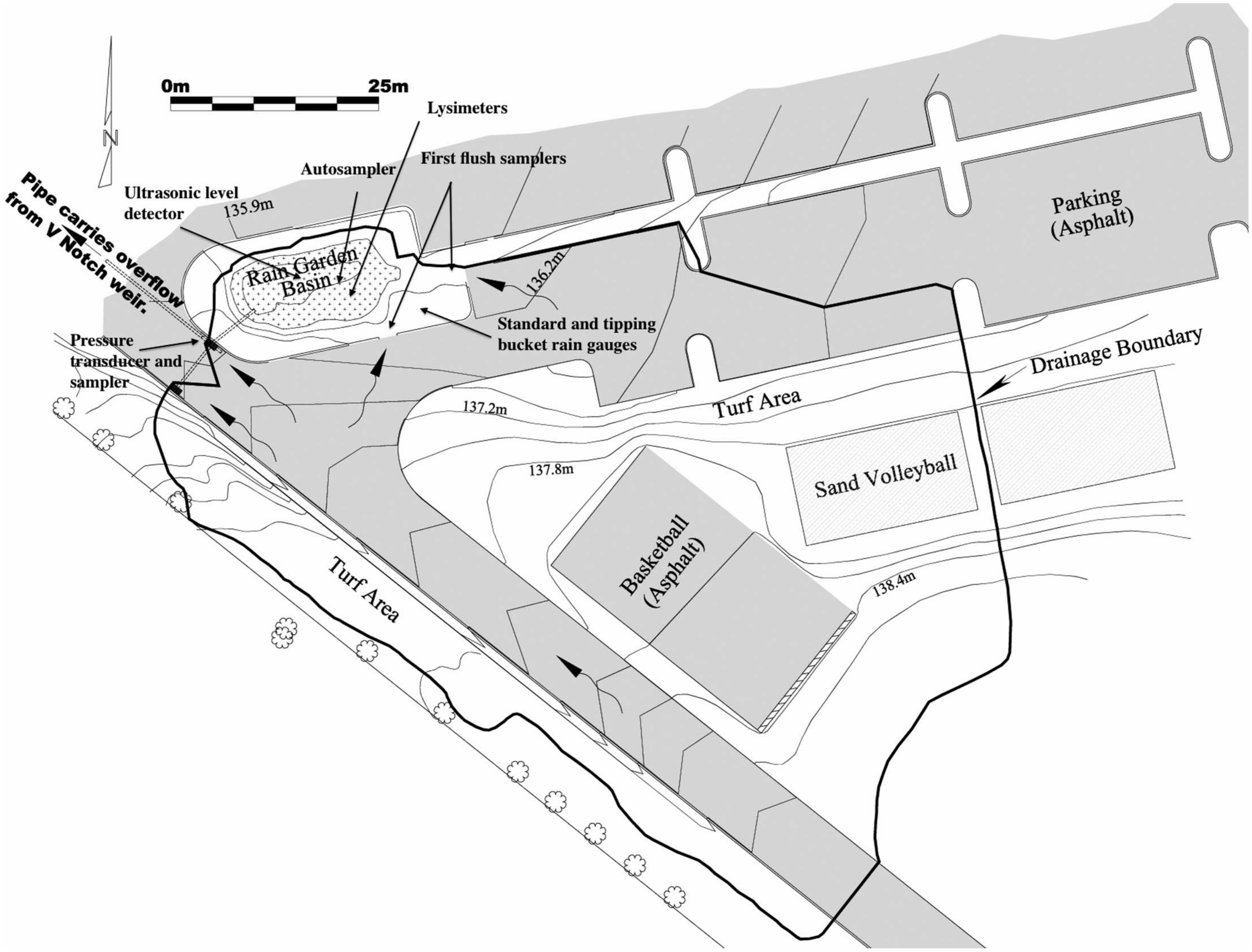

Fig. 5. Instrumentation at rain garden

Table 6. Visual Inspection of Rain Garden

Monitoring criteria	Winter	Spring	Summer	Fall
Infiltration rate				
Ponded water present for more than 48 h after rainfall event	No	No	No	No
Inflow and outflow				
Sediment accumulation in basin area	Some sediment visible on rocks leading into basin	Some sediment visible on rocks leading into basin	Some sediment visible on rocks leading into basin	Some sediment visible on rocks leading into basin
Clogged inlet structures	No	No	No	No
Clogged outlet structures	No	No	No	No
Excessive erosion	No	No	No	No
Plant diversity and coverage				
Presence of invasives	Yes	Yes	Yes—see plant inventory	Yes
Vegetative cover (%)	—	35	50	50
Presence of wetland plants (cattails, arrowheads, marsh smartweeds)	No	No	No	No
Color, quality, and size of leaves, stems, and flowers	—	Good	Good	Good

Although the vegetation has changed since the rain garden was installed, this plant inventory indicates that no maintenance is required. Notes and photos were taken to document the health of the plants, noting color, quantity, and amount of leaves, stems, and flowers, and these can be used later to compare the change in plants at the site.

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Table 7. Plant Inventory at Rain Garden

Species	Height (m)	% area	Present
American beach grass[a]	—	0	No
Coastal panic grass[a]	—	0	No
Mugwort	2.0	15	Yes
Astor	1.1	10	Yes
Golden rod[a]	2.7	1	Yes
Switch grass[a]	1.2	14	Yes
Box elder	0.9	<1	Yes
Little bluestem[a]	1.7	6	Yes
Smartweed	0.6	1	Yes
Green foxtail	1.7	1	Yes
White snakeroot	0.3	<1	Yes
Beech plum[a] (2)	2.9, 2.1	—	Yes
Winterberry[a] (4)	2.1, 2.6, 1.8, 2.4	—	Yes
Black chokecherry[a]	2.7	—	Yes
Groundsel tree[a] (2)	3.4, 1.8	—	Yes
Sycamore	2.3	—	Yes
Marsh elder[a]	—	—	No

[a]Original plantings.

Medium-Level Monitoring Results

The medium-level monitoring builds on the low-level monitoring by adding more hydrologic monitoring. This additional monitoring includes using a standard (graduated cylinder) rain gauge and seasonal measurements of the infiltration rate by using a staff gauge. To place the precipitation results into perspective and to show the clear advantage of on-site precipitation measurements, the data from the rain gauge were compared to precipitation data from the closest USGS weather station [Station 01473169 near Valley Forge, Pennsylvania, approximately 16 km (10 mi) from the site].

To assess the infiltration rate, the depth of water in the rain garden was measured for four storm events, one during each season (Fig. 6). In all four cases, the monitored storm event was preceded by at least three dry-weather days; thus, it can be surmised that the soil was at or near field capacity. The depth of water in the rain garden was measured every hour for 8 h, with the first reading beginning within 1 h of the cessation of rain. The slope of these graphs can be used to determine the infiltration rate (Table 8). To facilitate comparison, the data for both medium and high levels of monitoring are included in Table 8. A true comparison of the infiltration rates is obtained by norming the values to a given temperature to account for the changes in viscosity that occur from changes in temperature. Although there is some variability in the infiltration rate, the results indicate that the infiltration rate at this SCM is not degrading over time (Emerson and Traver 2008).

High-Level Monitoring Results

At high-level monitoring, a tipping-bucket rain gauge was used record precipitation, an ultrasonic level detector was used to obtain the elevation of the water in the basin to compute infiltration rates, a V-notch weir with a pressure transducer was used to monitor outflows, and water samples were obtained from first-flush and grab samplers. The ultrasonic level detector provided elevation readings every 5 min. These data were graphed (Fig. 7) and were used to determine the infiltration rate in the rain garden previously shown in Table 8. The level of the water in the basin was present until all of the water had infiltrated (spring and fall) or until the next storm event (winter and summer). These infiltration rates are similar to those obtained from the medium-level monitoring; however, they are more accurate.

This rain garden accepts inflow from a number of sources; thus, the precipitation data were used in conjunction with the data from the V-notched weir to determine the runoff inflow and outflow rates and the percentage of the rainfall that was captured by the SCM. This capture rate was computed for four storm events each year (one in each season). The simple method (Schueler 1987), which computes runoff on an annual basis in inches, was adapted slightly

Table 8. Infiltration Results for Medium- and High-Level Monitoring at Rain Garden

Temperature and infiltration rates	Winter	Spring	Summer	Fall
Average temperature during storm event (°C)	13.3	16.1	18.9	17.8
Medium-level monitoring results				
Infiltration rate (cm/s)	1.4E-04	6.9E-05	2.3E-04	2.1E-04
Infiltration rate normed to 20°C (cm/s)	1.7E-04	7.6E-05	2.5E-04	2.3E-04
High-level monitoring results				
Infiltration rate (cm/s)	2.7E-5	1.6E-4	2.3E-04	2.0E-4
Infiltration rate normed to 20°C (cm/s)	3.2E-5	1.8E-4	2.4E-4	2.2E-4

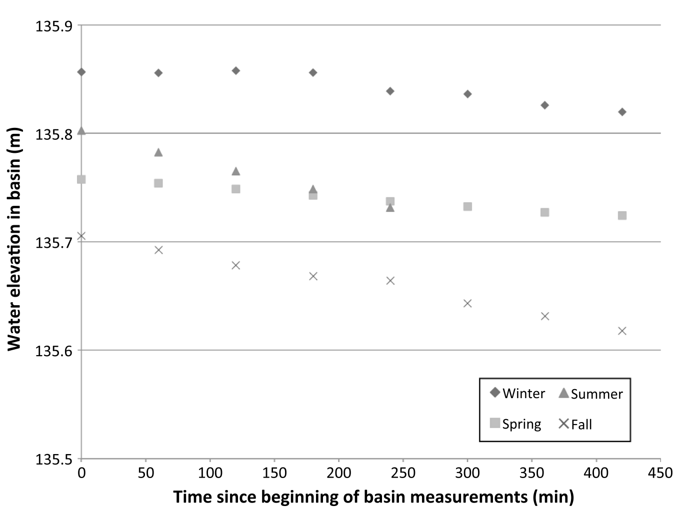

Fig. 6. Depth of water over time at rain garden; used for medium-level monitoring

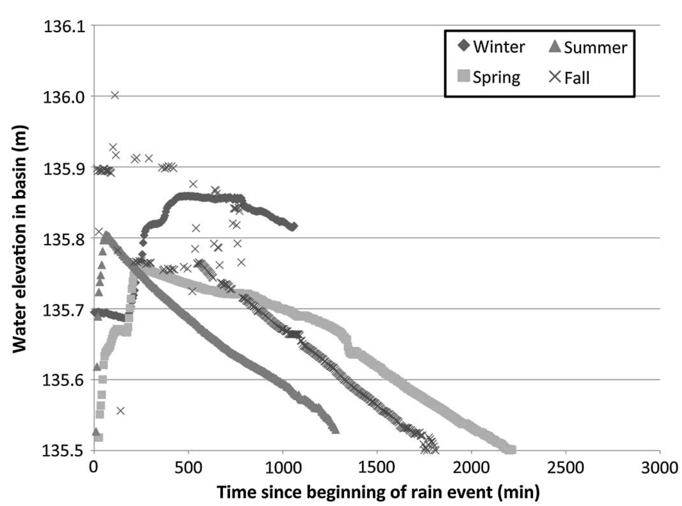

Fig. 7. Depth of water over time at rain garden; used for high-level monitoring

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Table 9. Inflow Volume and Capture Rates for Four Storms at Rain Garden

Storm	Rainfall measured on site (cm)	Rainfall measured off site (cm) and % difference	Calculated runoff (cm)	Calculated inflow volume (m^3)	Measured overflow (m^3)	% capture
Winter	1.45	0.81 (−44)	0.68	39	0	100
Spring	1.40	1.27 (−9)	0.66	37	0	100
Summer	1.85	2.46 (33)	0.89	51	0	100
Fall	1.73	0.86 (−50)	0.83	47	0	100

Table 10. Water Quality for Four Storms at Rain Garden

Constituent	% captured	Concentration and mass captured	Winter	Spring	Summer	Fall
TSS	100	mg/L	132.9	17.4	431.4	357.3
		kg	5.2	0.6	21.9	16.8
TDS	100	mg/L	1,414.0	235.2	18.7	34.2
		kg	54.9	8.8	0.9	1.6
Chloride	100	mg/L	2,353.9	21.6	1.1	5.7
		kg	91.4	0.8	0.1	0.3
NO_2	100	mg/L	ND	0.7	0.1	0.1
		kg	—	0.0	0.0	0.0
NO_3	100	mg/L	19.7	0.0	0.1	1.1
		kg	0.8	0.0	0.0	0.1
Phosphorous	100	mg/L	1.0	0.8	1.2	3.8
		kg	0.0	0.0	0.1	0.2
Copper	100	ppb	127.2	25.0	84.5	51.7
		g	4.9	0.9	4.3	2.4
Lead	100	ppb	167.9	ND	40.0	116.1
		g	6.5	—	2.0	5.5

Note: ppb = parts per billion; ND = nondetect.

to determine the amount of runoff that would enter the SCM on a per storm basis:

$$R = (P - 0.05) \times R_v \quad \text{and} \quad R_v = 0.05 + 0.9 \times I_a$$

where R = runoff in inches; P = precipitation in inches; and I_a = fraction of impervious area.

The equation was modified by decreasing the precipitation value by 0.13 cm (0.05 in.) to account for the initial abstractions and removing the term used to account for the fraction of the storms that create runoff. This runoff value was then multiplied by the area of the watershed to find the volume of water entering the SCM. Data collected from the V-notched weir was assessed by using the V-notched weir equation to determine the volume of water exiting the SCM. In the case of the four storms analyzed, no overflow was observed, so the capture rate of the SCM was 100% (Table 9). This capture rate is expected because, as discussed previously, the rain garden was designed to capture storms that are 3.8 cm or less.

Water-quality samples were obtained from first-flush samplers installed at the interface between the pavement and the rain garden entrance. The water samples collected were analyzed for TSS, TDS, chlorides, and selected nutrients and metals. This information was combined with the runoff capture information to determine the amount of contaminants retained by the SCM (Table 10). The percentage and mass of contaminants captured allows one to evaluate how effective the SCM is at meeting the goal of pollutant control. However, there can be transfer of pollutants from a rain garden to the groundwater table. For the contaminants analyzed, it is reasonable to assume that solids, copper, and lead are removed by the soil. Previous studies on SCMs in Villanova's campus have found that metals are contained within the first few centimeters of soil (Kwiatkowski et al. 2007; Welker et al. 2006). A study of orthophosphate removal at this SCM found that it is removed by the soil as well and will continue to be removed for at least another 20 years (Komlos and Traver 2012). The removal of nitrogen is more complex; however, some studies

Table 11. Cost Analysis for Rain Garden Monitoring

Equipment		Personnel		Laboratory		
Item	Cost	Hours	Cost	Suite of tests (TSS, TDS, nutrients, metals, chlorides)	Cost	Total
Low level						
—	—	8	240	—	—	240
Medium level						
Rain gauge (graduated cylinder)	35	34	1,020	—	—	1,065
Staff gauge	10					
Total	45					
High level						
Rain gauge (tipping bucket)	400	64	1,920	335	4,020	10,565
Ultrasonic level detector	700					
V-notch weir	200					
Pressure transducer	200					
Data logger	1,200					
Automated sampler	1,300					
First-flush samplers	250					
Lysimeters	375					
Total	4,625					

Note: Costs are in U.S. dollars.

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indicate that rain gardens with slower infiltration rates are more effective at removing nitrogen (Davis et al. 2009). Chloride was captured by the rain garden; thus, the chloride did not directly run into the nearby stream as it would have done without the rain garden in place. However, chlorides are conservative; hence, eventually, the chlorides will be transferred to the groundwater.

Cost Analysis

The cost for each of three levels of monitoring at this site was calculated. The equipment, hours spent collecting and analyzing data, and the cost of performing the laboratory testing for the preceding events were used to calculate the costs associated with each monitoring level (Table 11). The initial start-up, or equipment costs, required for the highest level of monitoring is quite high; however, the equipment at this level would not be typically used to monitor only four storms; thus, the cost of usage per storm would decrease over time. The hourly rate used for personnel was \$30/h. The costs used are for comparison purposes only and may not reflect the cost of the items at the time of publication.

Conclusions

A three-tiered monitoring plan was presented to aid municipalities and engineers in developing a monitoring program that is consistent with the SCM type and its design goals while considering the realities of budget and personnel constraints. The monitoring plan provides recommendations on a holistic approach to monitoring the effectiveness of structural, nonproprietary SCMs. A case study using a rain garden was presented. This case study provided an example of the types of equipment needed and the data generated to monitor a site at low, medium, and high levels. The lowest level of monitoring indicated that the SCM is functioning well and that the rain water is infiltrating within 48 h. The medium level of monitoring provided more accurate information on the infiltration rate and rainfall amounts that fell on site. The highest level of monitoring, which includes collecting water-quality data, enabled the calculation of the amount of constituents retained by the SCM.

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