water

MDPI

Article

Low Cost Monitoring of Stormwater Control Measures

Laura Toran [1]

[1] Temple University, Department of Earth and Environmental Science, Philadelphia, PA 19122; ltoran@temple.edu; +01-215-204-2352

Academic Editor: name
Received: date; Accepted: date; Published: date

Abstract: Stormwater control measures (SCMs) are a key component to 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 evaluating 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 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 timing and location of stormwater overflows, which help 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 to identify 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 reduce both volume of water and contaminant loads that threaten streams due to increased impervious surfaces [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 [4,5,6]. 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 x 10-3 km^2 to 11 km^2 [7]. 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. 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. The inlet pipe is sometimes connected to a roof to drain stormwater to a subsurface retention chamber instead of directly sending it to municipal stormflow pipes. In addition to redirecting roof drainage 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 so to slow 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 road ways, and in parking lot berms.

Although use of SCMs has increased since the 1990's when stormwater control ordinances become 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 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 are more effective.

Monitoring is important for evaluating design problems and causes for failure in SCMs. Instrumentation is added to SCMs to conduct a water budget which can evaluate capacity [15,16,17]. Various instrumentation is needed from rainfall to flow meters to soil moisture sensors, often at multiple monitoring points [11]. Long term monitoring is conducted to evaluate potential clogging, a common problem [9,12,14]. In some cases stream monitoring is implemented to evaluate SCM impact on catchments [18,19]. However, monitoring tends not to be included because of the additional cost.

Some stormwater control issues can be addressed by low cost monitoring techniques. Although the 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. Water level loggers were installed in pairs to evaluate the timing and size of storm responses. One positioned at the source or pool can measure input and a second logger at the outlet can measure overflows. A poorly constructed basin has rapid flow from the inlet to outlet; improved designs delay the response and show lower response in the outlet. An additional barometric logger is also needed to correct water level data for changes in barometric pressure. Sometimes local rainfall data can be obtained from weather stations that report online, but if possible each site should have a rain gauge. A monitoring system that includes three loggers, software, computer connectors and a rain gauge costs only $1750 based on using the Onset HOBO water level logger ($300 each) and rain gauge ($420 each). Nearby sites can share rain gauge and barometric loggers. The water level loggers also include a temperature sensor, which sometimes provides additional information on stormflows.

The sites selected for this project were all in Philadelphia or suburban Philadelphia, an urban setting where stormwater impairs the many 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 were monitored, one parking lot infiltration trench, one parking lot infiltration chamber, and one blue roof. Two SCMs are inside the city and four are outside the city. One to three water level loggers were installed and data collected at 15 minute intervals. The specific locations of loggers and questions addressed are described below with each case history.

3. Results

3.1. Comparison of overflow in two stormwater retention basins

Two stormwater basins were installed on the suburban campus of Temple University which included aspects of award-winning designs from the International Flower Show. The field installation tested how design was put into practice. One basin delivered water from a roof to a basin with permanent water and wetland plants; additional surface runoff from nearby pavement also ended up in the wetland. Water was observed to overflow the wetland and a small gully formed. A water level logger was installed in the gully to record how often water overflowed the wetland.

Based on monitoring for a year, overflow occurred for 100% of storms greater than 1 cm. Furthermore, for storms less than 1 cm, overflow occurred 70% of the time (Figure 1). There was no difference in storage between seasons. The wetland design was not sufficient to store all of the water it received. The berm on one side of the wetland was not elevated enough for storage, resulting in overflow even for small storms.

The second basin received surface runoff from paved areas, then diverted it through a meandering channel to a small depression that could pond water. This depression was typically dry, and planted with grasses left unmowed and young trees on the rim. Again there was a gully formed at one end of the basin that diverted overflow. A water level logger was placed in the overflow gully, and storm events were recorded for a year. In this basin, only 50% to 75% of storms overflowed the depression (Figure 1); less overflow was observed in the winter but only small storm events were recorded. Overflow was presumably reduced due to infiltration along the meandering channel and in the vegetated depression. Placement of rocks in the channel was observed to slow the flow of stormwater.

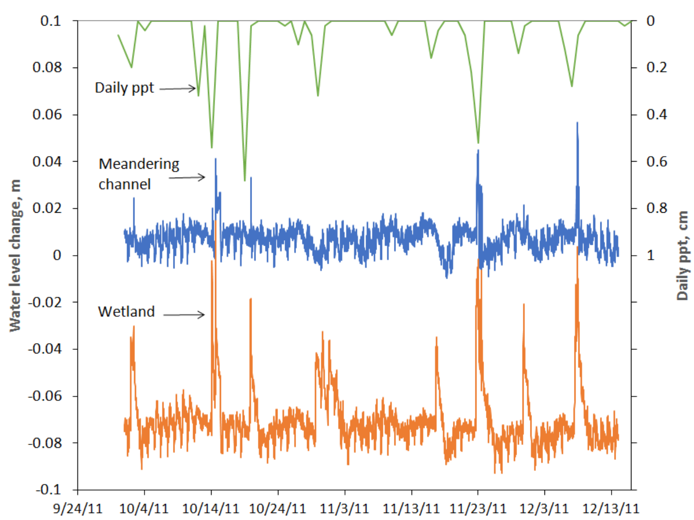

Figure 1. Comparison of stormwater overflow in two retention basins. The basin with a meandering channel overflowed less frequently than the wetland basin with a low berm. The baseline for the wetland was shifted down 0.08 m to show responses on the same plot.

This example showed how low cost monitoring could quantify how often overflow occurred in an observed overflow gully. Monitoring also contrasted differences in design which lead to increased basin overflow.

3.2. Monitoring before and after retrofit of a basin

Stormwater basins often fail to infiltrate because mowing compacts the soil or the inlet and outlet are well connected and water isn't given enough storage time. Both issues decreased basin effectiveness 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 deepening about 0.3 m to reach a shallow water table and planting with wetland vegetation that did not require mowing (Figure 2b). Water level loggers were placed in the inlet and outlet structures before and after retrofitting.

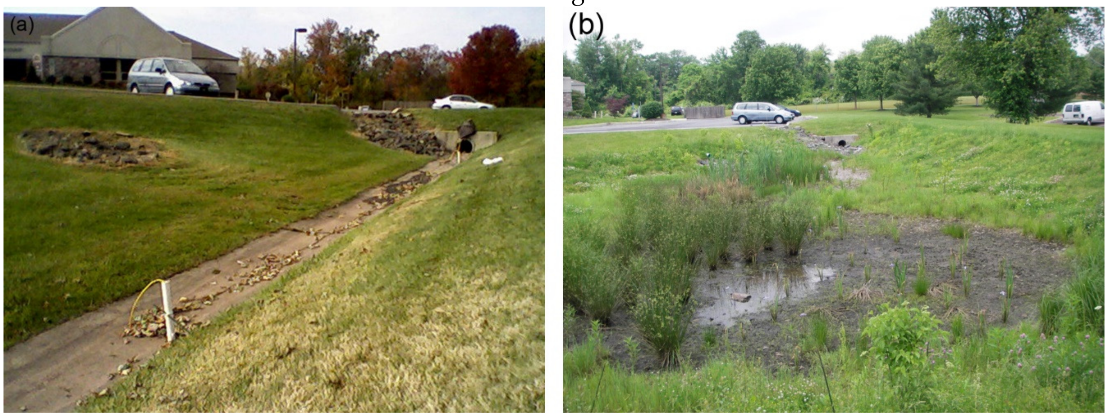

Figure 2. Photograph of a basin (a) before and (b) after retrofitting. The retrofit removed the concrete track, deepened the basin, and replanted with wetland vegetation. Before retrofitting the basin was mowed.

Before the retrofit, every storm reached the outlet and the timing and water level indicated no significant infiltration occurred (Figure 3a). In some cases the water level was higher at the outlet due to capture of additional water from the other side of the basin. After retrofitting, there was little to no water level increase at the outlet for similar size storm input (Figure 3b). This example provided quantitative measures of improvement in stormwater retention after retrofitting.

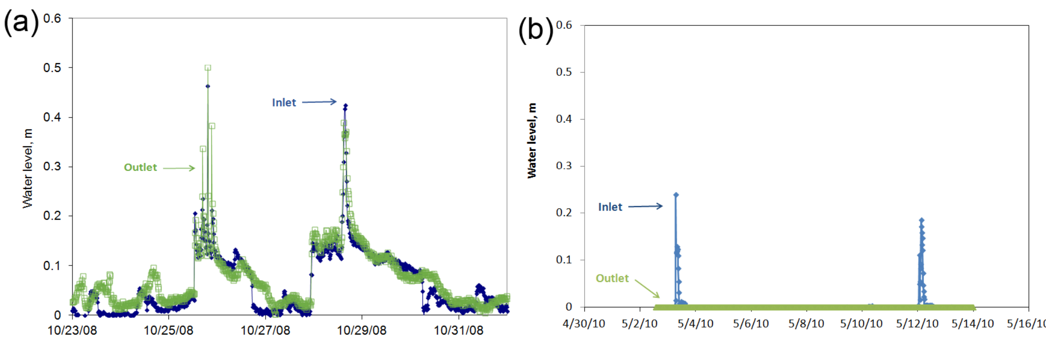

Figure 3. Water level response to storm events (a) before and (b) after retrofitting. The 10/25/08 storm was 2 cm and the storm from 10/27 to 10/29/08 was 0.6, 1, and 0.3 cm spread over the three days. The May 2010 storms were 0.7 cm each

3.3. Blue roof for stormwater storage control

Paseo Verde, an apartment complex next to the Temple University campus, 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. The roof drains to a basin in the garage and out to the street; 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.

The low cost monitoring with water level loggers was used to evaluate some simple questions. (1) What size of a rain event creates a response on the roof? Only 5 mm of rain produces a measureable response on the roof (Figure 4). This response was consistent across seasons for a year of monitoring in 2015 and consistent between the two blue roofs monitored. (2) How long is the water stored on the roof? For small storms (an hour or less) there is no storage, and the roofs immediately drains after the storm event ends. For longer storms lasting 6 to 12 hours, the roofs stored water while the storm intensity declines, 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 concrete manhole going to the street (Figure 4). The outflow pipe in the manhole constricted flow leading to slower drainage. (3) How often did the street level pipes receive water compared to the roof? Every storm was recorded 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 slow the travel time would be to decrease the size of the roof inlets, but care must be taken not to allow the water level to exceed the roof capacity.

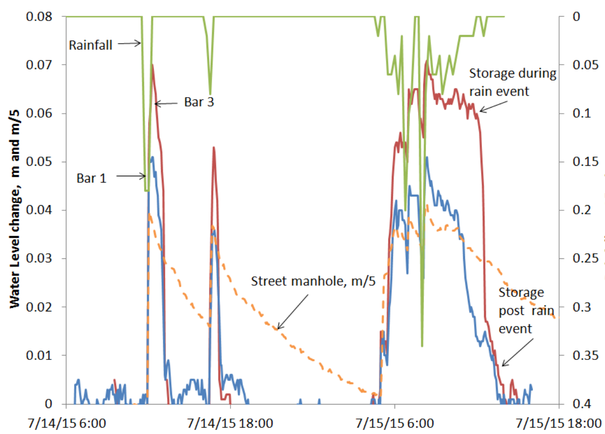

Figure 4. Water level responses on two blue roofs (Bar 1 and Bar 3) and a street manhole. The street manhole water level is divided by 5 to show on the same plot as the roof loggers. For short storms, no storage was observed on the roof. For longer storms, the water is stored as the rain event tapers off, then declines within about an hour after the rain ends. The street manhole stores water longer.

3.4. Comparison of an infiltration trench and a traditional stormpipe in a parking lot

A stormwater trench was 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 perforate pipe and underlay a grass berm; the traditional pipe was in the paved section of the parking lot, had no external storage, and drained directly to the municipal combined sewer outfall. 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 paved inlet showed a water level rise to every storm event (Figure 5). Water rose 0.05 to 1.5 m. In the inlet connected to the infiltration trench, water level rose only for storm events of 1 cm or greater, showing that for smaller storms the water was stored in the gravel. Runoff across the parking lot would reach the gravel trench before the paved inlet based on the slope, so there would not have been by-passing of this inlet. The water level rise was typically was higher in the pipe with the gravel stormwater trench, but exceptions where the water level was higher in the traditional paved pipe also occurred.

Higher response in the pipe with paved inlet was linked to flow reversals. The paved pipe water showed a temperature shift to warmer water when the water level response was higher. For a storm on 9/8/11, the warmer water appeared at 1:00 AM; however, warmer water is not expected for a night time rain event (Figure 6). Stormwater stored in the street 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.

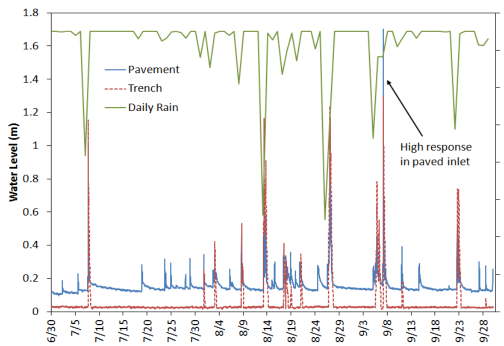

Figure 5: Water level response in parking lot infiltration trench and traditional storm pipe with a paved inlet. The paved pipe showed a response to every storm, but the pipe in the infiltration trench only responded to storms greater than 1 cm. Typically, the trench pipe had a higher response, but on 9/8 the paved pipe had a higher response (see detail in Figure 6).

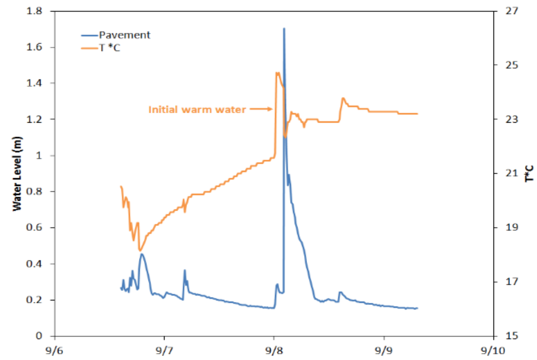

Figure 6: Water level and temperature for storm on 9/8/11. The temperature at the beginning of the inflow was higher although the storm started at 1:00 AM. Backflow from the street pipe would explain the warmer water at night

3.5. Long term monitoring of infiltration chamber performance

An infiltration chamber was 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 encompasses 8 x 13 m. Water enters the chamber by a drop inlet as well as porous pavement on part of the parking lot. The system was designed to capture events for the 2-year 24-hour 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 and 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 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 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 water level response. In the partial monitoring of 2009, there were two storms with high precipitation and one had water level response. Thus, there was no evidence of decline in effectiveness based on stormwater response. The storm peaks varied from 0.1 to 0.5 m although some storms had multiple peaks so the volume may have been spread out.

The recession times were short, 7 hours or less with an average of 4.5 hours. This recovery is considerably less than the 72 hours required by the PA DEP 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 the difference was not significant. There was only one storm as large as the designed 2-year, 24-hour storm event (Table 1, 4/16/07), 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.

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

	Daily Rain, cm	Storm Peak, m	Recession, hours
3/2/2007	4	0.25	3.5
4/16/2007	10	0.25	3
4/27/2007	3.6	0	
10/9/2007	3.2	0	
10/27/2007	3.7	0	
2/1/2008	3.3	0	
2/13/2008	5	0.1	6
3/8/2008	3.5	0.2	3
10/28/2008	3	0	
12/12/2008	5	0.08	7
6/13/2009	3.4	0	
8/2/2009	5	0.5	5

.

In summary, the infiltration gallery effectively captured and infiltrated the largest storms observed. Furthermore, the trench does not show signs of degradation after 2.7 years of monitoring. The typical trench shows signs of degradation at this point in time if clogging is an issue. By creating an appropriately sized trench with a good filtration system, the effectiveness and longevity of the PERT parking lot infiltration gallery was improved.

4. Discussion

Low cost monitoring can be effective to answer certain types of questions related to SCM design. It does not provide quantitative assessment of performance or capture volume. Instead, the low cost monitoring is suggested to provide a level of assessment that supplements observations and anecdotal evidence of SCM functioning. The type of question addressed with low cost water level loggers involved evaluating how often stormflow reaches an overflow monitoring point and for which storm events. The timing of the hydrograph also provides information about 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 in order 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.

In the examples presented here, there were several types of assessment provided by the low cost monitoring. Monitoring the inlet and outlet of two retention basins revealed differences in design that influenced how often the basin overflowed. At another basin, monitored showed that retrofitting reduced the number of storms that overflowed to the outlet structure. On a blue roof the retention time was recorded and the timing of overflow to the street pipe, which showed water storage on the roof was short. Comparison of storm response in a traditional storm pipe and an infiltration trench showed improved storage in the trench, as expected. The stormpipe monitoring also showed warm water entering during storms which may indicated 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, showed little change in storage capacity in a 2.7 year study.

These observations help 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.

Acknowledgments: Funding for these projects was provided by grants from the U.S. EPA and the William Penn Foundation to Temple University's Center for Sustainable Communities. Cultec, Inc. donated materials for the PERT infiltration chamber and the Warrington Environmental Action Council provided monitoring equipment and arranged funding for the retrofit of the township basin. Over the years a number of different students helped download data at the field sites; their help is gratefully acknowledged. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by Temple University or the U.S. Government.

References

1. O'Driscoll, M.; Clinton, S.; Jefferson, A.; Manda, A.; McMillan, S. The effects of urbanization on streams in the southern US: A Review. *Water* **2010**, 2, 605-648.
2. National Academy of Sciences. *Urban Stormwater Management in the United States*. National Academies Press: Washington, D.C., 2009; 598 pp.
3. Environmental Protection Agency. *Low impact development (LID). A literature review*. EPA Office of Water: Washington, D.C, 2000; EPA-841-B-00-005
4. Environmental Protection Agency. *Stormwater Technology Fact Sheet: On-site Underground Retention/Detention*. 2001; EPA 832-F-01-005 http://www.epa.gov/npdes/pubs/sw_tech_fs_runoff.pdf (accessed on 4.27.16)
5. Davis, A.P. Green engineering principles promote low-impact development. *Environ. Sci. Technol*. **2005**, 39, 338A–344A.
6. Ahiablame, L. M.; Engel, B. A.; Chaubey, I. Effectiveness of low impact development practices: literature review and suggestions for future research. *Water, Air, & Soil Pollution* **2012**, *223*, 4253-4273.
7. Emerson, C. H.; Welty, C.; Traver, R. G. Watershed-scale evaluation of a system of storm water detention basins. *Journal of Hydrologic Engineering* **2005**, *10*, 237-242.
8. Philadelphia Water Department. *Stormwater Management Guidance Manual V 3*. 2015, 494 pp. http://www.pwdplanreview.org/manual-info/guidance-manual (accessed on 4.27.16)
9. Brown, R. A.; Borst, M. Evaluation of Surface and Subsurface Processes in Permeable Pavement Infiltration Trenches. *Journal of Hydrologic Engineering* **2014**, *20*, 04014041
10. Roy, A.H.; Wenger, S.J.; Fletcher, T.D.; Walsh, C.J.; Ladson, A.R.; Shuster, W.D.; Thurston, H.W.; Brown, R.R. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environ. Manage*. **2008**, 42, 344–359.
11. Strecker, E. W.; Quigley, M. M.; Urbonas, B. R.; Jones, J. E.; Clary, J. K. Determining urban storm water BMP effectiveness. *Journal of Water Resources Planning and Management*, **2001**, *127*, 144-149.
12. Emerson, C. H.; Wadzuk, B. M.; Traver, R. G. Hydraulic evolution and total suspended solids capture of an infiltration trench. *Hydrol. Process*. **2010**, 24, 1008–1014.
13. Natarajan, P.; Davis, A. P. Performance of a 'Transitioned'Infiltration Basin Part 2: Nitrogen and Phosphorus Removals. *Water Environment Research* **2016**, 88, 291-302.
14. Ellis, J. B. Infiltration Systems: A Sustainable Source-Control Option for Urban Stormwater Quality Management? *Water and Environment Journal* **2000**, *14*, 27-34.
15. Lewellyn, C.; Lyons, C. E.; Traver, R. G.; Wadzuk, B. M. Evaluation of Seasonal and Large Storm Runoff Volume Capture of an Infiltration Green Infrastructure System. *Journal of Hydrologic Engineering* **2015**, *21*, 04015047.
16. Jia, H.; Wang, X.; Ti, C.; Zhai, Y.; Field, R.; Tafuri, A. N.; Cai, H.; Shaw, L. Y. Field monitoring of a LID-BMP treatment train system in China. *Environmental monitoring and assessment* **2015**, *187*, 1-18.
17. Li, H.; Sharkey, L.J.; Hunt, W.F.; Davis, A.P. Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland. *J. Hydrol. Eng.* **2009**, *14*, 407-415.

18. Page, J. L.; Winston, R. J.; Mayes, D. B.; Perrin, C.; Hunt, W. F. Retrofitting with innovative stormwater control measures: Hydrologic mitigation of impervious cover in the municipal right-of-way. *Journal of Hydrology* **2015**, *527*, 923-932.
19. Loperfido, J. V.; Noe, G. B.; Jarnagin, S. T.; Hogan, D. M. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. *Journal of Hydrology* **2014**, *519*, 2584-2595.
20. Pennsylvania Department of Environmental Protection. Pennsylvania Stormwater BMP Manual. 2006, 685 pp. http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-68851/363-0300-002.pdf (accessed on 4.27.16)