Long-Term Assessment of Infiltration Best Management Practices

Clay Emerson
Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Villanova University

Abstract:
Infiltration Best Management Practices (BMPs) are becoming a widely used tool in an effort to better manage storm water runoff. Many new storm water regulations require the implementation of storm water BMPs to reduce the volume of storm water runoff. The most widely implemented volume reduction BMPs are engineered infiltration practices. Even with such widespread use questions remain about how infiltration BMPs will function over the course of a year and more importantly; their lifetime. The focus of this research is on the actual infiltration process central to the operation of such BMPs. An attempt has been made to provide information that could be relevant to any infiltration BMP. In total over nine year of hydrologic monitoring data were collected at three infiltration BMPs located on the campus of Villanova University in Southeastern Pennsylvania. The BMPs include a Pervious Concrete Infiltration Basin, a BioInfiltration Traffic Island, and an Infiltration Trench. Analysis of the monitoring data has provided valuable insight into the characteristics of long-term concentrated infiltration of storm water runoff. The BMPs all show significant seasonal variation and one demonstrates a systematic decrease in performance.

Introduction:
Past stormwater management regulations have focused largely on peak flow control. These early regulations were the impetus for the construction of thousands of detention basins which can generally be found alongside any commercial or residential development that was built within the last 30 to 40 years. This method of stormwater management has left watersheds with an uncoordinated network of basins that provide little or no watershed wide benefits and can actually serve to increase the peak flow rate downstream (Emerson, Welty et al. 2005). Detention basins and peak flow control does not address the quantity of runoff. Under the post construction conditions compacted soils and impervious surfaces generate runoff well in excess of the predevelopment conditions. These increases in the quantity or volume of runoff act in a cumulative fashion over a watershed. Therefore flooding, channel erosion, and aquatic habitat degradation will continue under a peak flow based system.

Controlling the peak flow rate from developed areas is only one piece of a complete solution to stormwater management. In hindsight, detention basins represent an “end of the pipe” solution to managing the increased runoff. The term stormwater management has often been used to describe the structural measures taken to counteract the negative impacts of typical land development practices. A more comprehensive outlook on stormwater management is to develop land in a way that first minimizes the amount of structural measures required to offset the hydrologic impacts of the development process. These methods are often collectively referred to as low impact development. One of the main objectives is to limit the volume of runoff that leaves the site. This is first accomplished by limiting the amount of soil compaction and impervious surfaces. The runoff that is still produced can be captured and reused, evapotranspirated through the use
of vegetated BMPs like green roofs, or it can be infiltrated. Due to financial and practical considerations infiltration is often the most commonly applied technique.

Recent regulations have placed a new focus on water quantity control and infiltration is often either required or the tool of choice for many applications. The increase in popularity of infiltration BMPs has lead to widespread implementation. Due to the relatively new rise in popularity of the infiltration BMP, little is known about the long-term and annual performance of stormwater infiltration BMPs. It is important for the profession to understand how to properly design and maintain infiltration BMPs to guarantee continued operation over the long-term. With this objective in mind the Villanova Urban Stormwater Partnership (VUSP) has designed, built, and monitored numerous infiltration BMPs on the campus of Villanova University. This paper focuses on three of the infiltration BMPs and examines the continuous data record in an effort to answer the following questions:

- Are the BMPs showing signs of a systematic degradation in performance?
- Does the efficiency of infiltration BMPs vary over the course of a year?

While this work is based on the experience gained from three specific infiltration BMPs, an effort has been made to normalize the assessment methods of the BMPs such that the results can be compared and applied to other BMPs outside the scope of this work.

**Site Descriptions:**
The three sites at the focus of this work all are retrofit infiltration BMPs. First is the Pervious Concrete Infiltration Basin (PCIB). The BMP consists of three shallow crushed stone filled infiltration beds. The majority of the runoff at the BMP comes from the four story rooftops of the adjacent dormitories. One of the storage beds at the PCIB has been instrumented to recorded water depth and temperature. The BMP has a relatively small ratio of impervious surface to BMP area; for the instrumented bed this ratio is only about 3:1. The BioInfiltration Traffic Island (BTI) is a retrofit of an existing traffic island located in a parking area for a student dormitory. The BTI was constructed by excavating the original soil to a depth of approximately six feet. The excavated soil was then mixed at a 1:1 ratio with sand and placed back in the excavation to a depth of four feet leaving a slight depression. The area was then mulched and planted. The BTI drains 1.3 acres and has an impervious surface to BMP area ratio of about 10:1. The BTI has also been instrumented to record depth and temperature. The newest of the three BMPs is the Infiltration Trench (IT). This BMP uses a small but relatively deep (six feet) crushed stone storage bed. The drainage area for this BMP is about 0.5 acres and is 100% impervious. This along with the relatively small footprint of the IT results in an impervious area to BMP ratio of 130:1. Clearly this ratio well exceeds the recommendation of the PA Stormwater BMP Manual (~5:1). It is important to note that the BMP was intentionally designed with this high of a loading ratio to accelerate any potential longevity related issues. This BMP was instrumented in a similar fashion to the other two BMPs.
Performance Indicator:
The recession rate of the ponded water following the cessation of inflow is used as the basis of the performance indicator in this study. The BMPs all pond soon after the beginning of inflow and are often ponded for long periods of time (hours) before the recession of the ponded depth begins. Clearly the rate that the water surface recedes is dependant on the rate on infiltration into the soil at the BMP. The infiltration process is dependant on many factors. However the infiltration into a soil surface that has been ponded for extended periods of time generally approaches a gravity flow condition where soil moisture potential gradients are sufficiently small and the flow is primarily dictated by the hydraulic conductivity of the system and the ponded depth of water above the soil surface. Due to the shallow and flat geometry of the PCIB and BTI the infiltration process is assumed to be adequately described by a one dimensional approximation where the shallow depths are considered negligible. Therefore the ponded recession rate, corrected for the storage bed porosity, can be used as an estimate of the hydraulic conductivity. The IT however is not amendable to a one dimensional system and the depth is too significant to be considered negligible. Therefore a Monte Carlo-type analysis was used to analyze the IT. This model provided estimates for the hydraulic conductivity of the bottom and sides of the BMP independently based on analysis of each individual recession limb. By normalizing the performance of each BMP for each storm in the record to a single estimate of hydraulic conductivity (two for the IT), the performance of the BMPs can be compared over time and to one another.

The monitoring data for each site varies in length between the BMPs. In total more than nine years of data are used in this analysis, with the longest continuous period of record being 4.25 years for the BTI. In order to quantitatively and efficiently manage and analyze this amount of data a program was created to automatically find and provide statistics for each storm event in the data record.

Results:
The results of this analysis show no signs of a degradation in performance of the PCIB and the BTI. The IT does show a significant and rapid change in performance over the data record. All three infiltration BMPs show significant seasonal variation with the highest performance occurring in late summer and the slowest in late winter. The BTI results are summarized in Figure 1.
Figure 1 illustrated that the BMP is showing no evidence of a systematic decrease in performance. However it shows a clear cyclic (annual) variation. This seasonal variation is significant and on average the rate that the BMP empties doubles over the course of the year. The results from the PCIB (not shown here) are similar with significant, roughly two-fold, seasonal variation and no signs of a systematic decrease. The IT however shows a significant decrease in performance in addition to seasonal variations. The recession limb of the IT is curvilinear. Therefore the recession limb can be approximated by six straight line segments using a one foot depth increment. Figure 2 shows the observed incremental recession rates from the IT over the data record (2.75 years).
Figure 2. Incremental recession rates (slopes) for the IT (note the log scale y-axis).

Figure 2 illustrates that the IT has shown a drastic and exponential decrease in performance, especially over the first 1.75 years of operation. It is important to note that unlike the other two BMPs monitoring at the IT began with the very first storm to fill the storage bed, whereas the other BMP were not fully monitored for ~1.5 years into their operation. The IT originally only took hours to completely empty while later in the data record it takes days. In addition to this drastic decrease the seasonal variation is still apparent. The BMP actually experienced two periods of increasing performance due to this seasonal variation.

**Discussion:**
It is important to note that none of the periods of record examined here are representative of a lifespan analysis. However, the periods of record are significantly long to adequately look for evidence of depreciated performance, and indeed this was found in one situation. The fact that neither the PCIB or BTI show any evidence of degradation is encouraging and indicates that the design, construction, and maintenance techniques employed are conducive to long lasting performance. The IT however was intentionally designed to accelerate the aging process. First the BMP collects runoff from a high traffic parking garage that is ~130 times its size. Additionally, the BMP has essentially no pretreatment. Both of these design practices are not recommended. Also, the BMP when full is six feet deep, this ponded depth of water can compress any type of depositional seal that is expected to form in such a configuration. The effect of this compression is to further reduce the capacity of the BMP to infiltrate runoff (Bouwer 1989). Suspended solids loading and its consequent compression are assumed to be responsible for the drastic reduction in performance observed at this BMP. However, this should not be taken to be
representative for a typical installation of this type of BMP. The PA Stormwater BMP Manual recommends a 5:1 impervious to BMP ratio for this class of BMP. Therefore the IT was built to collect nearly 26 times the recommended suspended solids load with no pretreatment. While the BMP is only three years old, from a suspended solids perspective the BMP is the equivalent of 80 years old (using the 5:1 recommendation). This accelerated aging was one of the design objectives for the experimental BMP.

Interestingly all three BMPs show significant seasonal variation. Especially in the case of the BTI this variation has been passed off as the result of seasonal variation in evaporation and plant transpiration. However these processes can not account for the magnitude of variation displayed at the BTI. Also the fact that similar variation is observed at both the other underground BMPs suggests that the cause of the variation is not related to evaporation or vegetation uptake.

Hydraulic conductivity is not exclusively a soil parameter. Rather it is a function of both the soil pore geometry and the properties of the permeating liquid. This can be illustrated by the following definition of hydraulic conductivity:

\[ K = k \times \frac{\rho g}{\mu} \quad (1) \]

Where \( K \) is the hydraulic conductivity (L/T), \( k \) is the intrinsic permeability of the soil (L^2), \( \rho \) is the density of the fluid, \( g \) is gravitational acceleration, and \( \mu \) is the dynamic viscosity of the fluid. The fluid properties including gravitational acceleration are often collectively referred to as the fluidity of the permeating fluid (Hillel 1998). Fluidity and consequently hydraulic conductivity are therefore proportional to the density of the fluid and inversely proportional to the viscosity. The density of liquid water varies by less than 1% over a temperature range of 0 to 38°C and is therefore insignificant for most applications. However, dynamic viscosity varies by approximately 163% over the same range; essentially doubling over typical temperature ranges experienced in the Northeast. Therefore the hydraulic conductivity should be expected to vary proportionally to the temperature-induced viscosity changes of liquid water.

The temperature dependency of hydraulic conductivity is well established and has been documented extensively in laboratory column studies. It has also been documented on field scale infiltration experiments (Jaynes 1990). The temperature dependency of the infiltration process has also been examined at large scale soil aquifer treatment applications (Lin, Greenwald et al. 2003) and even been applied to explain diurnal variations in stream flow loss for stream reaches (Constantz, Thomas et al. 1994; Ronan, Prudic et al. 1998). This temperature dependency has clear design, operation, and assessment implications for stormwater infiltration BMPs considering the roughly two-fold variation in draw down time that should be expected.

To further analyze the seasonal variation of the BMPs equation one in conjunction with the temperature measurements were used to determine what portion of the variation could be attributed to temperature induced viscosity changes. This was accomplished with the
use of linear regressions setting temperature and the independent (predictive) variable and hydraulic conductivity estimates as the dependant variable. All three of these linear regressions are displayed in Figure 3 (raw data points not shown). The relevant statistics are summarized in Table 1. All regressions are significant at the 95% level and are supported by a full residual analysis. The blue line is the linear regression for the raw data along with 95% confidence regression bounds shown in red. The green line represents the temperature variation that should be expected based on viscosity effects alone (calculated with equation one). Only the last year of data was used for the IT regression due to the degradation shown early in the data record.

![Figure 3. Overlay of linear regressions for all three infiltration BMPs.](image)

Table 1. Summary of the observed temperature dependency for all three BMPs (blue lines).

<table>
<thead>
<tr>
<th>BMP</th>
<th>m</th>
<th>-95%</th>
<th>+95%</th>
<th>b</th>
<th>r²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pervious Conc. Inf. Basin</td>
<td>0.0023</td>
<td>0.00028</td>
<td>0.0044</td>
<td>0.081</td>
<td>0.32</td>
<td>2.9×10⁻²</td>
</tr>
<tr>
<td>BioInf. Traffic Island</td>
<td>0.0036</td>
<td>0.0015</td>
<td>0.0056</td>
<td>0.17</td>
<td>0.19</td>
<td>1.1×10⁻³</td>
</tr>
<tr>
<td>Infiltration Trench</td>
<td>0.011</td>
<td>0.0066</td>
<td>0.015</td>
<td>0.24</td>
<td>0.54</td>
<td>1.7×10⁻⁵</td>
</tr>
</tbody>
</table>

*P values less than 0.05 indicate significance at the 95% level (α = 0.05)

The relative magnitude of the plots from each BMP are corroborated by the particle size distributions of the soil at each BMP, with the IT being the most coarse and the PCIB the finest. Both the PCIB and IT appear to be showing nearly the same amount of temperature variation as should be expected from viscosity changes. The BTI is actually showing less that would otherwise be expected, although prediction barely exceeds the
regression confidence bounds. This is likely due to the location of the temperature measurement (at the soil surface). A more representative location may be just below the soil surface. Here the temperature would be slightly dampened and would result in an increase in the slope of the observed regression (blue line). This also shows that seasonal variations in evaporation and plant uptake are not significant factors in explaining the variation.

**Conclusions and Recommendations:**
The period of record examined in this study is not reflective of a lifespan study. However the study does provide valuable information on the longevity of infiltration BMPs. The sustained performance of the BTI may be accredited to sound design and construction techniques. During construction the soil at the BMP was never compacted or driven over with any equipment. The soil surface was mulched and planted. Since construction the soil surface has not been raked or seriously disturbed in any fashion. The vegetation has flourished and helped develop and maintain a loose organic surface layer conducive to infiltration. Freeze-thaw, root activity, and organic matter are all important in the natural, but engineered, self maintenance of the BMP. The two rip rap swales into the BMP have also provided some level of suspended solids removal. The PCIB does not have the advantage of organic matter, freeze-thaw, or root activity. Its sustained performance is a result of the low loading ratio and the characteristically low suspended solids loading due to the fact that the runoff originates from four story slate rooftops. The results from the IT show that when improperly designed, infiltration BMPs are susceptible to rapid decreases in performance which may ultimately lead the BMP failing to meet original design criteria.

Significant seasonal variation was found at all three infiltration BMPs. This variation should be expected at any stormwater infiltration BMP that experiences variations in the temperature of incoming runoff over the course of the year. The seasonal variation has major design, operational, and especially assessment implications. First, investigative infiltration tests should also account for temperature. Without properly designed infiltration experiments it may be difficult to accurately account for the influence of temperature. The design of infiltration BMP should account for the variable nature of infiltration in the presence of temperature fluctuations. Most importantly the temperature dependency should be explicitly accounted for in any as-built assessment of infiltration BMP performance. BMP assessment based on one or only a few ponded infiltration observations may greatly misrepresent the BMP performance, and may give false impressions of changes in performance. For example, if the recession time of a ponding event in early fall is measured, and another the following spring, the results would tend to indicate that the performance of the BMP is significantly decreasing over time. Conversely an infiltration BMP undergoing a systematic decrease in performance could appear to be maintaining or even improving in performance. Therefore temperature measurements should be an integral part of any type of monitoring effort at an infiltration BMP. Qualitative surveys which include details of the draw-down or recession rate should also report temperature. This is especially important in the case of field-scale tests where the BMPs themselves are intentionally flooded to determine the draw down time. These measurements should be expected to be highly dependent on the temperature.
of the supply water, which could potentially vary drastically from the temperature of incoming stormwater runoff.

**References:**


