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Assessing the Hydrology of Indianapolis Rain Gardens

Drew Scott
Environmental Science
University of Indianapolis
1400 E Hannah Ave.
Indianapolis, IN 46227

Faculty Advisor: P. Roger Sweets

Abstract

The construction of rain gardens is being actively promoted by the city of Indianapolis. However, there has been little scientific evaluation of the effectiveness of city's rain garden efforts. Five rain gardens and nearby control sites were selected for testing. To evaluate water infiltration, percolation tests were conducted on rain garden soils and nearby control soils. None of the rain gardens tested exhibited a measured percolation rate that was significantly faster than a control plot of similar soil composition and elevation. Four of the rain gardens had percolation rates that were slower than control areas. Therefore, the current Indianapolis rain garden construction could not be used to prevent wastewater overflow (the mixture of rainwater and domestic sewage that enters local waterways during a sufficient rain event) since the percolation rate of the rain garden would be slower than the soil it would replace. This indicates that rain gardens should be constructed and monitored carefully.

Keywords: Hydrology, Rain Gardens, Indianapolis

1. Introduction

1.1 Rain Gardens and Storm-water Runoff

All urban areas must have to have systems to deal with storm-water runoff. Many cities simply allow the runoff to enter the sewage system through storm drains. Urban sewer systems that handle both wastewater and storm water are known as combined sewer systems. When it rains, the combined sewers can overflow, causing flooding in some areas and also allowing raw sewage to enter the local waterways that supply drinking water.

The city of Indianapolis has a combined sewer system that has become inadequate as the city has grown. Currently, as little as a quarter-inch of rain causes wastewater-overflow[1]. This forces residents to deal with the unpleasant odor and sight of untreated sewage in local waterways[1]. Currently, the White River, the main watershed for the metropolitan area, is non-compliant with the clean water act even in dry conditions[2]. After a small rain event, all waterways are non-compliant with the Federal Clean Water Act. Currently, 4 billion to 5 billion gallons of wastewater overflow occur per year. To deal with this issue, the city of Indianapolis has proposed a storage tunnel system. One branch will extend along Fall Creek and White River and another runs between the secondary treatment plant in Southport (southern metropolitan area) into downtown. The planned Indy Tunnel System will store wastewater along the White River and Fall Creek. This will allow wastewater to be treated at times of lower demand. The estimated cost of this option is between $1.55 billion and $3.02 billion. This option will reduce wastewater overflow by 97%[2]. However, because of large amount of wastewater overflow there will still be an estimated 120 to 150 million gallons of overflow per year.

Storm-water runoff issues are common because most cities do not have separate sewers. There are several solutions, many of them very expensive. One solution is retrofitting and building separate storm-water sewers[3]. Another solution is to construct systems to temporarily store wastewater overflow for later treatment[2]. A local solution is to build retention ponds, but these can be dangerous because they can attract potentially disease-carrying mosquitoes[4] and be the site of accidental human fatalities[5].

Contrary to the aforementioned solutions, rain gardens provide a less expensive, environmentally sound local solution. A rain garden is vegetation that is strategically placed to intercept storm water runoff and reduce wastewater overflow and erosion[6]. Rain gardens are typically built next to large paved areas such as roads and parking lots. These paved areas do not allow water to percolate. Water runs off paved surfaces in sheets. Rain gardens break up the sheets of water and help water to percolate into soil, more readily allowing groundwater to replenish and the plants to retain some of the urban runoff water[7].

1.2. Construction

Rain gardens are a key piece of green infrastructure, i.e., infrastructure that mimics natural processes to evaporate, reuse, or return storm water to ground water. A well-constructed rain garden can perform with little or no maintenance. Rain gardens are constructed by excavating a low-lying area so water flows into the garden. A layer of gravel is laid down, covered by loose soil, and planted with native vegetation. Soil depth and presence of oxygen, soil composition, size of rain garden, and plant type determine a rain garden’s effectiveness.

The best rain gardens have both an aerobic (oxygen present) phase of water percolating through soil and an anaerobic (oxygen absent) phase[8]. The two phases are important because some compounds are best removed from water in aerobic conditions and some are best removed during anaerobic conditions. Depth of soil will allow there to be a decreasing amount of oxygen into the soil. Water flowing through two phases allows for a wider range of contaminant removal. Plants and associated microorganisms can filter, use, or degrade contaminants.

Preexisting soil composition can also be very important in affecting infiltration rate– the rate at which water percolates into the soil[9]. This is why soils are sometimes imported to construct rain gardens. An overabundance of fine sediment can settle and clog pore space. However, natural accumulation of fine particles over time does not have a significant impact on infiltration rate[9].

Establishing the proper area of a rain garden is critical[10]. A garden that is designed to be at 50% capacity of ‘full size’ (e.g., 188 m^2 according to North Carolina standards) reduces the water runoff load half as much as the full size garden. This means that water runoff load reduction is directly proportional to size. Knowing that the amount of water that can be processed by a rain garden is directly proportional to its size allows one to know what size rain garden is needed relative to other rain gardens in the area; this information is useful to city planners.

Plants that are native to the area where the rain garden is placed are the preferred species to be planted. As natives these plants require less maintenance and reduce the risk of invasive species escaping to neighboring areas [11]. Plants that take up a great deal of water should also be used. Some plants recommended for use in Indiana are: fox sedge, swamp milkweed, bottle gentian, blue false indigo, foxglove beardtongue, showy black-eyed Susan, and prairie dropseed[10]. The planted species should be able to withstand greater water stress as depth increases. The composition of plants can vary slightly depending on area conditions, such as amount of shade[11].

1.3. Site Description

Five rain gardens were chosen as test sites out of eighteen identified rain gardens in Indianapolis (Table 1). Study sites selected were displayed using GPS (global positioning system) coordinates in ArcMap 10 GIS (data files made available by author at https://drive.google.com/?pli=1&authuser=0#folders/0B-bSzo4QXV-eczRGQTNfUTFMMkk). The map was created using 2009 TIGER files obtained from the US Census Bureau. Rain gardens were chosen so that test areas were evenly spread across the city. Rain gardens that have shallow liners to prevent water damage to nearby buildings were removed from consideration for this study.

Table 1. GPS coordinates and soil types of rain gardens used in this study

Point	GPS Coordinates	Soil Type	Abbreviation
1	39.757559, -86.140068	Urban land-Miami Complex, 0 to 6 percent slopes (UmB)	KIB (large)
2	39.828919, -86.112089	Urban land-Fox complex, 0 to 3 percent slopes (UfA)	CFA
3	39.829063, -86.184141	Miami silt loam, 0 to 2 percent slopes, gravelly substratum (MmA)	IMA
4	39.705772, -86.101973	Miami complex, 12 to 18 percent slopes, eroded (MxD2)	Timbers
5	39.757862, -86.140497	Urban land-Miami Complex, 0 to 6 percent slopes (UmB)	KIB (small)

The chosen rain gardens varied in size, plant diversity, and plant density to give a representative sample of Indianapolis rain gardens. Variables such as soil depth and soil composition were similar for all Indianapolis rain gardens. The Keep Indianapolis Beautiful (KIB) small rain garden had the smallest size (10 m^2), low plant diversity (five species present), and low plant density (one plant per square ft. or less). The Indianapolis Museum of Art (IMA) rain garden had the largest size (70 m^2), a high plant diversity (more than ten species present) and, medium plant density (two to four plants per square ft.). The KIB (large) had a medium size (35 m^2), high plant diversity, and high plant density (more than four plants per square ft.). The rain garden at the Timbers had a small size (25 m^2), medium plant diversity (six to nine species present), and medium plant density. The Challenge Foundation Academy (CFA) had a medium size (40m^2), medium plant diversity, and high plant density.

Control areas were chosen proximal to (with the exception of the CFA site) and in the same soil type as the selected rain gardens[12]. The control areas chosen were flat, had little plant life, had no loose soil, and had a similar elevation to the rain garden. There were some exceptions to this because of digging restrictions. The control used for the CFA was not proximal to the rain garden, but the soil type (Miami clay loam) was similar. The amount of compaction in both study and control areas is unknown. The IMA control area had been covered with a thin layer of loose topsoil. This was brushed away to reveal an untilled area. The minor inconsistencies in the control areas are a possible limitation of this study.

2. Procedure

2.1 Hydrology

A three-inch soil corer was used to dig side-by-side holes to create an oval shaped well twelve inches deep. This had roughly the same surface area of soil as a six-inch diameter circular well; this allowed the Gustafson and Machmeier rules of thumb regarding time to saturate soil to be used[13]. A circular well has a surface area of 254 m^2; the ellipsoidal well has a surface area of 240 m^2. The tops of the dug cylinders were left open. The bottom of the well was filled with two inches of gravel and the sides were scarified to reduce soil smoothing.

The percolation rate was determined for the rain gardens and control areas in this study by using the procedure described by Gustafson and Machmeier[13]. The well must first be saturated by maintaining a ten-inch water column above the gravel. This allows comparisons of percolation rates to be made. If the well is drained within ten minutes, indicating a sandy soil, testing can begin immediately. If the well does not drain within ten minutes, the water column must be maintained for at least four hours before testing can begin. It takes longer to saturate a slower draining well because clay soils will typically absorb more water than sandier soils[13].

Once the well is saturated the well is filled to six inches above the bottom with water. To calculate the percolation rate the time was measured for a one-inch drop in the six-inch water column. In order to more easily read the distance of water drop, markers were put on the ruler at five and six inches. Once three consecutive measurements had been taken and had a range with ten percent error or less, the average of the three measurements was recorded for the test well[13]. The average of three wells in each rain garden or control was used to determine the percolation rate for that rain garden. The percolation rate of each rain garden was compared to the respective control area using a two-tailed paired t-test (α=0.05). The percolation rates are reported in seconds per inch (SPI). The average percolation rate for all the rain gardens was used to calculate the additional surface area of rain gardens needed to prevent wastewater overflow. Based on the total area of the rain gardens studied (279,001 in^2) and the average percolation rate of the rain gardens (7.88 min/in) these five rain gardens are only allowing 2.8x10^{-5} cubic inches of storm water to percolate per minute of a rain event. However, rain gardens may be able to retain additional water due to the depression shape, preventing stormwater from entering the combined sewer.

2.2 Evaluation of Rain Garden Required Area

Citizen's Water estimates there are currently four to five billion gallons of wastewater overflow per year in the city of Indianapolis. The construction of the Indy Tunnel System is estimated to reduce this figure by 97%[2]. This suggests that there will be approximately 135 million gallons of wastewater overflow per year after 2025. The overflow per year can be used to calculate the additional surface area of rain gardens needed to prevent wastewater overflow in that year. The measurements of percolation rates were used to determine an average Indianapolis percolation rate (reported in seconds/inch), which was also used in the calculation of additional rain gardens needed to prevent wastewater overflow. When no wastewater overflow occurs: the sum of the wastewater rate and the inverse of percolation rate multiplied by area, A, equals zero. The equation can be written as follows

$$\text{Equation (1):}\ A\left[\left(\frac{1}{perc}\right)_{rain\ garden} - \left(\frac{1}{perc}\right)_{control\ area}\right]$$

Solving for the area yielded the additional rain garden area needed to prevent wastewater overflow. This equation assumes the constructed rain gardens will replace existing soil. The terms are given in units of volume/time. In this case percolation rates were reported in seconds/inch.

3. Results

3.1 Hydrology

The percolation rates of varied between areas because of soil type. The KIB rain gardens and control areas were in an area with a sandy soil texture and thus had lower percolation rates than the other areas (figure 1).

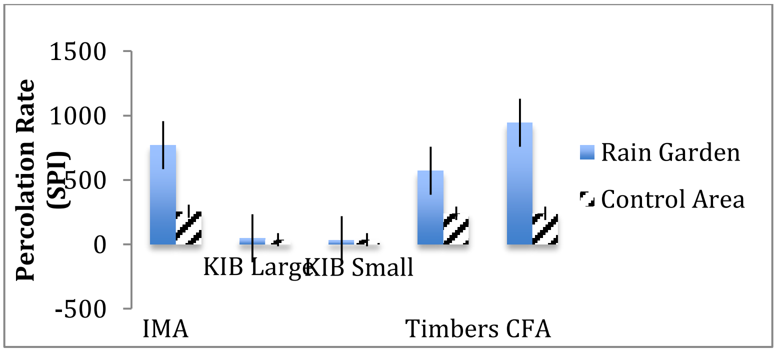

Figure 1. The Percolation rates of all rain gardens in the study are shown paired with the respective control areas. Standard error bars are displayed.

The Indianapolis Museum of Art rain garden had a significantly slower percolation rate (p=0.0045) than the control area (Figure 2). None of the other four rain gardens had percolation rates significantly different than their associated control areas (Figures 3-6). The KIB (large), Timbers, and CFA rain gardens had percolation rates that were slower than the respective control areas, but the difference was not statistically significant.

For logistical reasons, the CFA rain garden (Figure 5) was compared to the control area for the Timbers site, 9.6 miles away. The CFA site was surrounded by gravel and concrete making it difficult to evaluate a nearby control site. Although soil types were similar, it is possible the amount of compaction could be different. The KIB (small) rain garden had a faster percolation rate than the control area, but the difference was not statistically significant.

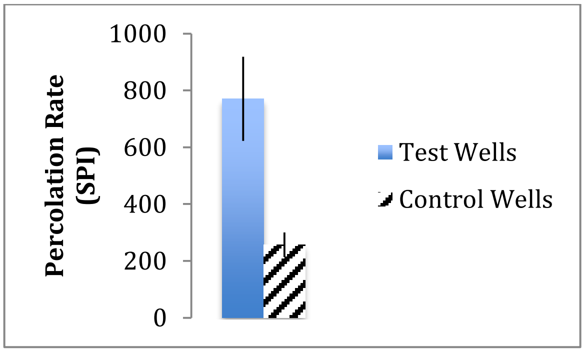

Figure 2. The average percolation rate of the Indianapolis Museum of Art (IMA) was compared to the average percolation rate of the IMA control plot.

Although the control plot was within ten feet of the rain garden there appeared to be less clay in the control plot. Error bars are displayed with one standard deviation in both directions from the mean. The test wells were significantly slower than the control wells (p= 0.0045).

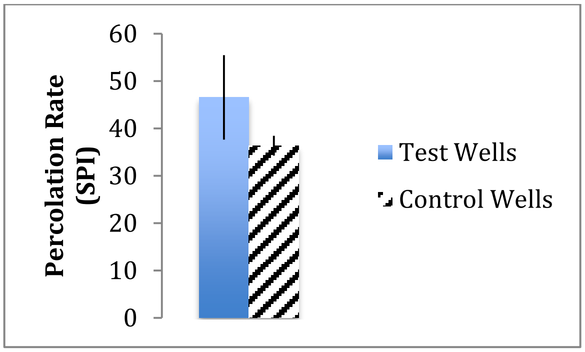

Figure 3. The average percolation rate of the Keep Indianapolis Beautiful (KIB) large rain garden was compared to the average percolation rate of the KIB control plot.

Error bars are displayed with one standard deviation in both directions from the mean. There was no statistical difference between the test wells and control wells (p= 0.1254).

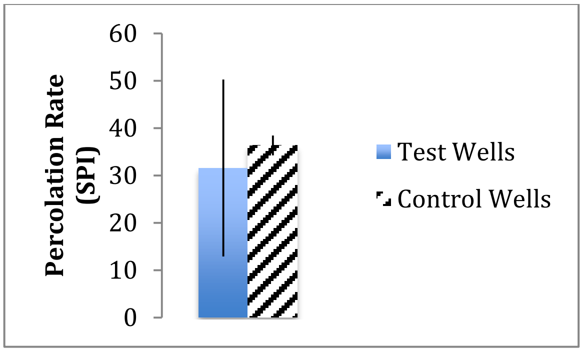

Figure 4. The average percolation rate of the Timbers rain garden was compared to the average percolation rate of the Timbers/Challenge Foundation Academy control plot.

Error bars are displayed with one standard deviation in both directions from the mean. There was no statistical difference between the test wells and control wells (p= 0.5541).

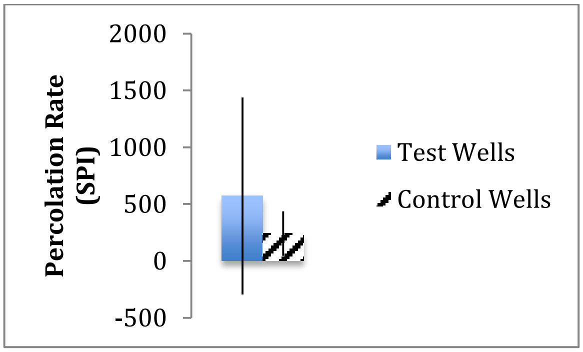

Figure 5. The average percolation rate of the Challenge Foundation Academy rain garden was compared to the average percolation rate of the Timbers/Challenge Foundation Academy control plot.

Error bars are displayed with one standard deviation in both directions from the mean. There was no statistical difference between the test wells and control wells (p= 0.1081).

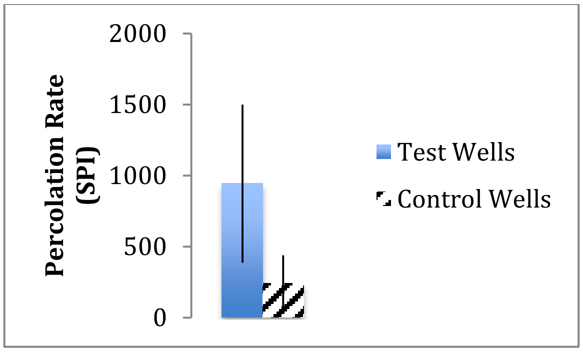

Figure 6. The average percolation rate of the Keep Indianapolis Beautiful (KIB) small rain garden was compared to the average percolation rate of the KIB control plot.

Error bars are displayed with one standard deviation in both directions from the mean. There was no statistical difference between the test wells and control wells (p= 0.6823).

3.2 Evaluation of Rain Garden Required Area

Since the measured rain garden percolation rates were slower than the measured control area percolation rates, equation one is not useful. The equation results in a very large negative number. This indicates rain gardens, as currently constructed, are not preventing wastewater overflow.

4. Discussion

This urban hydrology study is important because it highlights adverse effects associated with wastewater overflow. This is especially true in Indianapolis where there are streams that are not in compliance with the Clean Water Act

There was more variation in percolation rate measurements in the rain gardens than in the control areas. This is evident by the larger error bars in the rain gardens (Figures 2-5). The control sites generally had lower standard deviations. This could indicate the soil in rain gardens is more heterogeneous than surrounding soils. Creating a rain garden with homogenous conditions appears to be difficult.

Additional studies using infiltrometers could provide stronger evidence that Indianapolis rain gardens need to be better constructed. This would allow more data to be collected because of less time restrictions and less area altered by equipment. Aerial photography would have been useful to show well locations as well as estimating area of rain gardens. If digging restrictions because of gravel and concrete were not encountered, a proximal control may have been chosen for the Challenge Foundation Academy. There is a possibility that these locations had different levels of soil compaction.

The results of the hydrological analysis did not reveal that the five rain gardens examined were providing the benefit of an increased percolation rate as compared to similar soil conditions without rain gardens. Indianapolis rain gardens are not preventing wastewater overflow because the percolation rate is no different or slower than the soil they have replaced. The average control area percolation rate was no different or faster than that of the average rain garden. This means that as currently constructed in Indianapolis, rain gardens are not a viable solution to the Indianapolis wastewater overflow problem. This is a very surprising result. It is possible the studied rain gardens were in an area that had not been degraded much by urban activity. It is also possible that the studied rain gardens are not optimally constructed to prevent wastewater overflow. While the rain gardens in this study have little effect on Indianapolis wastewater overflow, there are likely sheet erosion and phytoremediation (removal or stabilization of pollutants using plants) benefits.

Soil conditions and slope are likely the cause of poorly percolating rain gardens. If a rain garden is constructed with a steep slope little topsoil will be able to develop because of gravity eroding the topsoil. The Keep Indianapolis Beautiful large rain garden and the Indianapolis Museum of Art have steep slopes. Urban soils often have been stripped of topsoil. They are also often heavily compacted. Because of these two problems hard clay minerals are near the surface. This does not allow plants to create more pore space, since root systems will grow shallowly[14]. Many Indianapolis rain gardens studied seem to have been constructed using existing soil. Bringing in soil from an area with lower amounts of clay-sized particles could help increase the percolation rate. Time can also be a factor. As roots of plants grow they move sediment aside, a process known as bioturbation[15]. It can take years for roots to create pore space. The oldest rain garden in Indianapolis is only three years old.

5. Conclusion

The rain gardens of Indianapolis in this study do not percolate faster than surrounding areas. One of the five studied rain gardens had a percolation rate that was slower than the control area. Four of the five rain gardens had percolation rates no different from the respective control areas. Additional rain gardens, as currently constructed, would not prevent wastewater overflow. The rain garden would percolate water no faster than the soil it would replace. The results of this study suggest that if rain gardens were to be built on a large scale, some monitoring of their effectiveness and optimal placement would be worthwhile. Although this study was specific to the Indianapolis area, the general procedure could be used to guide local governments in other cities. Understanding plant community composition effects on percolation rates could help improve urban hydrology. Another area that warrants further study is assessing the feasibility of replaces impermeable surfaces such as concrete and asphalt with more permeable alternatives.

6. Acknowledgements

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