Sustainable stormwater management using rain gardens in urban areas

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Abstract. Stormwater runoff and combined sewer overflows in urban areas are the leading causes of flood and water quality degradation. Green infrastructures (GI) were introduced to treat stormwater runoff onsite to reduce these effects. A project was conducted in St. Louis, Missouri, US to assess the impact of installing one type of GIs (rain gardens) on the volume reduction of stormwater runoff from urban streets served by a combined sewer system. The rain gardens were installed in a six-block area between late 2013 to early 2014. After separating stormwater runoff flow from base flow in the sewer system, rain gardens efficiency was evaluated based on comparing the pre-installation condition in 2011/2012 and the post-installation condition in 2014. A reduction in the volume of stormwater runoff by installing the rain gardens was significant only at two sites. However, analysis was hampered by the high variability of the flow data and the difficulty in measuring flows in the sewers. For this type of field experiment, it is important to develop advanced flow measurement devices to overcome the problems of high variation in data and pay high attention to selecting the proper statistical tests to evaluate the stormwater runoff reduction.

Keywords: rain gardens, combined sewer overflow, stormwater quantity reduction.

1. Introduction

1.1 Problem of Combined Sewer Overflow

The Combined Sewer System (CSS) is a sewer system that collects and conveys sanitary sewage with surface runoff in the same piping system. During heavy storms, CSS receives higher flows than wastewater treatment plant (WWTP) capacity and discharges the excess directly into waterways to avoid sewage backup to homes. This problem is known as the combined sewer overflow (CSO). The CSO may entail undesirable effects on human health, spoils the quality of receiving water bodies and causes aquatic life toxicity effects. Hence, from a sustainable point of view, it is preferable to manage stormwater runoff as its source to reduce combined sewer overflows. The onsite treatment was introduces as a part of the concept of green infrastructures (GIs) [1]. Rain gardens, green roofs, permeable pavements are some examples of GIs. Because of the environmental degradation with CSOs [2], investigating appropriate stormwater managing methodologies in urban areas to reduce CSO is vital.

1.2 Rain Gardens

Rain gardens integrate the management of storm runoff with landscaping. GIs enable stormwater to be infiltrated to groundwater, evaporated to the atmosphere, and/or uptake by plants, causing a reduction in the CSOs and introducing benefits to water quality. They are used mainly to bring back a site’s natural
evapotranspiration and infiltration hydrology [3]. In addition, rain gardens may add green spaces to cities which contribute to increasing environmental, social, and economic benefits [2, 4-5].

Recently, due to its adaptability and versatility, rain garden is one of the most commonly used GIs [6-7]. It consists of creating a depression filled with high porous medium to allow water infiltration into the soil structure. The medium comprises topsoil mixed with sand and organic matters. It is generally planted with native vegetation [4, 6].

Although many experiments on rain gardens efficiency showed high stormwater volume reduction [8-9], it is still unclear how they perform on-field and how they perform regarding CSO especially with high variation in data collected in such field studies. The objective of this paper is to test –on the field- the water quantity reduction efficiency of rain gardens installed in an urban area served by combined sewer. Alyaseri et al. [10] conducted an experiment and used the results to show the implication of rain garden installation mainly on water quality, while this paper is focusing entirely on runoff reduction and deepening the analysis on quantities of runoff water.

2. Materials and Methods

2.1 Rain Garden installation and Flow Measurement

The rain gardens in this case study were installed by the East-West Gateway Council who started an initiative at the City of St. Louis, Missouri, U.S. in a number of old Streets. Four intersections (Humphrey, Wyoming, Connecticut, and Juniata) in the South Grand Boulevard in the city were put in rain gardens. The efficiency of these rain gardens was tested by comparing the post-installation runoff volume to the pre-installation condition. The rain gardens were established at walkway corners of the street’s intersections. The construction of rain gardens started and soil was added in October and November 2013. After excavation and geotextile fabric installation, each rain garden cell was constructed using a 45 cm mixture of planting soil positioned on 15 cm of crushed aggregate. Figure 1 shows a picture of one cell and shows that the concrete sidewalk is 30 cm higher than the surface of the garden soil. No under-drains were installed to take water directly to the sewer system. When the level of stormwater runoff rises in the garden, the runoff flows to the sewer system through an overflow inlet.

![Figure 1](image_url)

**Figure 1.** Rain Garden in the Grand and Wyoming Site during the Post-Construction Phase in June 2015 with the Inlet of Runoff from the Wyoming Street.
The data collection for the pre-installation condition was conducted between September 2011 and August 2012. The collection of data for the post-installation condition was carried out between January and September 2014. During the two conditions, data of flow and rainfall were continuously collected, except when detaching the flowmeters for maintenance or because of malfunctioning.

2.2 Flow and Rainfall Data Analysis
A flow monitoring equipment was placed by Metropolitan St. Louis Sewer District (MSD) at every manhole located downstream flow in sewer from a rain garden. The flow rates from the pre- and post-installation and rainfall data were gathered from September 2011 to September 2012 and from January to September 2014, respectively. The gathered data were reported in 15-minute intervals and processed to be illustrated at an hourly rainfall rate [10].

Taking into consideration the hydrologic configuration in the site, it was important to define the “rainfall event” in the study. Runoff may not occur to manholes in every rainfall event. A hydrologic method must be selected for minimum runoff assessment. The Natural Resources Conservation Service (NRCS) had established a methodology for estimating direct runoff from a precipitation event. The methodology is known as “Curve Number (CN)”. CNs replicate how much rainfall runs off under the effect of the hydrologic soil-cover compound [11]. Equations and curve numbers for different hydrologic conditions, treatment approaches, and land uses can be found in the books of hydrology. Because drainage during small rainfall events to the sewer mainly comes from impervious surfaces that are connected directly to the sewer system, a CN of 98 was taken as the baseline for definition [11]. Applying NRCS equations showed that the minimum precipitation depth resulted in runoff is 0.045 inches (0.113 cm). Therefore, the rainfall event was set as the event when a minimum of 0.045 inches cumulative rainfall occurred in a day. All precipitation events that have cumulated daily rainfall less than 0.045 inches were excluded from the analysis.

Because the quality of data may be affected by turbulence, sensor malfunctioning, sensor fouling due to debris and sediments' build-up, and insufficient liquid depth due to extremely low flows, assessment for the data was performed for acceptability and reliability. Flows with negative values were neglected.

2.3 Base Flow Separation
For every rainfall event during pre- and post-installation conditions, the volume of stormwater was separated from the base sanitary flow in the combined sewers by the method of Antecedent/Subsequent Dry-days Estimation Method (ASDEM) as described in [10, 12]. Then, the volumes of stormwater runoff were divided by the depths of rainfall before the comparisons between the pre- and post-conditions were taken place. The runoff reduction because of rain garden installation was estimated using the following formula:

\[
\text{Reduction} = MCT_{\text{post}} \left\{ \frac{F_i - \left( \frac{\sum_{j=1}^{k} F_j}{R_i} \right)}{R_i} \right\} - MCT_{\text{pre}} \left\{ \frac{F_i - \left( \frac{\sum_{j=1}^{k} F_j}{R_i} \right)}{R_i} \right\}
\]

Where, \(MCT_{\text{post}}\) is the proper measure of central tendency (MCT) (e.g. means, medians, or geometric means) for the group of data of stormwater runoff discharged into the CSS for the post-installation condition per depth of rain, \(MCT_{\text{pre}}\) is the MCT for the group of data of stormwater runoff discharged into the CSS for the pre-installation condition per depth of rain, \(n\) is the number of rainfall events employed in the analysis during post-condition, \(m\) is the number of rainfall events used in the analysis during pre-condition, \(k\) is the number of days before and after the rainy day that was used in base flow estimation, \(F_i\) is the combined flow during a rainy day; \(i\) measured in gallon/day, \(F_j\) is the flow in the CSS during a dry day; \(j\) before or after the rainy day measured in gallon/day, and \(R_i\) is the daily rainfall depth during rainy
day; i measured in inch.

As can be seen from equation (1), the reduction in stormwater runoff due to installing rain gardens was calculated based on the difference between runoff in pre- and post-installation for every site. The runoff volume and the number of rainfall events used for comparison at every location are illustrated in Table 1.

2.4 Statistical Analysis

For the purpose of selecting the proper comparison approach, a nonparametric Kruskal-Wallis test was conducted to find out if there are identical distributions between the populations in the four sites. The test showed that there is a significant difference within at least one of the sites. Therefore, the comparison was made within each of the four sites.

For better representation of data, it was important to figure out how these data were statistically distributed. The handy tool embedded in Minitab software was used to conduct a distribution identification tests to compare how well data fit different distributions. Two measures were used to identify the best fit. These measures were; P-value and Anderson-Darling (AD) test. Since null hypothesis in every test was that the data is following the tested distribution and the alternative is not, a high p-value means data more likely to follow this distribution. A low p-value means that the data don’t fit that distribution. Hence, for every set of data, p-values were compared between distributions and the one with the highest was selected. Three parameter distributions were excluded due to impossibility to calculate a p-value for them. For AD test, the lower AD statistics point to a better fit for distribution. Table A-1 in Appendix A shows the result of comparison for five major distributions. The Table shows that except for Wyoming and Juniata in post condition, lognormal was the dominant distribution in the data.

To discover the differences between the stormwater runoff flows in pre- and post-establishing the rain gardens, a parametric t-test was first conducted for every site. However, the parametric tests are not always the most proper in all cases. For example, if the data was not normally distributed and largely skewed, the two-sample t-test commonly used to compare differences between groups is not appropriate for this data set and the need, in this case, is to a nonparametric test [13].

The non-parametric test compares the results obtained from the experiment to the results that would be obtained when repeatedly randomizing the data across the groups. Because the high fluctuation in the data, it was important to use a proper statistics representation for it. MCTs were calculated at each site each phase for comparison. Then, a randomized test was performed and the difference between the two phases at every site was considered as the test statistics, $t_{obs}$. The test uses Monte Carlo simulation creating a distribution assuming that the observed data happened by chance. The test assumes that an observed data from the whole population (from pre- and post-) is coming likely from either phase equally. 20,000 iterations in the Monte Carlo simulation were performed for every site to simulate the difference in MCTs. In every sampling iteration, data were unstacked based on site subscription, and the differences between the two MCTs were calculated and denoted by $t_{ran}$. Then a computation was conducted to the possibility of observing a statistic $t_{ran}$ equal or more than $t_{obs}$ assuming that an observation randomly selected from the population is likely to come equally from the two groups of data. This probability is known as a p-value which is the possibility of seeing such a difference between the two MCTs by chance. The p-value equal to $\frac{C}{N}$, where C stands for the number of times $t_{ran} \geq t_{obs}$. If the p-value is less than the level of significance ($\alpha = 0.05$) we reject the null hypothesis and conclude that the difference was not by chance.

3. Results and Discussion

The comparison was made based on the stormwater runoff per rainfall depth during the pre and post-installation conditions. The Kruskal-Wallis test showed p-values of 0.00004 and 0.00007 from the pre- and the post-installation data, respectively indicating that the distributions of the four sites are
significantly different. Therefore, each site was tested separately. Table 1 shows the number of events and average runoff at each site in the project. Table 1 also shows the results of parametric and nonparametric tests. The randomization tests are based on means, medians and geometric means. The null hypothesis in the nonparametric test was that the MCT in the pre-installation condition was equal to the MCT in the post-installation condition, while the alternative hypothesis assumes a smaller MCT from the post-installation condition.

Table 1. Number of rainfall events and mean, median, and geometric mean volume of runoff per rain depth at the four sites during the pre- and post-installation Phases.

| Site         | Runoff Volume/Rainfall Depth (gallon/inch) | Wyoming | Connecticut | Humphrey | Juniata |
|--------------|--------------------------------------------|---------|-------------|----------|---------|
| Phase        | Pre- | Post- | Pre- | Post- | Pre- | Post- | Pre- | Post- |
| Number of rainfall events | 50  | 46  | 33  | 21  | 53  | 16  | 32  | 25  |
| Mean         | 715 | 127 | 727 | 722 | 875 | 544 | 6186 | 5842 |
| Geometric mean | 377 | 84  | 154 | 374 | 396 | 43  | 2541 | 3920 |
| Standard deviation | 840 | 109 | 2730 | 754 | 1372 | 915 | 7410 | 3641 |
| Median       | 357 | 87  | 178 | 432 | 355 | 25  | 3036 | 5462 |
| p-value from parametric t-test | 0.0001 | 0.9911 | 0.2710 | 0.8192 |
| p-value from randomized test (based on means difference) | 0.0001 | 0.6118 | 0.19730 | 0.4224 |
| p-value from randomized test (based on geo means difference) | 0.0001 | 0.9925 | 0.0001 | - |
| p-value from randomized test (based on medians difference) | 0.0001 | 0.9888 | 0.00015 | 0.9671 |
| Change based on means, % | 82% decrease | 1% decrease | 38% decrease | 6% decrease |
| Change based on geometric means, % | 82% decrease | 143% increase | 89% decrease | 54% increase |
| Change based on medians, % | 76% decrease | 143% increase | 93% decrease | 78% increase |

a Significant  b Not significant

Table 1 shows that the standard deviations for all data were relatively high, demonstrating an elevated level of uncertainty expected in the calculated reduction. All sites showed a decrease in mean runoff from the pre- to the post-condition. This decrease in means was significant only in the Wyoming site. This significance was shown in both the t-test and the randomized test. When considering medians for comparisons, increases in the runoff were showed from Connecticut and Juniata sites but was not significant. This increase was more likely because of the process of data collection, especially when base flow subtracted from the combined flow to estimate the stormwater flow. The base flow was estimated from subtracting the flow during wet day from the average flow in dry days before and after the wet day which may contain high level of variability. The decrease in runoff in the Humphrey site was a little perplexed. It was not significant based on the differences between means using both t-test and randomized tests, while it was significant when differences between medians or geometric means were tested in the randomized test. Table 1 shows that the mean before installation was 875 gal/inch and had reduced to 544
gal/inch after. One randomization test showed that no significant difference between means but, another randomization test showed a significant difference between medians (355 gal/inch reduced to 25 gal/inch) and geometric means (396 gal/inch reduced to 43 gal/inch). The expected reason is the high sensitivity of means to the extreme observations while medians are less sensitive, therefore, the randomized test showed that there is a small probability that the difference between the pre- and post- median data came by chance. Table 1 and Figure 2 show the results from the parametric t-test for comparisons between the pre- and post- installation phases.

Figure 2. A comparison of runoff volume per rain between the pre- and post-construction of the rain gardens in the four sites (Connecticut in top left, Humphrey in top right, Juniata in the bottom left, and Wyoming in bottom right). The large box represents the 25th percentile, median, and 75th percentile; the whiskers represent the 5th and 95th percentiles; the small circle represents the mean.

Testing data from Wyoming site shows a significant difference in all tests. Assuming there is no difference between the pre- and the post- installation data, the low p-value indicating a very low probability to observe the difference in runoff by chance. This result showed that the runoff at the Wyoming site had reduced significantly due to installing rain gardens. Hence, the significant reduction that can be identified is from the Wyoming site and from Humphrey to some extent (76% to 82%). Some studies showed that the average reduction of runoff when installing rain gardens is 61% [14]. This average is lower than the reduction observed in this study. The reduction achieved from the installation of this GI in Wyoming and Humphrey sites is higher than what was reported by Trowsdale and Simcock who indicated a 41% reduction [15]. Also, the result is consistent to the upper range of the 40% to 80%
reduction that was indicated by Battiata et al. [16].

In addition to complexity in statistical analysis for determining the percentage reduction in the runoff volume, there were troubles associated with data collection. The flow measurement device requires a flow of more than one inch of water before it takes a velocity reading causing gaps in flow data. Meter malfunctions, failure to recover data due to missing connection to the cellular tower, and drop in from the surface to the grated manhole’s lid leading to swirling are other possible problems associated with data collection.

4. Conclusions and Recommendations
This study shows that field experiments to test GIs efficiency are hampered by the high variability of the flow data and the difficulty in measuring low flows in the sewers. Among four sites installed rain gardens and analyzed, only one site showed a significant reduction in the runoff in the combined sewer. This limitation to one site is more likely due to high variability in the data collected. The reduction achieved was higher than the averages reported from some other experiments.

Other problems associated with testing GIs’ efficiency were the malfunctioning of the flow measurement devices, treating and arranging data, separating stormwater runoff from base flow, and selecting the proper statistical analysis. It is recommended to search for alternative methods for flow measurements in sewers.

5. Data Availability Statement
Flow data that normalized to gallons per rainfall amount for stormwater events for pre and post installation phases are available from the corresponding author upon reasonable request.

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Appendix A: Distribution Identification Analysis

Table A-1. Identification analysis between five distributions. The location and scale parameters are shown as well. The scale parameter is a numerical parameter in which the larger the scale, the more spread out and wide the distribution is.

| Site       | Phase | Distributions | AD   | P-value | Location | Shape | Scale           | Best fit |
|------------|-------|---------------|------|---------|----------|-------|-----------------|----------|
| Connecticut| Pre   | Normal        | 9.963| <0.005  | 727.43785|        | 2730.63272      |          |
|            |       | Lognormal     | 0.352| 0.447   | 5.03666  |        | 1.51731         | ✓        |
|            |       | Exponential   | 11.508| <0.003  | 727.43784|        | 335.92335       |          |
|            |       | Weibull       | 1.341| <0.010  | 0.57493  |        | 353.92335       |          |
|            |       | Gamma         | 2.597| <0.005  | 0.42039  |        | 1730.39960      | ✓        |
|            | Post  | Normal        | 1.258| <0.005  | 721.63185|        | 754.34530       |          |
|            |       | Lognormal     | 0.422| 0.294   | 5.92348  |        | 1.40370         |          |
|            |       | Exponential   | 0.202| 0.042   | 721.63185|        | 999.02680       | ✓        |
|            |       | Weibull       | 0.138| >0.250  | 0.93221  |        | 678.81537       |          |
|            |       | Gamma         | 0.136| >0.250  | 0.88970  |        | 811.09738       |          |
| Wyoming    | Pre   | Normal        | 5.145| <0.005  | 714.74749|        | 840.44199       |          |
|            |       | Lognormal     | 0.325| 0.514   | 5.93087  |        | 1.20287         | ✓        |
|            |       | Exponential   | 1.373| 0.042   | 714.74749|        | 108.85316       |          |
|            |       | Weibull       | 0.900| 0.020   | 0.90703  |        | 678.81537       |          |
|            |       | Gamma         | 1.100| 0.010   | 0.91062  |        | 784.90135       |          |
|            | Post  | Normal        | 1.701| <0.005  | 126.91992|        | 108.85316       |          |
|            |       | Lognormal     | 0.748| 0.048   | 4.43329  |        | 1.07245         |          |
|            |       | Exponential   | 0.727| 0.250   | 126.91992|        | 135.18108       | ✓        |
|            |       | Weibull       | 0.199| >0.250  | 1.36129  |        | 93.23500        | ✓        |
|            |       | Gamma         | 0.193| >0.250  | 0.88970  |        | 811.09738       |          |
| Humphrey   | Pre   | Normal        | 7.003| <0.005  | 875.13337|        | 1371.65068      |          |
|            |       | Lognormal     | 0.223| 0.817   | 5.98096  |        | 1.28831         | ✓        |
|            |       | Exponential   | 2.623| <0.003  | 875.13325|        | 2.97001         | ✓        |
|            |       | Weibull       | 0.898| 0.021   | 0.79722  |        | 751.35414       |          |
|            |       | Gamma         | 1.317| <0.005  | 0.75396  |        | 1160.71050      |          |
|            | Post  | Normal        | 2.501| <0.005  | 543.62425|        | 915.43048       |          |
|            |       | Lognormal     | 0.500| 0.178   | 3.76417  |        | 2.97001         | ✓        |
|            |       | Exponential   | 13.313| <0.003  | 543.62425|        | 543.62425       |          |
|            |       | Weibull       | 0.696| 0.061   | 0.39547  |        | 175.58117       |          |
|            |       | Gamma         | 0.914| 0.026   | 0.27586  |        | 1970.63079      |          |
| Juniata    | Pre   | Normal        | 2.890| <0.005  | 6186.40143|       | 7410.31227      |          |
|            |       | Lognormal     | 1.016| 0.010   | 7.84039  |        | 1.74109         |          |
|            |       | Exponential   | 1.056| 0.097   | 7.84039  |        | 6186.40142      |          |
|            |       | Weibull       | 0.297| >0.250  | 0.78451  |        | 5419.33477      | ✓        |
|            |       | Gamma         | 0.294| >0.250  | 0.68177  |        | 9970.46463      | ✓        |
|            | Post  | Normal        | 0.225| 0.799   | 6186.40143|       | 7410.31227      |          |
|            |       | Lognormal     | 2.018| <0.005  | 7.84039  |        | 1.74109         |          |
|            |       | Exponential   | 1.483| 0.030   | 6186.40142|       | 5419.33477      |          |
|            |       | Weibull       | 0.758| 0.043   | 0.78451  |        | 9970.46463      |          |
|            |       | Gamma         | 1.029| 0.014   | 0.68177  |        | 9070.46463      |          |