Using Green Infrastructure to Minimize Combined Sewer Overflows

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ENGR 2196 Technical Communication
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December 7, 2015

Source: http://www.wrdesign.com/projects/detail/philadelphia-green-infrastructure
Abstract

This project addresses the problems posed by combined sewer systems in high-density urban environments, and aims to minimize combined sewer overflows through an innovative green infrastructure solution. In order to identify the best solution, bioretention basins, green roofs, and permeable pavement were analyzed according to the following criteria: runoff volume reduction, peak flowrate reduction, pollutant treatment rates, greenhouse gas emissions contribution, cost effectiveness, and implementation feasibility. Bioretention basins were found to perform best in almost all criteria considered. Thus, implementation of bioretention basins is the proposed solution. Bioretention has significant potential in cost savings, as well as positive impact on the local economy, and environmental and social benefits.

ENGR 2196 document scenario: This document proposes an engineering design project to reduce combined sewer overflows through green infrastructure technology. I envision this design document as a proposal submitted by a planning and engineering firm to a government agency charged with providing stormwater services, such as Philadelphia Water. The technical proposal would be reviewed by engineers at the government agency. The Executive Summary is tailored to managers and government officials who are responsible for approving the project and budget.
Executive Summary

High-density urban areas face a unique challenge in combined sewer overflow (CSO) control compliance. Impervious surfaces increase both the velocity and volume of stormwater entering the combined sewer system (CSS). When the conveyance network and treatment plants are unable to handle the increased stress\(^1\), raw wastewater is released directly into nearby rivers. The raw wastewater contains harmful pollutants including human waste, industrial waste, toxic substances, and trash debris that are picked up by stormwater runoff. These CSO events damage local and downstream ecosystems, contaminate drinking water supply, and disrupt recreational activities due to human health risks. The water department is required to develop and implement a Long Term Control Plan (LTCP) through the CSO Control Policy, published by the U.S. Environmental Protection Agency in 1994. Ensuring cost effective LTCP implementation is challenging for many cities. Moreover, several studies have concluded that climate change will exacerbate CSOs, increasing costs of compliance and the negative effects on environmental and human health.

Conventional approaches to CSO control adversely affect the hydrology and quality of runoff in urban areas. Green infrastructure is an innovative approach that has been found to be more cost effective and resilient to climate change, as well as provide benefits beyond CSO control. Thus, this project focuses on three green infrastructure technologies as the candidate solutions: bioretention basins, green roofs, and permeable pavement. In order to successfully minimize CSOs and maintain compliance, the candidates must meet certain criteria. Namely, the solution must reduce runoff volumes, reduce peak flowrates, treat water pollutants, contribute minimally to greenhouse gas (GHG) emissions, be cost effective, and be feasible to implement.

This analysis found bioretention basins to be the optimal candidate solution. Of all three candidates, bioretention basins performed the best in runoff volume reduction, peak flowrate reduction, GHG emission contribution, cost effectiveness, implementation feasibility, and almost all pollutant treatment rates. Bioretention basins consist of a soil-vegetated layer at the surface, with a sand layer directly underneath, followed by a gravel drainage layer. The basin can be designed to infiltrate stormwater into underlying soils or capture runoff for reuse. Bioretention basins have an added advantage of flexibility in design, which allows for easier integration into existing infrastructure such as walkways and street sides. Bioretention basins are also found to be the most cost effective, which would provide investment savings in LTCP implementation.

The hydrologic improvements brought about by bioretention basins would reduce stresses on the CSS conveyance network and treatment plants. This would prolong the operational lifespan of key infrastructure, avoiding substantial replacement costs. The addition of new components downstream or at the treatment plants would also be avoided. Implementation of this project would introduce many new positions in sustainability to the local economy, as skilled workers will plan, implement, and maintain a sustainable distribution of bioretention basins. Bioretention basins also provide aesthetic, social, and environmental benefits. Bioretention trees remove air pollutants, mitigate traffic noise, provide shade, improve biodiversity, and abate the urban heat island effect. Urban green space improves the wellbeing of citizens and communities, as well as decreases crime rates.

\(^1\) Please refer to the Glossary for definitions of various technical terms.
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Problem Statement

This section summarizes the problems caused by combined sewer systems (CSSs) and combined sewer overflows (CSOs) in high-density urban regions. Both conventional and innovative approaches to CSO control are explored. The design requirements of the candidate solutions are also explained, and a brief historical account will showcase the trajectory of CSSs and stormwater management.

Initial Problem Description

A CSS transports both sanitary sewage and stormwater runoff to the wastewater treatment plant in a shared conveyance network. Significant wet weather events may increase the stormwater runoff volumes and flowrates beyond the capacity of the CSS or treatment plants. The CSS is designed to release untreated sewage—containing contaminants such as microbial pathogens, suspended solids, and floatable trash debris (U.S. Environmental Protection Agency [EPA], 2014)—directly into nearby bodies of surface water (Mays, 2001, section 18.1.). Such occurrences are referred to as CSOs. Figure 1 depicts a generalized diagram of a CSS during wet weather. CSOs can damage ecosystems, including fisheries, contaminate drinking water supplies, and disrupt recreational activity with river and beach closures (U.S. EPA, 2014).

Figure 1. Combined Sewer System Diagram

Source: http://greenlearningstation.org/stormwater.aspx
Due to pollution concerns and costly wastewater treatment, sewer systems in new or emerging communities transport sanitary sewage and stormwater separately (Burian et al., 1999). However, CSSs remain intact in older cities; there are over 700 cities in the U.S. that operate combined sewers (U.S. EPA, 2014). In order to help municipal and government agencies control CSOs and maintain compliance with the Clean Water Act (CWA), the U.S. EPA published the CSO Control Policy in 1994 (U.S. EPA, 2014).

High-density urban communities face a unique challenge with CSO Control Policy compliance due to large percentages of land covered by impervious surfaces. Walsh, Fletcher, and Burns (2012) explain that “impervious surfaces, such as roofs and roads, reduces both the volume of water infiltrating into soils and the volume of water lost to the air through evapotranspiration, thus increasing the volume of runoff following rain events” (p. 2). Figure 2 shows the significant difference between runoff in pre-developed and high-density urban environments. Additionally, studies show that runoff over impervious areas contains higher pollutant concentrations than that over pervious areas (James, Wilbon, & DiVincenzo, 2010; Lee & Bang, 2000). Moreover, increases in precipitation frequency and intensity due to climate change may result in more CSOs and additional challenges with compliance over the coming decades (Bi, Monette, Gachon, Gaspéri, & Perrodin, 2015; Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008; Yazdanfar & Sharma, 2015).

**Overall Analysis and Objectives**

In order to maintain regulatory compliance and avoid negative ecological impacts, the main objective of this project is to minimize CSO volumes. CSO volume has been identified as the most accurate indicator of ecological impacts, as opposed to frequency of CSO occurrences (Engelhard, Toffol, & Rauch, 2008). In order to achieve the main objective, each potential solution will be analyzed based on the following criteria:

- Runoff volume reduction
- Peak flowrate reduction
- Pollutant treatment rates

*Figure 2. Comparison of Runoff Hydrology on Natural and Impervious Covers*

Source: [http://water.epa.gov/polwaste/nps/urban_facts.cfm](http://water.epa.gov/polwaste/nps/urban_facts.cfm)
- Greenhouse gas (GHG) emissions contribution
- Cost effectiveness
- Implementation feasibility

The proposed solution should take both runoff quantity and quality into account. Runoff volume reduction and peak flowrate reduction will reduce CSO volumes directly, and also decrease stress on the CSS. There are additional benefits to treating stormwater runoff before it reaches the CSO outlet or treatment plant. Namely, a lighter pollutant load increases insurance of CWA compliance and decreases resource demand at the treatment plant. Additionally, given the widely anticipated effects of climate change on CSOs, failing to consider GHG emissions would be a serious oversight. Cost effectiveness and implementation feasibility should be considered, as the water department strives to keep rates affordable and consistent with limited resources.

Conventional CSO control approaches incorporate conveyance systems and downstream storage facilities that allow runoff to infiltrate or evaporate. Such facilities are designed to temporarily store runoff until it can be conveyed to a treatment plant after flowrates decrease (Mays, 2001, section 18.1.). Mays (2001) states that “traditional drainage practices, coupled with the imperviousness of urban land, deleteriously affect the quantity, quality and timing of runoff” (section 11.1.2., para. 1). Additional shortcomings include prolonged stress on the treatment plants, which must continue to treat the stored runoff at peak flowrates after the wet weather subsides; and, relatively high CSO volumes when the runoff exceeds the storage tank capacity (Lucas & Sample, 2015).

In response to the adverse effects of impervious surfaces on runoff, innovations in CSO control incorporate green infrastructure into the urban watershed. Integration of green infrastructure is a decentralized and distributed approach. These technologies, such as green roofs and rain gardens, delay or completely divert runoff from entering the CSS at the source. While green infrastructure will rarely replace conventional, downstream infrastructure, it is widely acknowledged to improve management efforts and results (Lucas & Sample, 2015; Mays, 2001; Phillips & Buchanan, 2011). For example, strategic implementation would reduce the demand for new downstream infrastructure, saving money and resources (Mays, 2001, section 11). Additionally, Mays (2001) states that the capture of rainwater from small-scale, frequent storms has value (e.g., irrigation, landscape architectural designs). Lucas and Sample (2015) found that green infrastructure is more resilient to climate change than conventional approaches. For these reasons, this project will focus on green infrastructure as a means to control CSOs and meet regulatory requirements.

Historical and Economic Perspectives

The late 1800s was a pivotal era for sewer system technology. At the time, human waste was collected in privy-vault cesspool systems. The cesspools were localized holes in the ground, placed near residences and in cellars; removing the waste from these cesspools was labor-intensive and inefficient (Tarr, 1979). Figure 3 depicts a cross section of a typical cesspool. Tarr (1979) explains two main factors that rendered the privy-vault cesspool systems inadequate: rapid population growth and increased potable water supply (pp. 309-313).
Rapid population growth and urbanization in Europe and America increased pressure on the privy-vault cesspools. The cesspools would often overflow, resulting in the need for more frequent maintenance and contaminated well water supply (Tarr, 1979). Additionally, during this period of growth, cities began implementing piped-in potable water systems for residential and fire-fighting uses. The increased potable water supply, along with the general adoption of the water closet, substantially increased wastewater quantities. At the time, if any underground sewer existed in American cities, it was to transport stormwater from urban streets. While many cities built potable water conveyance networks, they did not build any complementary wastewater sewers (Tarr, 1979). According to Tarr (1979), “wastewater was initially diverted into cesspools or existing storm water sewers or street gutters, often causing serious problems of flooding and disposal” (p. 310). As a result, cities began discussing sewage system alternatives to the privy-vault cesspools.

Conveying sanitary waste in a separate system allowed waste to be utilized for fertilizer production; this was the main economic argument for separate sewer systems. Proponents of separate systems asserted that the fertilizer production would outweigh the costs of constructing the separate piping network, which would even be “self-financing” (Tarr, 1979, p. 313). However, some engineers argued that the costs of the separate system would actually outweigh the benefits of agricultural uses. Moreover, Tarr (1979) explains that “from a cost-benefit perspective, the combined system was cheaper than a separate system that provided separate pipes for house wastes and rainwater and more practical for densely-built up cities that [already] required street drainage” (p. 314). Due to the large capital
investment required, engineers were reluctant to “experiment” with separate sewer systems, which had no successful precedents (Tarr, 1979). In addition to these economic arguments, there was a perception that urban stormwater runoff became as polluted as sanitary sewage, and “...ought to be treated as such” (Tarr, 1979, p. 314). Thus, when faced with the choice of combined or separate sewer systems, most early adopters chose combined. Early plans called for the combined sewage to be released into local waterways, supported by “the theory that running water purifies itself” (p. 315).

The mainstream preference for combined systems prevailed until health concerns arose, exemplary separate sewer systems were established, and wastewater treatment requirements became more demanding. George E. Waring, Jr. had the first notable winning proposal for a separate sewer system in Memphis (Tarr, 1979). In response the City’s yellow fever outbreak in the late 1870s, Waring asserted that separate systems were more sanitary and would prevent disease. Waring also made some faulty economic arguments to win the bid. He boasted a $7,000 per mile cost for the Memphis separate sewer system, as compared to $25,600 per mile for the Brooklyn combined system (Tarr, 1979, p. 325). Waring, however, failed to mention that the Memphis separate system did not include any stormwater sewers. Nevertheless, other cities began adopting separate systems as more were put into place. Burian et al. (1999) also mention the fact that wastewater treatment regulations were minimal in the 1800s (p. 8). This made combined and separate systems more competitive, depending on the context. More regulations were established as sanitary waste discharges increased, and the relationship between polluted water and illness was supported by more research (Burian et al., 1999). Cities could no longer release excessive amounts of sanitary sewage into nearby waterways. Due to the increased volumes during wet weather events, the higher costs to meet treatment requirements rendered CSSs financially impractical. By the 1930s and 1940s, newer cities were establishing separate systems for sanitary sewage and stormwater (Burian et al., 1999).

This historical trajectory has had implications for older cities in the Northeast, which must control CSOs and stresses on the CSS during wet weather events. Traditionally, urban stormwater designs aimed to remove runoff as quickly as possible to prevent flooding from large-scale storms (Mays, 2001, section 11.1.4.). Zimmer, Heathcote, Whitely, and Schroter (2007) explain that approaches “expanded from quick removal of stormwater to include control of peak flows (1970s) and removal of pollutants (1980s)...[and] further concerns arose in the 1990s related to changes in flow patterns in urban receiving waters” (p. 193). Moreover, the U.S. EPA published the CSO Control Policy in 1994 (U.S. EPA, 2014). In response, cities have begun focusing on green infrastructure as a means to mitigate CSOs. Conventional approaches called for more underground piping or upgraded wastewater treatment plants. The alternative green infrastructure approach has gained popularity due to its far-reaching benefits. For example, controlling runoff at the source reduces the need to install downstream infrastructure (Mays, 2001). Capturing rainwater from small-scale wet weather events provides a valuable resource for irrigation and, in some cases, potable uses (Mays, 2001). Green infrastructure also provides community and aesthetic value. Some technologies go beyond stormwater benefits. Green roofs, for example, abate air pollution and reduce the cost of heating and cooling buildings (Berndtsson, 2010).

**Candidate Solutions**

This section presents each candidate solution and their ability to meet the design requirements detailed in Overall Analysis and Objectives. It also provides a concise comparison of the candidates.
Bioretention Basins

Bioretention basins contain a soil-vegetated system at the surface level, with a sand filter layer directly underneath, followed by a gravel drainage layer. Depending on the design, the basin can include a geofabric that promotes infiltration into the ground, or an impervious layer to capture runoff for reuse (Lucke & Nichols, 2015, p. 785). A rain garden, for example, is a type of bioretention basin that typically refers to a small-scale system on an individual property (Virginia Department of Environmental Quality [VA DEQ], 2011). Strategically distributed, small-scale bioretention systems are more typical of urban environments due to limited land space. Figure 4 displays an example of an urban bioretention system design. The bioretention basin temporarily stores rainwater above the top soil layer, which then quickly drains through the filter mediums (VA DEQ, 2011). The performance of bioretention basins is affected by the ratio of soil, compost, and sand in the filter layer; the surface area and depth of the filter layer; the infiltration rate of the underlying soil; and, the inclusion of trees in the vegetation (VA DEQ, 2011, Section 3: Design Tables).

![Figure 4. Urban Bioretention Diagram](source: VA DEQ (2011))

A study conducted by Lucke and Nichols (2015) found that bioretention basins significantly reduce peak outflow rates and volumes of runoff. For the three basins monitored in the study, the average outflow rate reduction was 89.9% and average volume attenuation was 67.8% (p. 789). Figure 5 illustrates the difference between inflow and outflow rates during a typical precipitation event.
Figure 5. Bioretention Basin Inflow and Outflow Rates


Wang, Eckelman, and Zimmerman (2013) report relatively high pollutant treatment rates for bioretention basins. The rates reflect the “pollutant reduction from the influents to the effluents of a system” (p. 11191). The analysis reports treatment rates of 59%, 50%, and 60% for total suspended solids (TSS), total phosphorous (TP), and total nitrogen (TN), respectively. For heavy metals, there is an 81%, 84%, and 79% treatment rate for copper, lead, and zinc, respectively.

Bioretention basins were also found to have the lowest GHG emissions of the various technologies analyzed by Wang et al. (2013), with a total of about 700 kg carbon dioxide equivalent (kgCO2e) per year. Table 1 breaks down the emissions by life cycle stage.

Table 1. Bioretention Basin GHG Life Cycle Assessment Results

<table>
<thead>
<tr>
<th>Life Cycle Stage</th>
<th>Annual GHG Emissions kgCO2e/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Processing</td>
<td>340</td>
</tr>
<tr>
<td>Installation</td>
<td>120</td>
</tr>
<tr>
<td>Maintenance</td>
<td>240</td>
</tr>
<tr>
<td>Total</td>
<td>700</td>
</tr>
</tbody>
</table>

Source: Wang et al. (2013), data extracted from graph on p. 11194

Additionally, Wang et al. (2013) performed a cost-benefit analysis to determine the economic cost of bioretention basins with respect to improvements in water quality, for which they use “kg P eq.

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Wang et al. (2013) defined each green infrastructure according to its “capacity to store the runoff associated with 2.5 cm (1 in.) of rainfall generated over the defined 1 acre watershed” (p. 11192). Thus, the bioretention basin was sized as 137 m² for their life cycle assessment. See Wang et al. (2013) “Functional Unit” section for more details on sizing criteria.
reduction" as the indicator unit (p. 11195). The authors determined the economic and environmental tradeoffs: economic costs are represented by the U.S. dollar, climate footprint by kgCO2e, and resource consumption by kg oil equivalent (kgoe). Wang et al. (2013) found bioretention basins to be financially cost effective at only $98 per kg P eq. reduction (p. 11195). Bioretention basins were also found to cost 61 kgCO2e per P eq. reduction, and approximately 65 kgoe per P eq. reduction (p. 11195).

The use of bioretention in urban areas has been growing in popularity over the past ten years. Lucke and Nichols (2015) attribute this to high flexibility in design, which allows for relatively seamless integration into existing infrastructures. Bioretention systems also provide social and aesthetic value (Lucke & Nichols, 2015). In addition, small-scale bioretention systems are typically added to city-owned streets and walkways. This increases the feasibility of widespread implementation by a city-owned agency.

Green Roofs

As cited in Berndtsson (2010), green roofs have several benefits which include reducing stormwater runoff; decreasing the cost of heating and cooling buildings; abating air pollution; and, enhancing wildlife biodiversity by providing habitat. In addition to these benefits, green roofs provide sought-after aesthetic value. The popularity of green roofs has been growing in urban areas, due to a limited capacity to construct new green spaces at the ground level (Berndtsson, 2010)—approximately 40 to 50% of impervious surfaces are rooftops in urban regions (Mentens, Raes, & Hermy, 2006).

A green roof typically consists of four major layers: vegetated, soil substrate, filter, and drainage, as shown in Figure 6. Additionally, waterproofing and protection against root penetration must be applied to the underlying roof surface (Berndtsson, 2010).

![Figure 6. Green Roof Media Layers](source)

Green roofs are widely acknowledged to reduce both the volume and peak flowrates of stormwater runoff. As explained by Mentens et al. (2006),

> The reduction consists in: (i) delaying the initial time of runoff due to the absorption of water in the green roof system; (ii) reducing the total runoff by retaining part of the rainfall; (iii) distributing the runoff over a long time period through a relative slow release of the excess water that is temporary [sic] stored in the pores of the substrate. (p. 128)

Figure 7 depicts how runoff behaviors differ between traditional roofs and green roofs.
Many factors affect the performance of green roofs, such as the depth of the substrate soil layer, roof slope, roof age, sun exposure, and rainfall intensity (Berndtsson, 2010). Deeper soil substrate layers provide more storage space for the stormwater (Berndtsson, 2010). Green roofs can be categorized according to the depth of the substrate layer: those with deeper substrate layers are intensive, while those with relatively shallow substrate layers are extensive. Each type has advantages and disadvantages, and choosing which one to construct is highly dependent on context.

While intensive green roofs typically retain more stormwater than extensive green roofs, both options retain significantly more than traditional roofs. For example, Mentens et al. (2006) performed a literature review to collect data about green roof runoff. The study found that the annual runoff from traditional roofs was as high as 91%, while the annual runoff from intensive green roofs was as low as 15% (p. 220). The average percentage of runoff for intensive green roofs, extensive green roofs, and non-greened roofs were 25, 50, and 81, respectively (p. 221).

Moran, Hunt, and Smith (2005) monitored two green roofs to investigate their hydrologic performance. One was monitored for 67 rain events, and the other was monitored for 13 rain events. Based on the data from Moran et al. (2005), the average peak flowrate reduction for the two green roofs was 72.0% (p. 7). This reduction is determined by dividing the runoff flowrate by the peak rainfall rate (Moran et al., 2005), and reflects the reduction of peak flows between green roofs and traditional roofs (Berndtsson, 2010).

Stormwater may pick up fertilizers applied to green roof vegetation and increase the nutrient concentration in runoff, which presents a potential drawback (Morgan, Celik, & Retzlaff, 2012, p. 475). Such nutrients include forms of phosphorous (P) and nitrogen (N). Berndtsson (2010) notes that the contribution is highly variable and depends on how much fertilizer and what type is used. She also lists three studies which conclude that green roofs increase pH values of rainwater from about 5 to 7. This effect decreases the acidification of receiving water bodies and abates moderate acid rain (p. 357). In addition, it was found that green roofs generally do not have a negative or positive effect on heavy metal concentrations in runoff. In fact, Wang et al. (2013) assumed, conservatively, that green roofs have no significant treatment capabilities (p. 11191).
The GHG contribution of green roofs is relatively low when compared to other conventional and alternative stormwater management technologies. Wang et al. (2013) found that green roofs are responsible for approximately 2,025 kgCO2e per year (p. 11194). The authors also explain that a credit of 280 kgCO2e is obtained by “avoiding the annual maintenance of [a] conventional roof...by implementing a green roof” (p. 11194). Thus, the net GHG contribution of the green roof is approximately 1,745 kgCO2e per year. The results are summarized in Table 2.

Table 2. Green Roof GHG Life Cycle Assessment Results

<table>
<thead>
<tr>
<th>Life Cycle Stage</th>
<th>Annual GHG Emissions kgCO2e/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Processing</td>
<td>780</td>
</tr>
<tr>
<td>Installation</td>
<td>1,125</td>
</tr>
<tr>
<td>Maintenance</td>
<td>120</td>
</tr>
<tr>
<td>Credits</td>
<td>(280)</td>
</tr>
<tr>
<td>Total</td>
<td>1,745</td>
</tr>
</tbody>
</table>

Source: Wang et al. (2013), data extracted from graph on p. 11194

Green roofs were found to have a financial cost effectiveness of $500 per kg. P eq. reduction—a moderately low value as compared to the other technologies (Wang et al., 2013, p. 11195). Moreover, the environmental costs were found to be roughly 200 kgCO2e per kg P eq. reduction and 210 kgoe per kg P eq. reduction (p. 11195).

It is important to note implementation feasibility concerns. Installing a green roof is an investment that would most often by made by the property owner. As a city-owned department, incentives and credits to ratepayers could aid in wide-spread implementation; however, it may prove to be more challenging than establishing green infrastructure on city-owned land, such as streets.

Permeable Pavement

Permeable pavement consists of several layers, as shown in Figure 8. The top layer is the permeable surface, such as permeable concrete or porous asphalt. The stone reservoir temporarily stores runoff within the voids of the stones. The depth of this layer can be varied to meet storage capacity needs (Water Environment Federation [WEF], 2011). If the underlying soil does not allow infiltration, drainage infrastructure may be installed. Permeable pavements are usually implemented in parking lots and side streets with light truck traffic.

A variety of factors influence the effectiveness of permeable pavements. As stated in WEF (2011), “permeable pavement capacity is determined by the storage capacity of the stone reservoir, the permeability of the surface pavement, and the porosity of the soil” (section 7.3.3.1., para. 2). Mustafa (2014) found that rainfall intensity also affects runoff volume reductions in permeable pavement systems.

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3Wang et al. (2013) sized green roofs at 1298 m² for their life cycle assessment (p. 11192). See Wang et al. (2013) “Functional Unit” section for more details on sizing criteria.
As cited by Mustafa (2014), the City of St. Louis conducted a study from 2008 to 2011 to assess the ability of permeable pavements to reduce runoff volume. The study monitored three sites and three types of permeable pavements: permeable concrete, permeable asphalt, and permeable interlocking concrete blocks. Mustafa (2014) analyzed the data from the St. Louis study, and reported runoff reduction values for various rainfall intensities that were grouped into four categories. The long-term average rainfall intensity in Philadelphia is 0.14 in/hr (Philadelphia Water Department, 2009, p. v5-4). Thus, rainfall intensities in Philadelphia fall within Group 1, as classified by Mustafa (2014, p. iii). The runoff reduction, averaged across all three pavement types, was found to be 55% for Group 1 (p. iii).

Collins, Hunt, and Hathaway (2008) monitored four types of permeable pavement for one year and determined peak flowrate reductions compared to that of traditional asphalt. The average peak flowrate reduction for the four types of pavement was 72.6% (p. 1155).

Wang et al. (2013) reports permeable pavement treatment rates of 89%, 25%, and 25% for TSS, TP, and TN, respectively (p. 11191). The analysis also reports treatment rates of 86%, 74%, and 66% for copper, lead, and zinc, respectively.

In terms of GHG emissions, permeable pavement is quite costly at 10,487 kgCO2e per year (Wang et al., 2013). Permeable pavement receives a significant credit by avoiding the annual maintenance of traditional asphalt pavement. Even with this credit, permeable pavement contributes the largest amount of GHG of the three candidate solutions. Wang et al. (2013) attributes most of the emissions to concrete manufacturing, which is reflected in the materials processing life cycle stage (p. 11194). Table 3 displays the breakdown of emissions by life cycle stage. The study also analyzed how lifespan affected emissions, and found an annual reduction of 3,000 kgCO2e if the permeable pavement lifespan was increased from 25 to 40 years (p. 11195). This was the most significant emissions reduction due to increased lifespan of all candidate solutions.

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4 Wang et al. (2013) sized permeable pavement at 4047 m² for their life cycle assessment (p. 11192). See Wang et al. (2013) “Functional Unit” section for more details on sizing criteria.
Table 3. Permeable Pavement GHG Life Cycle Assessment Results

<table>
<thead>
<tr>
<th>Life Cycle Stage</th>
<th>Annual GHG Emissions kgCO2e/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Processing</td>
<td>4,000</td>
</tr>
<tr>
<td>Installation</td>
<td>2,925</td>
</tr>
<tr>
<td>Transportation</td>
<td>1,650</td>
</tr>
<tr>
<td>Maintenance</td>
<td>3,000</td>
</tr>
<tr>
<td>Credits</td>
<td>(1,088)</td>
</tr>
<tr>
<td>Total</td>
<td>10,487</td>
</tr>
</tbody>
</table>

Source: Wang et al. (2013), data extracted from graph on p. 11194

Wang et al. (2013) found permeable pavement to be the least financially cost effective of all technologies analyzed at approximately $1,650 per kg P eq. reduction (p. 11195). Permeable pavement was also found to have relatively high environmental costs at about 1,300 kgCO2e per kg P eq. reduction and 375 kgoe per kg P eq. reduction (p. 11195).

The implementation feasibility of permeable pavement faces similar obstacles to that of green roofs. Parking lots are ideal for permeable pavement due to large surface areas and low traffic volumes; however, they are often privately-owned and operated. Existing legal framework requires owners of large parcels to establish stormwater management technologies on the property. This existing framework could be used to incentivize private investment in permeable pavement, increasing the feasibility of wide-spread application. Moreover, permeable pavement could be installed on city-owned side streets. The maintenance needs of permeable pavements differ from those of traditional pavements. For example, vacuum sweeping should be performed at least three times annually to mitigate clogged void spaces (WEF, 2011). Such changes could be a challenge in beginning stages, and would require collaboration with the streets department and training of personnel.

Candidate Comparison

The three candidate solutions are compared in Table 4, which is discussed further in Proposed Solution. Each one was assessed according to runoff volume reduction, peak flowrate reduction, pollutant treatment rates, GHG emissions, cost effectiveness, and implementation feasibility. The values of each criterion were obtained from the references cited in Bioretention Basins, Green Roofs, and Permeable Pavement. For green roofs, the annual runoff percentages were averaged between extensive and intensive green roofs, and then subtracted from 100% to reflect volume reduction.

As previously explained, numerous studies conclude green roofs have no treatment benefits, and even increase TP and TN concentrations in some cases. For this reason, pollutant treatment rates of green roofs are not applicable. The implementation feasibility rating is based on the level of autonomy a city-owned agency would likely have when implementing the candidate solution.

The cost effectiveness of the three candidates are also compared in Figure 9 below.
Figure 9. Cost-Benefit Analysis Results, Candidate Comparison

Graph adapted from Wang et al. (2013)
### Table 4. Candidate Solutions Comparison

<table>
<thead>
<tr>
<th></th>
<th>Bioretention Basins</th>
<th>Green Roofs</th>
<th>Permeable Pavement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Runoff Volume Reduction</strong></td>
<td>68%</td>
<td>63%</td>
<td>55%</td>
</tr>
<tr>
<td><strong>Peak Flowrate Reduction</strong></td>
<td>90%</td>
<td>72%</td>
<td>73%</td>
</tr>
<tr>
<td><strong>Pollutant Treatment Rates</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>by Pollutant Type</td>
<td>TSS</td>
<td>TP</td>
<td>TN</td>
</tr>
<tr>
<td><strong>Copper</strong></td>
<td>81%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Lead</strong></td>
<td>84%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Zinc</strong></td>
<td>79%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pollutant Treatment Rates</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>by Pollutant Type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Runoff Volume Reduction</strong></td>
<td>59%</td>
<td>-</td>
<td>89%</td>
</tr>
<tr>
<td><strong>Peak Flowrate Reduction</strong></td>
<td>50%</td>
<td>-</td>
<td>25%</td>
</tr>
<tr>
<td><strong>Pollutant Treatment Rates</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>by Pollutant Type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GHG Emissions</strong></td>
<td>700 kgCO2e/year</td>
<td>1,745 kgCO2e/year</td>
<td>10,487 kgCO2e/year</td>
</tr>
<tr>
<td><strong>Cost Effectiveness</strong> (per kg P eq. reduction)</td>
<td>$98</td>
<td>$500</td>
<td>$1650</td>
</tr>
<tr>
<td><strong>Implementation Feasibility</strong></td>
<td>High</td>
<td>Low</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

### Proposed Solution

The bioretention basin candidate solution performs best in almost all criteria (see Table 4). Permeable pavement outperforms bioretention in TSS and copper treatment rates, but has considerably poor performance in GHG emissions and cost effectiveness. Of all criteria considered, runoff volume reduction and peak flowrate reduction are the most directly related to minimizing CSO volumes. Bioretention basins had the highest observed runoff volume and peak flowrate reductions. Additionally, the net GHG emissions and cost effectiveness of bioretention basins yield the best results. Lastly, implementation feasibility is ranked the highest, because the bioretention systems would be installed, in majority, on city-owned land. This allows the water department to strategically place basins where conditions are ideal to meet objective(s). Moreover, it bypasses the need to establish incentivizing programs to gain private-sector participation.

While these candidate solutions may complement each other in certain settings, this analysis finds that bioretention basins are the best option for wide-spread application. Thus, it is concluded that the design team should focus on bioretention basins in order to minimize CSO volumes. Moving forward, an evaluation of the urban watershed will need to be performed. Bioretention designs should be developed based on the evaluation. For example, if the underlying soil allows for infiltration and the groundwater table is shallow, the bioretention system may not need an underdrain.
Major Design and Implementation Challenges

Wide-spread implementation of bioretention basins will require a detailed evaluation of the urban watershed. Phillips and Buchanan (2011) completed such an evaluation for the City of Seattle. The main objective was to implement wide-spread green infrastructure in order to control CSOs. The authors performed geographic information system (GIS) analyses to ultimately determine the most suitable subbasin to install rain gardens. They also calculated the total area of rain gardens needed in order to control CSOs via Microsoft Excel worksheets that utilized various models (pp. 1471-1473). The extensive evaluation requires large amounts of data (e.g., topography, hydrology, soil type, land use, surface perviousness). Much of the data is publically available, but some criteria data might need to be collected via surveying. Fortunately, like Phillips and Buchanan (2011), resources that inform evaluation and analysis methods have become more accessible as green infrastructure grows in popularity. These resources will guide the planning process. Although surveying will require time and resources, the data collection will ultimately ensure the bioretention basins are installed in optimal locations.

Another implementation challenge for this project is ensuring compliance with the CSO Control Policy. The U.S. EPA encourages the incorporation of green infrastructure in CSO Long Term Control Plans (U.S. EPA, 2014). However, Roy-Poirier, Champagne, and Filion (2010) state that some regulations do not allow bioretention to be a “stand-alone” management practice (p. 885). As a result, redundant conventional components are added to meet “established design guidelines” due to the outdated legislation and lack of knowledge on bioretention systems (p. 885). It will be important to balance implementation scope with total compliance of regulations within the political framework.

In addition to balancing scope and compliance, the bioretention basins should be monitored regularly to ensure their success. Monitoring flowrates and volumes, treatment rates, and storage amounts will present opportunities to improve designs. For example, through monitoring, Lucas and Sample (2015) found bioretention systems that had outflow controls—such as raising the outlet to increase storage capacity and adding openings to decrease flows—were better at minimizing CSO volumes than those without controls. The study states,

The Green-Free SCM\(^5\) discharges at rates that are twice the exceedance rate, while the Green-Control SCM takes more time to fill up to its higher outlet, resulting in a dip after the peak...This results in a 45% reduction in CSO volume, even in a large event. (p. 9)

This presents a design challenge; the bioretention basins should be designed with the capability to monitor them easily and, ideally, remotely. While incorporating remote sensors would increase upfront costs, less employee hours would be spent monitoring the basins at the physical site, and the demand for more CSO control measures would decrease due to improved bioretention performance. Figure 10 displays the automatic monitoring equipment used by Lucke and Nichols (2015) for bioretention testing.

In their review, Roy-Poirier et al. (2010) describe some implementation and design challenges for bioretention systems. Poor construction practices is a notable concern that decreases the performance of bioretention systems. Roy-Poirier et al. (2010) attribute this challenge to “most contractors being unfamiliar with bioretention construction, which has led to improper soil mixture selection or placement and poor vegetation establishment” (p. 884). This is an obstacle that should be addressed closely by the design team, as Roy-Poirier et al. (2010) state these choices can be the difference between 92.0% and 40.2% average stormwater volume retention (p. 884). The design must incorporate the appropriate soil mixture ratio of compost, sand, and topsoil.

\(^5\) Here, SCM stands for stormwater control measure. Green-Free refers to bioretention basins without outflow controls, and Green-Control refers to bioretention basins with outflow controls.
Lastly, a challenge may arise in maintaining the bioretention systems. While the water department and City can assess systems on public land relatively easily, any systems on private land will require the owner to perform maintenance. This project will focus on public land in its beginning phases due to this challenge. However, it will be important to address this concern with educational outreach efforts in the future. Moreover, the bioretention basins should be designed so that they are easy to maintain.

**Implications of Project Success**

Wide-spread infiltration can elevate the groundwater table and present concerns of basement flooding and adverse effects on waterways. Maimone, O’Rourke, Knighton, and Thomas (2011) studied this effect and found the groundwater table could raise temporarily by 1 meter after significant wet weather events. Their models also showed that the groundwater table could eventually raise by 1.5 meters permanently due to wide-spread infiltrating green infrastructure (p. 2). Maimone et al. (2011) state that these implications could be managed by “avoiding infiltration in areas of shallow groundwater, and by keeping infiltration trenches more than 3 m from nearby buildings” (p. 11). These are important considerations that should be taken into account by the design and planning team.

There are also many positive implications of a successful project. Wide-spread bioretention implementation would improve the current hydrology, reducing both peak flowrates and volumes (James & Dymond, 2011). In a successful project, such hydrologic improvements would minimize CSO volumes and ensure regulatory compliance, as well as reduce stresses on the CSS and treatment plants. Reducing stresses on sewer mains, for example, would prolong the lifespan and decrease replacements costs. Similarly, costs to update the treatment plants would be avoided. Furthermore, the need for downstream, conventional infrastructure would be reduced, resulting in more cost savings. As found by Wang et al. (2013), the cost effectiveness of bioretention was at $98 per kg P eq. reduction, the best of all CSO control methods considered. Wang et al. (2013) adds, “for comparison, the operational cost of
removing 1 kg of phosphorus at a [wastewater treatment plant] WWTP is \( \sim 420 \) US $ on average and $2000–3000 when the capital costs are taken into account” (p. 11195). That equates to at least $322 savings per kg P eq. reduction when bioretention is utilized. These various forms of saving will become even more evident as precipitation frequency and intensity increases due to climate change.

In addition to the cost savings, the water department would establish a reputation of innovation and leadership. The department and the City would serve as examples for other cities looking to improve the sustainability and effectiveness of their current stormwater networks.

Another implication of success would be the addition of jobs in sustainability to the local economy. Many positions would be introduced to plan, implement, and maintain a sustainable and successful distribution of bioretention basins. This would contribute value to the local economy and overall quality of living in the City. To balance costs, these new positions could be filled by training existing employees as well as hiring new talent.

A successful project would yield more than just hydrological improvements. Mullaney, Lucke, and Trueman (2015) cite several environmental, social, and economic benefits of bioretention basins (pp. 158-159). Bioretention trees remove air pollutants, mitigate traffic noise, provide shade, improve biodiversity, and abate the urban heat island effect via evaporative cooling (p. 158). Urban green space also “promotes contact between community residents, encourages physical activity, [and] reduces stress” (Mullaney et al., 2015, p. 159). Several studies show urban areas with more vegetation have lower crime rates, as cited by Mullaney et al. (2015). The additional economic benefits of bioretention trees are often overlooked, such as reduced costs of heating and cooling and a consumer’s preference to spend more and shop at stores with street-side trees (p. 159).
Glossary

**Floatable debris**⁶ – refers to any foreign material that remains suspended in water, including plastic, aluminum, paper, and wood products

**Geographic information system**⁷ – a computer-based tool that allows spatial data to be analyzed, stored, manipulated, and visualized, often on generated maps

**Green infrastructure**⁸ – “refers to engineered infrastructure at a smaller scale in relation to green stormwater management practices...[that] make use of soils and vegetation, in combination with other decentralized storage and infiltration approaches...to infiltrate, evaporate, capture, and reuse stormwater”

**Life cycle assessment**⁹ – “a systems analysis method that has been used in recent years to support water management (supply, distribution, and treatment) decisions within municipalities and regions...and for analyzing industrial uses by different economic sectors, including direct and indirect supply chain uses”

**Peak flowrate**¹⁰ – the instantaneous maximum rate of combined sewage entering the CSS

**Potable water** – water that is treated and improved in quality to be used for drinking and cooking purposes

**Retention** – refers to temporary storage of stormwater which eventually infiltrates or evaporates without entering the CSS

**Sanitary sewage**¹¹ – sewage that consists of human excrement and waste from residents and businesses, and does not include stormwater

**Separate sewer system**¹² – a drainage system that conveys sanitary sewage and stormwater in separate piping structures and sewers

**Stress**¹³ – refers to the mechanical quantity that expresses loading in terms of force applied over cross sectional area

**Total suspended solids**¹⁴ – inorganic and organic solid materials that remain suspended in water

**Urban watershed**¹⁵ – refers to a watershed, an area of land where all water drains to the same destination, located in highly-developed areas that no longer have many natural tributaries

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⁶ [http://water.epa.gov/type/oceb/marinedebris/floatingdebris_index.cfm](http://water.epa.gov/type/oceb/marinedebris/floatingdebris_index.cfm)
⁷ [https://en.wikipedia.org/wiki/Geographic_information_system](https://en.wikipedia.org/wiki/Geographic_information_system)
¹⁰ [http://encyclopedia2.thefreedictionary.com/separate+sewage+system](http://encyclopedia2.thefreedictionary.com/separate+sewage+system)
¹² [https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/StressStrain.htm](https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/StressStrain.htm)
¹³ [https://www.ndhealth.gov/WQ/SW/Z6_WQ_Standards/WQ_TSS.htm](https://www.ndhealth.gov/WQ/SW/Z6_WQ_Standards/WQ_TSS.htm)
¹⁴ [http://www.indiancreekwp.org/watershed.html](http://www.indiancreekwp.org/watershed.html)
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