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COMPARING GREEN AND GREY INFRASTRUCTURE USING LIFE CYCLE COST AND ENVIRONMENTAL IMPACT: A RAIN GARDEN CASE STUDY IN CINCINNATI, OH[1]

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ABSTRACT: Green infrastructure (GI) is quickly gaining ground as a less costly, greener alternative to traditional methods of stormwater management. One popular form of GI is the use of rain gardens to capture and treat stormwater. We used life cycle assessment (LCA) to compare environmental impacts of residential rain gardens constructed in the Shepherd's Creek watershed of Cincinnati, Ohio to those from a typical detain and treat system. LCA is an internationally standardized framework for analyzing the potential environmental performance of a product or service by including all stages in its life cycle, including material extraction, manufacturing, use, and disposal. Complementary to the life cycle environmental impact assessment, the life cycle costing approach was adopted to compare the equivalent annual costs of each of these systems. These analyses were supplemented by modeling alternative scenarios to capture the variability in implementing a GI strategy. Our LCA models suggest rain garden costs and impacts are determined by labor requirement; the traditional alternative's impacts are determined largely by the efficiency of wastewater treatment, while costs are determined by the expense of tunnel construction. Gardens were found to be the favorable option, both financially (~42% cost reduction) and environmentally (62-98% impact reduction). Wastewater utilities may find significant life cycle cost and environmental impact reductions in implementing a rain garden plan.

(KEY TERMS: watershed management; stormwater management; sustainable technology; rain garden; best management practices; life cycle assessment; life cycle costing.)

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INTRODUCTION

Current Infrastructure and Combined Sewer Overflows

In combined sewers, stormwater and raw sewage are mixed in the sewers and transported to a wastewater treatment plant together. Many current combined sewer systems are improperly sized for their treatment volume and overflow frequently (USEPA, 2004). In such a system, excess wastewater is frequently stored underground in tunnels to avoid unpleasant smells and potential contamination. When a combined sewer system reaches its containment capacity and overflows, such as during heavy storms, the excess sewage is dumped untreated into nearby

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water bodies as a combined sewer overflow (CSO). CSO events, according to the USEPA (2004) report to congress, can have a variety of detrimental effects on both ecological and human health. These range from aquatic life die-off to increased gastrointestinal infection among those who use the polluted water bodies for recreation (e.g., fishing, swimming, etc.), to damaging sewer backups in residential and commercial properties. According to the Wet Weather Quality Act of 2000 (WWQA, 2000), annual cleanup costs for sewer backups range between \$305 million and \$654 million in 1999 dollars. Dorfman *et al.* (2004) suggests the detrimental effects of the United States (U.S.) combined sewer systems are underappreciated and only getting worse. To combat CSOs, the EPA has updated the clean water act (WWQA, 2000) and mandated that municipal districts must correct their CSO violations (USEPA, 1994).

As summarized in Narayanan and Pitt (2006), however, storage is only one part of the greater stormwater infrastructure system that comes at great expense. Stormwater infrastructure requires large amounts of metal and concrete, both of which are environmentally taxing to produce (Flower and Sanjayan, 2007). In addition, excess stormwater requires large amounts of energy to treat. Wastewater treatment is relatively cheap per unit, but in metropolitan volume the costs and impacts can add up; the USEPA estimates that three to four percent of U.S. energy use is devoted to drinking water and wastewater systems (USEPA, 2014b). EPRI (2013) states that electricity usage for wastewater treatment will continue to increase due to population increase. With stormwater being removed rather than allowed to infiltrate, groundwater is more easily depleted (Arnold and Gibbons, 1996).

Cincinnati, Ohio has formally agreed to eliminate 85% of its CSO volume in order to better comply with the Clean Water Act. As part of the planning process to comply with the Clean Water Act, a large wastewater storage tunnel was proposed for the Lick Run area. This tunnel was estimated to cost roughly \$250,000,000 and have a capacity of roughly 40,000,000 gallons (MSD Cincinnati, 2012). It would have been constructed deep underground in the bedrock beneath the city, connected to existing sewers by dropshafts for transporting water and personnel, and include a pump station and wastewater plant upgrades to facilitate the treatment of its volume. This proposition has been rejected in favor of a plan that includes a type of green infrastructure (GI) called rain gardens. Green infrastructure uses vegetation, soils, and natural processes to infiltrate and evapotranspirate rainwater, as opposed to the engineered collection systems of traditional "grey" infrastructure that capture, treat, and discharge it (USEPA, 2014c).

Alternative Stormwater Management

The specific use of rain gardens as an alternative to traditional stormwater infrastructure in residential development may have gotten its start in 1990. As detailed in PGC (1999), a large residential development called Sommerset in Prince George's County Maryland used rain gardens on each property to control runoff levels as an alternative to constructing stormwater ponds and traditional stormwater conveyance. Today, a number of major U.S. cities including Portland, Oregon; Philadelphia, Pennsylvania; and Chicago, Illinois have begun to incorporate GI into long-term CSO control plans. Many other U.S. cities have made commitments or are exploring the use of GI (De Sousa *et al.*, 2012; Houdeshel *et al.*, 2012). Therefore, there is great interest in the potential of GI as an alternative to traditional stormwater collection and treatment infrastructure.

Pros and Cons of Green Infrastructure

When assessed from a "triple bottom line" perspective, one that assesses social and environmental benefits in addition to the financial, GI is shown to have significant additional benefits (Wolf, 2003; Neukrug and Camp, 2009; Wise *et al.*, 2010). GI can complement or replace existing infrastructure, improving functionality or reducing costs (Bedan and Clausen, 2009; Wadzuk *et al.*, 2010; Opperman *et al.*, 2011; Steffen *et al.*, 2013). GI primarily benefits the environment by eliminating the need for traditional grey infrastructure and its associated environmental impacts. Green infrastructure can promote improved air and water quality (Nowak *et al.*, 2006; CWP, 2007). GI has the potential to sequester atmospheric carbon, remove atmospheric pollutants, and reduce the urban heat island effect to save energy and money in cooling costs (Odefey *et al.*, 2012). GI can restore natural hydrology, recharge groundwater, eliminate CSO contributions, and slow the flow of stormwater to streams to restore stream health (Dietz, 2007; Davis, 2008; Stephens *et al.*, 2012). Tzoulas *et al.* (2007) suggests there are considerable social benefits to the urban green space that accompanies GI.

On the other hand, GI can require large amounts of space, which is at a premium in many metropolitan areas. GI may not solve the problems associated with urban sprawl, but instead mitigate a portion of them (Jacob and Lopez, 2009). Infiltrative GI is unsuitable for use in areas with low soil permeability unless soil remediation is used (USEPA, 2011). Olson *et al.* (2013) found that soil tillage resulted in only a small average improvement in soil infiltration while tillage with compost amendment was shown to be more effective. GI needs specific conditions, in both local development and local soil conditions, to drain at an appropriate rate (Brander *et al.*, 2004). GI is better suited for small, frequent rainfall events and is impractical for flood control in large rain events (Holman-Dodds *et al.*, 2003; Dussaillant *et al.*, 2004; Hood *et al.*, 2007). GI may have difficulty filtering certain pollutants, potentially leading to groundwater contamination by salts, pathogens, nitrate-nitrogen, and/or phosphorous (Dietz and Clausen, 2005, 2006; Dietz, 2007; Weiss *et al.*, 2008; Davis *et al.*, 2009). GI requires careful planning, implementation, and maintenance to be effective (Brown and Hunt, 2012), and sometimes legal barriers to implementation can be problematic (Morzaria-Luna *et al.*, 2004).

Cost of Rain Gardens

According to a report by the American Society of Landscape Architects (Odefey *et al.*, 2012), GI solutions can be less costly to implement than their grey counterparts. GI has been found to be less costly to implement than grey infrastructure in several cases (Narayanan and Pitt, 2006; CRWD, 2012; USEPA, 2013a), and can offer the best stormwater management per dollar for GI (CRWD, 2012). Yet, reported installation and maintenance costs have high variability (Montalto *et al.*, 2007; Flynn, 2011; CRWD, 2012). Narayanan and Pitt (2006) compiled the total installation and maintenance costs of both traditional and green stormwater infrastructure from a variety of sources and found that GI has significant potential to reduce stormwater control costs when implemented as part of a larger plan. In the capitol region of Minnesota, CRWD (2012) installed various GI systems, including rain gardens, in place of a stormwater storage pipe; the project saved 20% in installation costs over the projected grey infrastructure strategy. The rain gardens stored roughly one cubic foot for every \$8 spent in installation and were projected to cost roughly \$0.04 per cubic foot of stormwater removed over a projected 35-year life. PGC (1999) found, in a Maryland pilot study, that rain gardens achieved stormwater reduction results similar to planned stormwater detention ponds for one quarter of the price; these price reductions were achieved by externalizing maintenance costs to homeowners, who are required to maintain the gardens. Rain garden maintenance suggestions range from an hour per year for debris removal (Flynn, 2011) to frequent, multi-hour maintenance (CRWD, 2012). Asleson *et al.* (2009) suggests periodically inspecting rain gardens for vegetation and infiltration after several rain gardens were found to be nonfunctional, presumably due to inadequate maintenance or construction; they suggest methods for inspection in Nestingen *et al.* (2007). GI installation may be much less costly when performed as part of an existing landscaping project rather than as a retrofit.

With rain gardens, soil media longevity is a concern. Once the infiltration media is clogged by filtered solids, the media will need to be either replaced or amended. Estimates of media longevity can vary considerably. Morgan *et al.* (2010) estimated the ability of a typical rain garden to adsorb zinc, copper, and cadmium would not be exhausted for centuries and is easy to rejuvenate. Jenkins *et al.* (2010) found that sediment accumulation had no significant impact on soil infiltration, at least in the first decade. Komlos and Traver (2012) suggest that soil may eventually become saturated with phosphorous after >20 years, which may limit effective life span or increase maintenance costs depending on the goal of the rain garden and risk to local groundwater. It is also possible that a rain garden will last significantly longer than its projected 35-year life (possibly indefinitely), but a lack of data prevents us from modeling this scenario.

Life Cycle Assessment

Life cycle assessment (LCA) is a an internationally standardized (ISO, 2006) framework for analyzing the potential environmental performance of a product of service including all stages in the life cycle of a product or service of interest including material extraction, manufacturing, use, and disposal. LCA involves defining the goal and scope of the study, collecting the needed data for all life cycle stages and assembling a life cycle inventory (LCI), calculating impacts using life cycle impact assessment methods, iteratively verifying and improving the results, and providing a proper interpretation. LCA is particularly valuable for comparing various alternative product or service systems that provide the same function. For a more in-depth summary of the background and methodology of LCA, see Life Cycle Assessment: Principles and Practice (Scientific Applications International Corporation and Curran, 2006). Life cycle costing (LCC) is a framework for life cycle evaluation of costs that may be used alongside or independently from LCA (Swarr *et al.*, 2011). The steps involved in LCC are similar to LCA but do not include an impact assessment phase.

Life Cycle Assessment of Green Infrastructure

Recent LCA and LCC studies have shown that alternatives to traditional water management, such as rainwater harvesting systems (Hallmann *et al.*, 2003; Schulz *et al.*, 2012; USEPA, 2013b), can provide life cycle benefits over traditional infrastructure, but only when designs are optimized to minimize impacts associated with new alternative components (Angrill *et al.*, 2012; Ghimire *et al.*, 2012, 2014). Rain gardens have been found to have lower pollutant emissions than conventional systems in LCAs. Flynn (2011) performed an LCA of a rain garden built at Villanova University. They concluded the project would result in large decreases in pollutant load over its lifetime (as opposed to standard wastewater treatment), but the project would cost more than $75,000 for each acre of impervious area serviced. Furthermore, the garden did not eliminate the need for standard grey stormwater infrastructure because it contained an underdrain which fed directly to the sewer. Andrew and Vesely (2008) compared a rain garden and a sand buffer strip and found the rain garden resulted in 30% less carbon emissions over its life cycle, with potential for greater reductions in future projects due to the unexpectedly high performance of the garden. De Sousa *et al.* (2012) found that a rain garden system emitted only 5% of the carbon dioxide of an equivalent detain-and-treat (typical combined sewer) system. Wang *et al.* (2013) modeled a comparison of hypothetical grey and GI, including rain gardens, and found that rain gardens outperformed other GI options; unfortunately, they did not include grey storage or CSO prevention in their assessment and based life cycle inventories on set standards rather than actual gardens. Rain garden emissions may be offset by the sequestration of carbon dioxide and the filtration of air pollutants by the gardens' plant life (Flynn, 2011). With such a small and highly varied sample set of rain garden LCA studies, further research is needed to better characterize gardens and help to weed out variations that can be caused by specific sites and specific projects.

Shepherd Creek Summary

The rain gardens used in this study were constructed as part of the Shepherd Creek Rain Garden project in Cincinnati, Ohio (TetraTech, 2007; Mayer *et al.*, 2012; Shuster *et al.*, 2013); a cross section of the gardens can be found in Appendix A. Roy and Shuster (2009) found that 13.1% of the Shepherd Creek catchment was impervious or semi-impervious surface, with 56.3% of that directly connected to local streams for stormwater removal. Eighty-one rain gardens were installed on residential properties in the Shepherd Creek watershed in 2007; 58 gardens contained underdrains while 23 did not. The gardens were constructed with the consent of homeowners who had bid in a reverse auction to have them installed. When possible, rain gardens were placed in optimal locations to receive stormwater runoff. Roughly, 10% of rain gardens were connected directly to one of the home's downspouts through a rain barrel's overflow. None of the rain gardens was reported to overflow, including those connected to the downspouts; the gardens were designed with the intention of adequately storing a two-inch runoff event from their tributary area. For the purpose of this assessment, only rain gardens without an underdrain were considered; due to the lack of flow monitoring equipment, the infiltration rates of gardens with underdrains cannot be estimated, while drainless gardens can be assumed to infiltrate or evapotranspirate all the water they capture. As estimated by the contractors, these gardens averaged 4.28 m^3 in storage capacity and drained an average of 475 square feet of roof area, plus lawn runoff. For a partial summary of the Shepherd Creek rain garden project, see Shuster *et al.* (2007).

The novelty of this study stems from the detail, quality, and sample size of our construction and maintenance data and because of the gardens' low-impact design. Despite the low permeability, clay-rich soils of the Cincinnati area, these gardens had their fill media amended rather than replaced. By using native soil and local materials, the developers hoped to limit both the environmental and the financial cost of the gardens. In addition, because of the large sample size of our project, we can reduce variance and make a more accurate estimate of the cost of rain gardens as implemented on larger scales. Our study is in contrast to the previously cited studies, which examined either modeled (Andrew and Vesely, 2008; Flynn, 2011; De Sousa *et al.*, 2012; Wang *et al.*, 2013) or single (Andrew and Vesely, 2008; Flynn, 2011) gardens.

Research Objectives

The objective of this research is to assess the costs and benefits of the Shepherd Creek rain gardens, both economically and environmentally, using LCA and LCC. We seek to compare these gardens to a grey default plan set forth by the EPA and ultimately rejected by the Cincinnati municipal sewer department (MSD Cincinnati, 2012); this plan consisted of building a large wastewater storage tunnel to capture CSO outfall. We believe that this case study may serve as a representative example by which to compare future stormwater management options from an LCA perspective.

METHODOLOGY

Goal and Scope Definition

The goal of this study is to compare the life cycle environmental impacts and life cycle costs of stormwater management using the Shepherd Creek rain gardens to the existing combined sewer and wastewater treatment systems (grey infrastructure). The intention of this comparison is to provide insight that communities may find useful in designing and implementing their own stormwater management projects more sustainably. The scope of the comparison is cradle-to-grave analysis of the costs and benefits of our constructed residential rain gardens. Figure 1 illustrates the two systems. All aspects of the two systems, from material production, to transportation, to construction, to operation and maintenance, to decommissioning and disposal, have been considered and included in the inventory.

The functional unit used for the study is the detention and treatment capacity of a single Shepherd Creek rain garden. Under normal conditions, an average representative of these gardens is estimated to detain 4.28 m^3 of water at a time and treat 1,650 m^3 of water over its expected lifetime of 35 years. Breaking down the garden function like this allows for direct comparisons between rain gardens and the existing infrastructure practices that can be translated to the municipal stormwater systems of other regions. This approach also allows the model to be tailored to the expected performance of new rain gardens constructed using similar specifications and to be compared to a variety of rainwater management options.

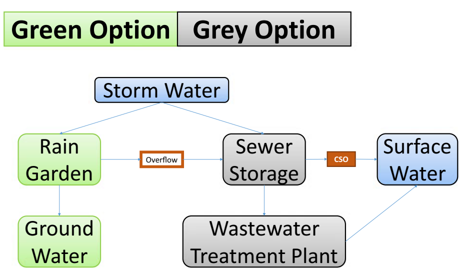


FIGURE 1. Comparison of Stormwater Flows in Grey and Green Infrastructure.

Life Cycle Inventory

For simplicity and accessibility of data, the rain garden life cycle was broken down into three phases: construction, operation, and decommissioning. Values used in this assessment can be found in Table 1.

Construction data were collected from contractor invoices and reports from Shepherd Creek rain garden construction in 2006-2011. Inventories were obtained from construction materials, construction equipment, and labor hours reported. Since transportation records were not kept by the contractor, we used average distances between the project sites and contractor offices. We assume that constructing a single rain garden requires a single round trip from the nearest contractor office to the site by a work van or work truck towing a small excavator machine. After initial construction, landscapers must return to the garden three times per year over three years to establish the plant life. For transportation distance from material "source" (mine, quarry, factory, plant) to contractor, materials were assumed to come from the nearest production facility of those materials according to Google Maps (Google and Sanborn, 2014). We acknowledge that this may not be a realistic assumption, as materials may be purchased from a larger distributor, which ships longer distances. Water usage was not recorded by the contractors and

TABLE 1. Inventory Flows Modeled per Rain Garden.

Life Cycle Stage	Inventory Flow	Value	References/Notes
Installation	Compost, at plant	186 kg	Contractor records
	Excavation, skid-steer loader	18.12 m^3	Contractor records
	Sand, at mine	315 kg	Contractor records
	Transportation (van)	102.4 v × km[a]	Identified with Google map, process edited to reflect road wear
	Transportation (lorry)	20.759 kg × km	Identified with Google map, assumed nearest source
	Seedlings, at greenhouse	56 items	Contractor records, USLCI process
	Extrusion, plastic pipes	5 kg	Contractor records
	Tap water, at user	100 kg	Estimation
Operation	Carbon sequestration	132.8 kg	Cameron *et al.* (2012)
	Transportation (van)	5 v × km	Identified with Google map, process edited to reflect road wear, assumed 5 km/visit round trip
Decommissioning	Excavation	4.53 m^3	Contractor records, ½ of garden volume
	Transport (van)	5 v × km	Identified with Google map, process edited to reflect road wear

[a]Vehicle kilometers, a standard LCA unit for passenger travel.

is conservatively estimated, but due to the low impacts of expected water use in comparison to recorded travel and construction this is assumed to be insignificant.

The Shepherd Creek rain gardens require no maintenance other than periodic weeding and cleaning once established. This maintenance is provided by the homeowners who own the gardens. This no maintenance option assumes both that a property owner will be able to maintain the garden after establishment at minimal cost or the difference between maintaining the garden and maintaining alternative landscaping will be insignificant. Thus, the no maintenance option assumes no cost and no LCA input.

Personnel transportation distances for maintenance were assumed to be five kilometers round trip. This assumes that multiple gardens can be reached and maintained in one workday. This transportation distance may decrease with denser rain garden implementation in the city and vice versa. The vehicle is assumed a standard transport van capable of carrying passengers and towing light equipment.

Rain gardens, like domestic gardens, may have the ability to sequester carbon in the soil. In order to estimate carbon sequestration, we use data from Cameron *et al.* (2012). We believe these are a useful, if conservative, approximation of the Shepherd Creek gardens. Since we are unable to determine soil carbon loss due to disturbance of the soil during garden installation and decommissioning, we assume no carbon loss in these processes.

Because rain gardens are a relatively recent technique, their end-of-life is not well studied and literature on their decommissioning is limited. For this assessment, we assume the gardens will be buried by collapsing the berms into the depression and flattening the area. We have included an alternative scenario in which the garden media are instead excavated, disposed of in a landfill, and replaced.

Results from the LCA and LCC of the Shepherd Creek rain gardens were compared to the grey alternative. Since the rain garden is multifunctional, both detaining and treating rainwater, these two functions were assessed with grey infrastructure systems. An underground deep storage tunnel detains the wastewater, then moves it along to a local treatment plant and releases it back into the urban water cycle. Life cycle inventory flows for the grey alternative can be found in Table 2.

The storage tunnel was calculated using a water storage unit process allocated to the size and life span of the rain garden. We assume that, since the type of storage tunnels used by Cincinnati MSD grows one dimensionally (lengthwise), there should be a roughly linear relationship between tunnel capacity and life cycle impacts and costs. The average rain garden was estimated to have a storage capacity of 4.28 m^3 according to contractor reports to the EPA. Since a garden has a capacity of 4.28 m^3, while the water storage unit process has a capacity of 2,500 m^3, we allocated a proportional fraction of the tunnel's outputs as rain garden offsets. Since the rain gardens are estimated to last 35 years on average, while the tunnel is expected to last 70 years (Narayanan and Pitt, 2006), we allocated again for the difference in life span. This assumes that building and operating a large number of gardens for two "generations" is equivalent in storage function to building a single wastewater storage tunnel. There is at least one flaw in this assumption: during the light, frequent rainfall events the gardens are designed to mitigate, the gardens may not use their entire storage capacity. In these cases, rainfall from outside the gardens' tributaries may contribute to a CSO event in severely underperforming combined sewers before the complete capacity of the garden is used; with a storage tunnel, this is less likely to happen, as the full capacity of the tunnel should be used before an overflow is allowed, unless the upstream infrastructure is overflowed before water can reach the storage tunnel.

The wastewater treatment offsets were obtained by estimating the water captured by the gardens over their life spans and calculating the impacts of treating that same amount of water in the local treatment plant. The ecoinvent process "treatment, rainwater mineral oil storage, to wastewater treatment, class 2" was selected because it is the closest representative of rainwater from a residential roof and lawn in the ecoinvent database. This process was created by sampling rainwater from a mineral oil storage facility and inputting its contaminant concentrations into their wastewater treatment models, which are derived from Suter (1996). This process may slightly overestimate contaminants found in the relatively clean (Torno, 1984) rain water, but it is the best analog available. Due to a lack of inflow/outflow monitoring in our gardens, we were forced to estimate the amount of rainwater being

TABLE 2. Grey Infrastructure Inventory Flows Modeled.

Life Cycle Stage	Inventory Flow	Value	References/Notes
Construction	Water storage, 2,500 m^3 (CH)	0.000855168 items	Ecoinvent 2.2
Operation	Treatment, rainwater mineral oil storage, to wastewater treatment, class 2	1,650 m^3	Ecoinvent 2.2

captured by the gardens. To do this, we estimated collected runoff volume by multiplying the average rainfall (42 inches per year for Cincinnati, Ohio) over the area of tributary directly connected to the rain garden; this leaves out possible flow from the much larger unconnected pieces of tributary, but we have no reliable way to estimate this flow.

In summary, our estimates for infiltration by the garden may underestimate the total volume of rainwater removed, but may overestimate the impact of the rainwater offset.

Life Cycle Modeling

The life cycle models were constructed and executed using OpenLCA 1.3.3, an open-source software for LCA (GreenDelta, Müllerstrasse, Germany). OpenLCA was used to model the construction of the rain gardens, the offsets generated by their operational phase, and multiple decommissioning options. Life cycle environmental impacts were calculated in OpenLCA using EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), version 2.1 (Bare, 2011). The life cycle impact categories used included acidification, ecotoxicity, eutrophication, global warming, ozone depletion, photochemical oxidation, carcinogenics, noncarcinogenics, and respiratory effects. The results are expressed in representative indicators for each category such as kg CO_2 equivalent for global warming and mol H^+ equivalents for acidification. To put the impact results in a national context to aid with interpretation, we applied U.S. yearly per capita normalization factors for TRACI from Ryberg *et al.* (2013).

Life Cycle Cost Analysis

To calculate the construction cost of the rain gardens, we averaged the contractor-quoted construction cost to build a rain garden and then added the average cost of follow-up maintenance to establish the plant life. Total labor hours and maintenance expense was variable between gardens. The average fee paid for installation of rain gardens on private property was relatively small in our study because the homeowner's possession of and rights to their property were not altered. We do not have data to properly estimate larger scale implementations on private property.

The Shepherd Creek gardens are maintained by the homeowner and, as such, require very little from the local government after establishment. While homeowner time is not free, we assume their labor to maintain the garden does not have significant market value from an economic perspective and is also offset by the reduction in lawn maintenance required for the garden-occupied space.

Decommissioning is assumed to require only the flattening of the garden by collapsing the berms and removal of a small hose. This is assumed to be completed with the same equipment as construction. Due to the necessity of construction equipment, labor hour costs are calculated using the \$115 estimate of labor including expenses and overhead. Work time is assumed four man-hours due to the relative ease and simplicity of decommissioning the garden. Different estimates of decommissioning costs are less likely to significantly affect present value estimates for the garden because these costs are incurred far off in the future.

Since costs of the construction, maintenance, and decommissioning occur at different times over the life of the rain garden, we computed the net present value (NPV) using appropriate real discount rates of 3, 5, and 7%. NPV gives different weight to costs and revenues incurred in different years through a discounting method, takes into account inflation and opportunity cost to reduce the weight of costs and revenues incurred in the future. The NPV of costs of the gardens was calculated using the following formula:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} + C_0 \tag{1}$$

where: C_t = cost in year t, r = real discount rate, and T = number of time periods

All prices were adjusted to 2013 dollars using the U.S. Bureau of Labor Statistics' Consumer Price Index (USBLS, 2010). Startup construction costs (for assembling, but not establishing, the garden) were determined to be roughly 45% of the average installation cost and were assumed to occur before the first period. The remaining 55% of the construction cost was broken up over the next three years of garden establishment as 35, 15, and 5% of the construction cost for the first, second, and third years, respectively. After that, the cost of maintenance was the only cost for the next 31 years until decommissioning occurred in the final year. This assumes the garden will be operational immediately after assembly and that maintenance costs will be broken up evenly over the garden's life rather than occurring in chunks.

The grey alternative storage tunnel was estimated to cost \$240,000,000 and have a storage capacity of 40,000,000 gallons (MSD Cincinnati, 2012). To compare the cost of this large tunnel to the cost of one small garden, we found the proportional cost per cubic foot for each and then multiplied that by the volume of a single garden. This yields the proportion of storage tunnel volume offset by each garden. While we do not anticipate the construction of single-garden-sized tunnels, we find that a single garden is a useful unit of measurement. Our study assumes that a cubic foot of garden storage volume is equivalent to a cubic foot of tunnel storage volume from a CSO reduction perspective and that the implementation of GI allows for equivalent replacement of grey infrastructure.

We were unable to find suitable estimates of the cost to maintain a storage tunnel, but they are likely to be significant: at least one full-time job equivalent to maintain, likely more, plus significant pumping, fuel, equipment, and repair costs, according to Murphy and Moore (2007). Fortunately, deep storage tunnels carry very little opportunity cost in that they do not occupy land or resources that might be used for other purposes. Our estimate does not include decommissioning costs for the tunnel, a process which could range from filling in the tunnel with construction debris to simply sealing the entrances. It is worth noting, however, that infrastructure such as storage tunnels are frequently used and maintained long after their expected useful lifetime has ended due to the expense of replacing such infrastructure. About 75-year projected estimates of tunnel life may underestimate the period of use. Due to a lack of data, we assume that at the end of the tunnel's 75-year life it will enter a phase of intensive maintenance and repair rather than decommissioning. This phase may be roughly economically equivalent to the first 75 years as modeled, but it is not within the scope of our study. To calculate the cost of wastewater treatment that would be offset by the garden, we took the total volume of water captured by the garden over its lifetime and multiplied that by the average cost per cubic meter of water that is treated by the Cincinnati Municipal Sewer District (MSD) (USEPA, 2014a). This assumes that stormwater has a similar treatment cost to the standard storm/sewage mix treated by the plant. This cost does not reflect the construction or decommissioning costs of the wastewater plant, which we expect to be minimal in comparison to the lifelong operation costs. To calculate the NPV of costs of the grey alternative, we used the same methods as for the green option. We assumed the tunnel would be built in 10 years, with costs spaced out evenly over those years, and the tunnel and wastewater plant would each last 75 years.

There are two equivalent methods to compare projects with different expected life span. The first method is to repeat the projects until the least common multiple number of years is obtained and use the NPV to compare the costs. Such an approach, while intuitive, can be cumbersome if the least common multiple is very large. An alternative method that is equally effective in comparing such projects is to use equivalent annual cost (EAC) where the NPV of costs for each project are computed first, and then these costs are distributed equally over their respective life span of each project using the annuity method. We chose EAC to compare the green and grey options. The EAC can be computed using annuity-due formula as

$$\mathrm{EAC} = \mathrm{NPV}\frac{(1+r)r}{\left(1-(1+r)^{-T}\right)} \tag{2}$$

where: r = the real discount rate and T = the expected life span, in years, of the project.

Thus, EAC averages the discounted costs and revenues of an investment over its life span, yielding an average yearly cost.

Sensitivity Analysis

To analyze the sensitivity of the model, we calculated costs and LCA results using the above methods for a variety of alternative scenarios. These scenarios may be used by decision makers and stakeholders to tailor their own analyses to better suit their own locations and expectations.

For example, it is possible the rain gardens will not function for their full projected life spans. An estimate of 35 years working life may be an optimistic estimate of a garden's functional life. Infiltration media may become clogged, garden surfaces may seal, plants may be destroyed, or property may change hands to a new owner with alternative landscaping ideas. We have included a scenario in which the garden life span is only 20 years instead of 35 years.

To align the high contractor costs encountered during the Shepherd Creek project with what is reported in the literature, we calculated costs of rain garden construction using rates from the literature rather than contractor reports. CRWD (2012) constructed and established several rain gardens of varying size for an average of \$10.88 per cubic foot of storage. We use lower cost to evaluate how more efficient construction methods and costs that are more competitive can affect the cost of GI. It should be noted, however, that this estimate may be unrealistic for small gardens of our scale since the CRWD gardens were all larger than our own. The smallest CRWD garden, at 209 cubic feet, costs approximately \$40 per cubic foot to construct and install. The CRWD gardens were established with the help of a small volunteer group, pushing the cost of labor down.

With the high variability in suggested maintenance shown by the literature, we decided it would be beneficial to examine the effects of different maintenance regimes on the cost structure of a rain garden. To do this, we added two maintenance options, one low, and one high. The low maintenance option is suggested to keep costs manageable, while the high maintenance option is suggested to ensure garden health. For the low maintenance option, we assume that a two-man crew will be required to maintain the garden and that this crew will visit once per year at two man-hours per visit. This visit would clean litter, check infiltration, weed undesirable invasive plants, and replant desirable species. This is the same assumption made by Villanova (Flynn, 2011). Other estimates of required maintenance range up to multiple hours per month (CRWD, 2012). The high maintenance option assumes that contractors will visit three times per year and invest an average of nine total man-hours per year in each garden. While this maintenance regime represents lower labor input than some literature suggests, we believe that this level of effort is plausible for the small size gardens we are analyzing. LCA results are expected to scale linearly with the number of annual visits to the garden.

As an extension of the maintenance assessment, we calculated the cost of the different regimes with three different hourly labor costs: one base, one high, and one low. To calculate these long-term maintenance costs of the gardens, we used the average cost of field labor hours quoted by the contractors and applied it to the expected hours of the maintenance regimes over the lifetime of the garden. This labor input assumes that regular grounds keeping activities such as mowing and cleaning would have and will continue to occur regardless of the presence of the rain garden. The cost of labor is thus the expected additional maintenance that will be required to keep the garden functioning. Contractor quotes for labor were high, at nearly $115 per labor hour, including expenses and overhead. With no expenses or overhead, labor hours cost a more reasonable $67. We used the $67 per hour figure for our base assessment; assuming higher or lower contractor costs could dramatically affect price estimates. Our high estimate uses the $115 figure from our contractor invoices. Our low estimate was drawn from the contractor quotes cited in CRWD (2012) and adjusted for inflation. These methods yield a low estimate of $39.25 per man-hour, a middle estimate of $67 per man-hour, and a high estimate of $115.35 per man-hour.

In the event that our rain gardens cannot be decommissioned by simply collapsing the berms, we have modeled a scenario in which the gardens must be excavated and their media replaced and disposed of. Additions (not replacements) to the demolition LCI are found in Table 3. The role of excavation is greatly increased, as the entire garden must be removed and fill soil must be retrieved, transported, and filled in; this model assumes that fill soil is readily available from other construction projects. The original media must then be transported to a nearby landfill and disposed of. We model this with significantly increased labor and transportation investment and the addition of inert waste disposal to the LCI; ecoinvent data may underestimate possible migration of media contaminants in this scenario. To calculate costs, labor investment was assumed to triple and a local landfill charge was applied.

TABLE 3. Landfill Disposal of Soil Media. Items are to be combined with base garden inventory.

Inventory Flow	Value	References/Notes
Excavation, skid-steer loader	13.59 m^3	Additional 3/2 of garden volume (excavation and replacement)
Disposal (inert waste)	14,400 kg	Approximate weight of garden media
Transportation (lorry)	248.07 t × km[a]	Identified with Google map, assumed nearest landfill and nearest source

[a]Ton-kilometers, a standard LCA unit for goods transport.

In addition to modeling alternative scenarios for the rain gardens, we modeled a few scenarios for the grey alternative as well.

To account for potential price complications present in Cincinnati, such as abnormal contractor rates, legal hurdles, or construction conditions, we remodeled the cost of the storage tunnel with a formula from Narayanan and Pitt (2006). The formula (2) predicts the hard (base construction) costs of wastewater storage tunnel construction based on volume.

We adjusted this equation to reflect inflation in construction costs using ENR Construction cost index values for Cincinnati, Ohio (ENR, 2014). The formula was adjusted again to reflect the proportion of hard cost to total cost estimated by the Cincinnati Metropolitan Sewer District for the proposed storage tunnel (MSD Cincinnati, 2012). We inserted the volume of the proposed Lick Run storage tunnel into this final formula (3) to yield a generic price that may be broadly applied:

$$C = 6.22\mathrm{V}^{.795} \tag{3}$$

$$C = 12.22\mathrm{V}^{.795} \tag{4}$$

$$V = \mathrm{Volume(Mgal)}, C = \mathrm{cost(M\$US)}.$$

In the event that rain gardens underperform or require an underdrain that allows captured water to reach the sewer, we modeled several scenarios in which the projected infiltration rates of the gardens were not met due to water escaping the garden. We modeled 15% escape, 50% escape, and 85% escape. Water is assumed stored in the garden up to 48 h after the start of the runoff event. These scenarios had no effect on the storage portion of the assessment, but they did affect the amount of wastewater treatment that was offset. This has an insignificant effect on cost but a large effect on the LCA output.

Finally, we modeled the effects of a 10% increase in rainfall to account for potential increases in rainfall associated with climate change. We, again, assumed the rain garden would be able to capture the entire additional stormwater load. For this scenario, we increased the stormwater treatment of the grey alternative by 10%. Similar to the underdrain escape scenario, we predict a very small change in monetary cost but a relatively large change in the environmental impact output.

Once all the alternative scenarios were modeled, they were aggregated into a few illustrative groups. We represented the Shepherd Creek gardens as they were intended to function, we represented the rain gardens as they could have been under less costly contractor rates, and we represented both best and worst case scenarios. We compared these scenarios, piece-wise and in aggregate, using standard 5, 7, and 3% discount rates.

RESULTS AND DISCUSSION

A breakdown of garden environmental impacts by contributing process for the Shepherd Creek gardens can be found in Figure 2. The Shepherd Creek gardens need only be installed and eventually decommissioned, as maintenance is assumed to be carried out by the homeowner at insignificant material and monetary cost. More than 90% of environmental impacts and more than 98% financial costs are incurred during the construction phase. A complete table of impacts and discounted costs by life cycle stage for both green and grey infrastructure can be found in Appendix B.

In the base case assessment, the construction phase was the main contributor to financial and environmental impacts. Compost production was the greatest contributor to CO_2 emissions, accounting for 75% of global warming potential. Operation of the transport van and operation of the skid-steer loader contributed the next largest proportions of the CO_2 emissions. These three processes, in the same order, contributed the greatest amounts of PM2.5 emissions and SO_2 emissions. Operation of the van and skid-steer loader was the greatest contributors to all other measured impact categories, likely due to the burning of diesel fuel in their engines. Our model indicates that 60% of CO_2 emissions are offset by carbon sequestration by garden plant life.

Installation was the most expensive part of the garden's life cycle primarily because of the high investment in labor hours and equipment use. Materials, such as sand, compost, and seedlings, were only a small part of the garden construction cost. Across projects, construction costs could fluctuate. Other cities are likely to see different contractor costs. As GI becomes more common, prices may decrease due to increased experience and more competition among contractors.

Decommissioning the rain garden required only the transportation of the skid-steer loader by transport van and the operation of the loader on-site. The burning of diesel fuel was again the greatest contributor to environmental impacts, but in contrast to the installation phase the skid-steer loader contributed more to the emissions than the transport van. Decommissioning of a rain garden, according to our proposed methods and estimates, should be a relatively quick and inexpensive

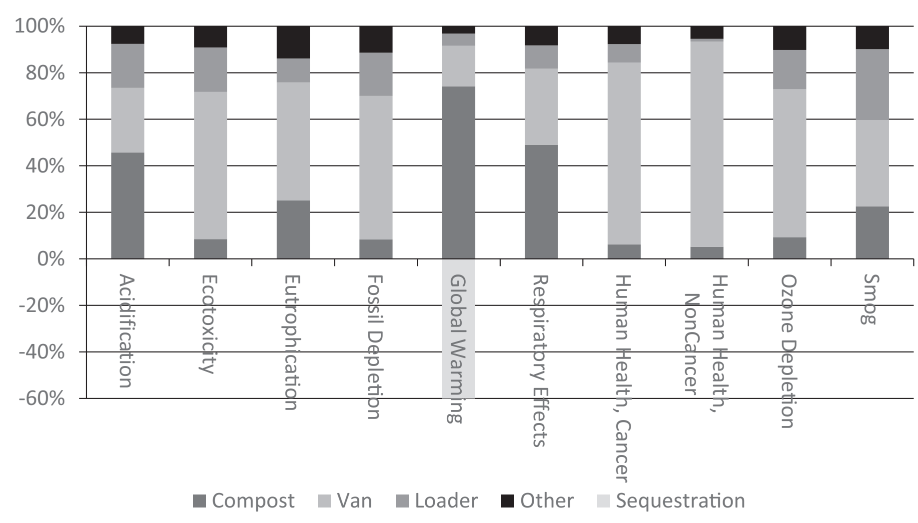


FIGURE 2. Breakdown of Proportional Garden Environmental Impacts by Process.

task, contributing very little overall to the gardens' cost, especially after discounting.

A comparison of the impact outputs and financial costs between deep storage tunnel and wastewater treatment offsets from the rain garden can be found in Figure 3.

Electricity use by the treatment plant was the greatest single source of impacts in the grey alternative. The plant discharged significant amount of nitrogen equivalents, likely due to unfiltered nutrient pollution in the wastewater; this nutrient discharge would likely be much less if the model properly represented stormwater rather than combined stormwater and sewage. Construction of the storage tunnel contributed environmental impacts primarily due to the manufacture and disposal of concrete and steel, but diesel burned in machinery was a significant contributor in many areas (especially smog formation). Construction of the tunnel consumed 98.5% of the funds devoted to grey infrastructure.

To put these values in perspective, impacts per functional unit (1,650 m^3 of water treated and 4.275 m^3 water storage capacity) were normalized against the U.S. average yearly impact per capita in each category. Normalized impacts can be found in Figure 4, below. The greatest normalized improvement can be seen in ecotoxicity impacts, followed by eutrophication. One garden offsets roughly 60 and 34%, respectively, of an average U.S. citizen's yearly ecotoxicity and eutrophication impacts. Although wastewater treatment plants allow large amounts of nutrient pollution into receiving waters, rain gardens detain nutrients and store them on site or potentially leach them into the ground. Energy savings of

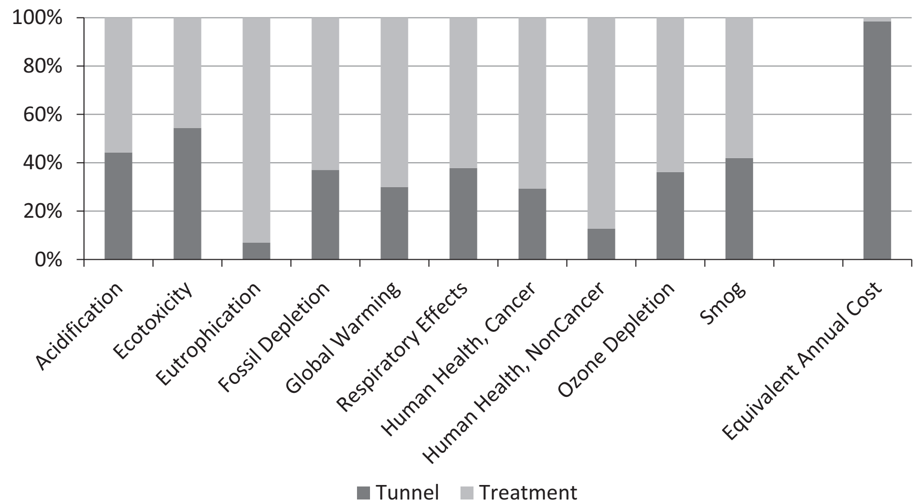


FIGURE 3. Breakdown of Proportional Grey Infrastructure Impacts and Costs by Component.

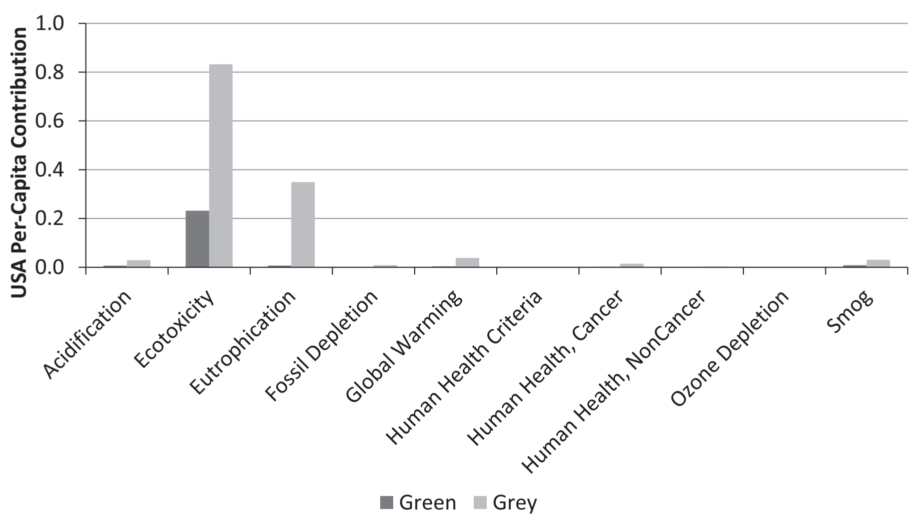


FIGURE 4. Normalized Values for the Environmental Impacts of the Shepherd Creek Rain Gardens and Their Grey Offsets. Results are normalized by average per capita impacts in the United States for each category.

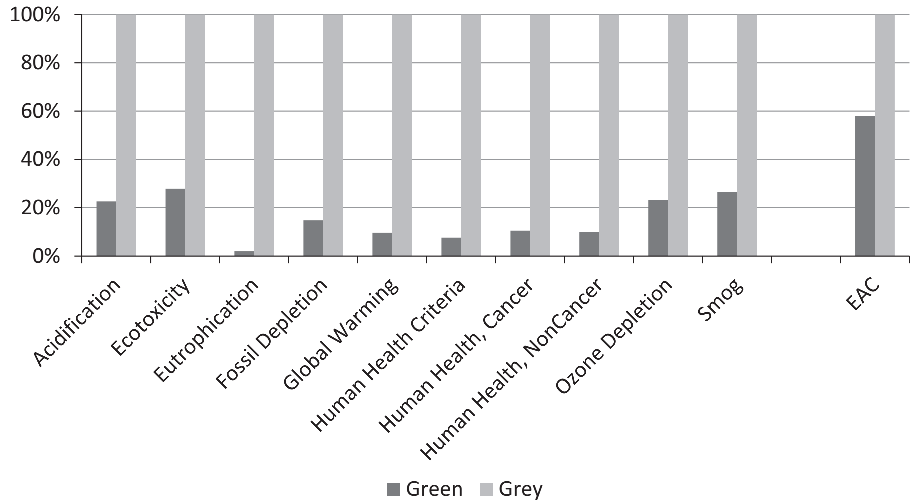


FIGURE 5. Comparison of Cost and Impacts between Gardens and Their Grey Counterparts. Results are expressed relative to the highest impact option (green or grey) for each impact category, which is assigned 100%.

reduced treatment lead to not insignificant benefits to acidification, global warming, and smog. This suggests that eutrophication and ecotoxicity benefits should be the focal point of our impact assessment, with consideration given to acidification, global warming, and smog.

Figure 5 compares the impacts of the Shepherd Creek rain gardens to their grey counterparts. The stormwater storage tunnel and the wastewater treatment plant together emitted more environmental impacts in every category than the base case rain garden. Choosing the green alternative offered important reductions in the eutrophication and global warming categories, which saw 98 and 90% reductions, respectively, according to our model.

Sensitivity Analysis

To supplement the assessment, results for a variety of alternative scenarios are presented to capture the variability and uncertainty inherent in choosing GI. A master list of scenarios analyzed, as well as representative aggregates of these scenarios, can be found in Appendix C.

A summary of cost differences under different discount rates, which affect the value of costs and revenues in the future and past, can be found in Table 4. The rate of discounting had a greater effect on the EAC of the grey infrastructure alternative than it did on the rain gardens. Because a deep tunnel is a long construction project, and because benefits of the tunnel are only reaped after completion, a high discount rate greatly inflates price. Because wastewater treatment, according to our data, is extremely cheap per unit of volume, discount rates have little effect on long-term costs. Rain gardens, without maintenance, are more frontloaded in cost and reap benefits immediately, so the effects of discount rate on them are minimal. With maintenance included, higher contractor rates and more frequent visits affect rain garden price less at higher discount rates. At low discount rates, the financial gap between rain gardens and storage tunnels narrows, with grey infrastructure being less costly than a garden with standard maintenance. If the environmental impacts can be assigned a monetary value, however, then it is possible that this disparity will narrow, as wastewater treatment was shown to be the source of most environmental impacts and may increase the effective long-term costs of the grey infrastructure option.

Using the generic tunnel formula yielded a lower price estimate for the construction of an underground storage tunnel than the specific estimate for Cincinnati. This may imply that Cincinnati has unfavorable conditions for tunnel construction. It implies that a tunnel may be less costly than a rain garden system in some areas, as the formula's yielded EAC was very close to the EAC of a Shepherd Creek garden with contractor maintenance included, as seen in Table 4.

The Shepherd Creek gardens had higher cost for construction than reported in the literature. When this cost is reduced to match values from CRWD (2012), as seen in Table 4, the gardens become much more cost effective. In a standard, homeowner-maintained garden, installation is the greatest expense, and the relationship between installation cost and EAC remains strong with contractor maintenance because future maintenance costs can be discounted.

Figure 6 compiles the LCA results of several alternative scenarios, including reduced garden life span, added maintenance costs, and increased rainfall. The

TABLE 4. Comparison of Equivalent Annual Costs (EAC) over Various Discount Rates and Implementation Plans. Results are rounded to the nearest whole dollar amount.

Year	Grey Alternative	Standardized Tunnel	Shepherd Creek Gardens	20-Year Garden	$67/h Maintenance	$39.25/h Maintenance	$115/h Maintenance	9 h/yr Maintenance	$10.9/cf Installation	Landfill Disposal
EAC 35 year (3%)	$314	$256	$234	$343	$351	$298	$424	$779	$80	$249
EAC 35 year (5%)	$504	$409	$292	$390	$403	$353	$472	$807	$97	$302
EAC 35 year (7%)	$738	$598	$354	$439	$459	$412	$524	$838	$116	$361

effects of a reduced garden life span are shown in Figure 6a. If the gardens function for an average of 20 years rather than 35, both average yearly cost and average yearly environmental impacts increase. A shorter average life span may be seen as a consequence of gardens being improperly constructed and failing, requiring them to be rebuilt elsewhere. Because the installation and decommissioning impacts are the same no matter the life span of the garden, these impacts cannot be spread as thin over a shorter lived garden. In real terms, if the gardens must be rebuilt, incurring the impacts of installation and disposal occur more often.

The Shepherd Creek gardens require no city-contributed maintenance. We understand, however, that due to legal and logistical boundaries many rain garden implementation plans may require some form of maintenance from local government or local contractors. We modeled two possible maintenance regimes, a single visit of two man-hours per year and three visits of three man-hours each per year. All operation phase emissions can be attributed to operation of the transport van, with manufacture and burning of diesel fuel being the largest contributor to most impact categories. As visits increase, so do cost, and environmental impacts, as seen in Figures 6b and 6c. Triannual visits were enough to eliminate impact benefits in ecotoxicity while severely cutting the benefits to ozone depletion and smog formation. The high labor hour investment rapidly became economically unfavorable, suggesting that rain gardens should not be implemented in areas that would require high maintenance.

Using contractor estimates from construction as the basis for an estimate of maintenance costs has again provided unusually high values for the Shepherd Creek gardens. If literature estimates for the maintenance of gardens were used, then increased maintenance regimes may become economically feasible, but even large changes in hourly maintenance cost have relatively small effects on EAC (Table 4).

Scenarios where garden soil media are disposed of in a landfill rather than buried are compared in Figure 6d. Significantly, increased excavation was needed to remove all soil rather than simply to collapse the berms, then replacement soil needed to be excavated from elsewhere, transported, and packed into the garden's former site. Meanwhile, the garden media needed to be transported to a landfill for disposal. Disposal by landfill had a relatively modest effect on cost, but the burden associated with disposal made the impacts of the green alternative higher for the ecotoxicity, ozone depletion, and smog categories while relatively increasing the impacts associated with the remaining categories.

If local rainfall rates increase as a result of climate change, then the beneficial effects of each garden will only increase as greater amounts of stormwater are

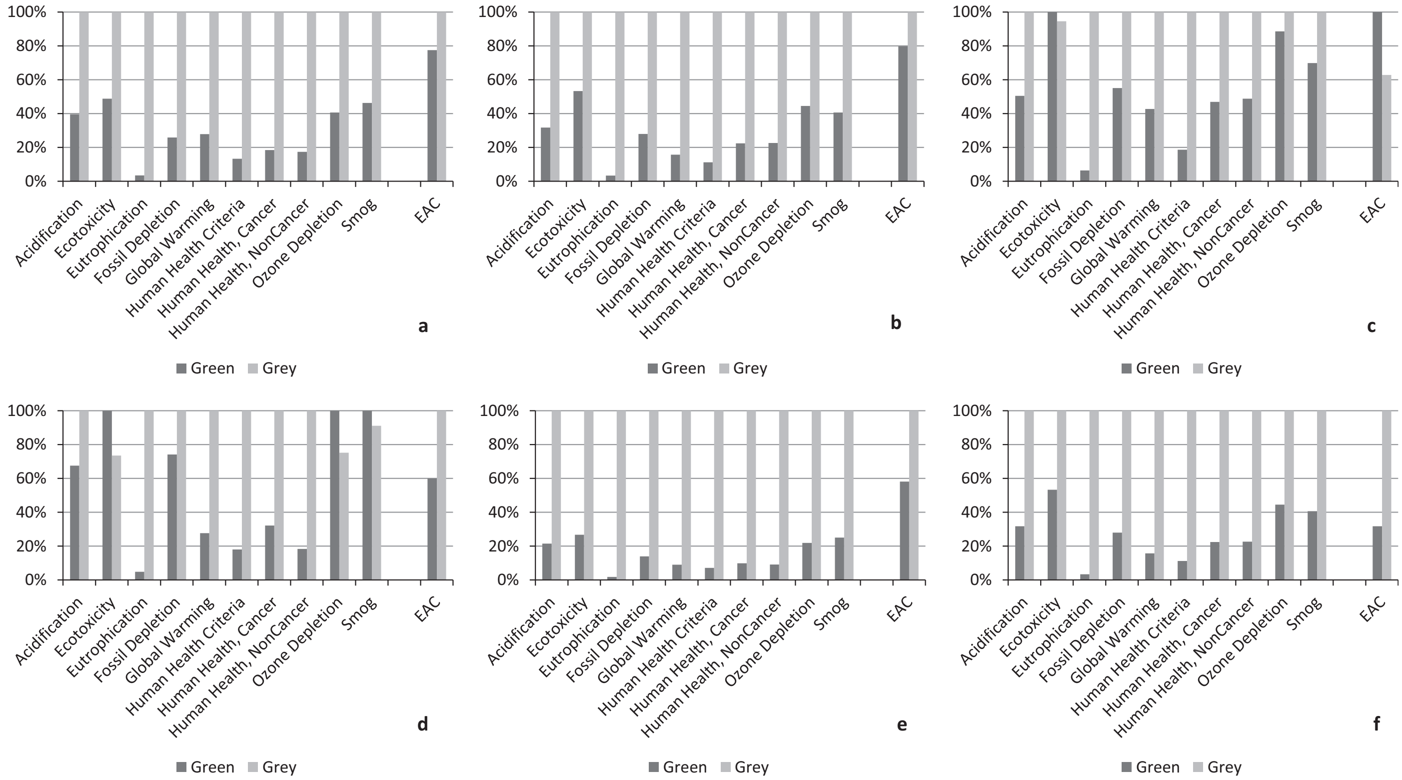


FIGURE 6. Comparison of Green and Grey Options with Specific changes to Systems: (a) A Reduced Life Span of the Rain Garden; (b) One Maintenance Visit per Year by a Contractor; (c) Three Maintenance Visits per Year by a Contractor; (d) Requiring Disposal of Soil Media in a Landfill; (e) 10% Increased Rainfall; (f) Reduced Contractor Rates, but One Yearly Maintenance Visit. Results are expressed relative to the highest impact option (green or grey) for each impact category, which is assigned 100%.

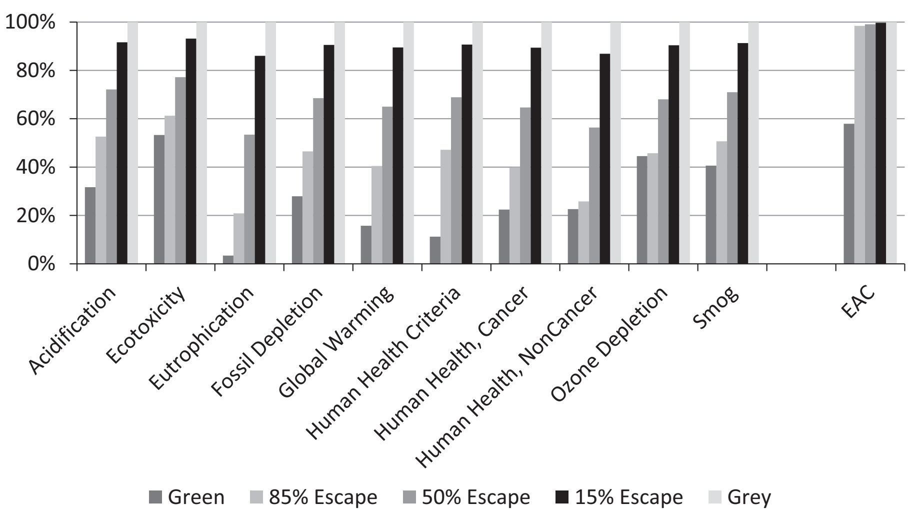


FIGURE 7. Comparison of Gardens to Grey Offsets under Various Underdrain Escape Rates. Results are expressed relative to the highest impact option (green or grey) for each impact category, which is assigned 100%.

captured (up to garden capacity) with more plentiful and more powerful rainfall events. Increased rainfall will create a linear increase in impact benefits, but effects on cost savings will be minimal, as seen in Figure 6e. However, with increased rainfall comes increased chance of overflow, so our assumption of 100% capture will be less applicable with higher rainfall rates. Though occurrence is infrequent, it is important to note that if rain gardens are unable to drain adequately in between rainfall events, the storage capacity will be proportionately reduced and plant life may die; this causes the soil surface to become impervi-

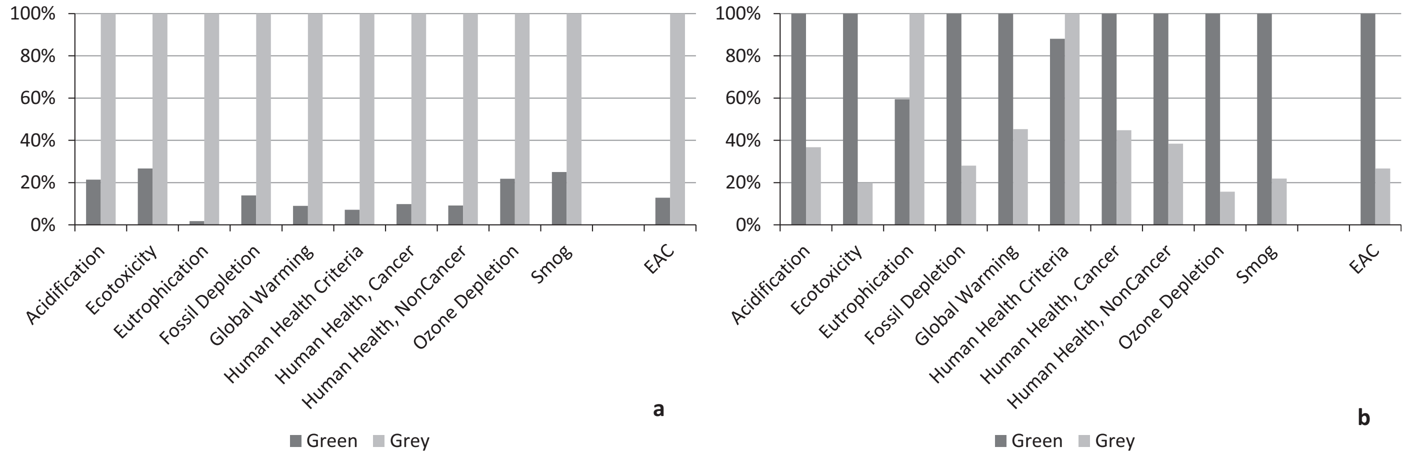


FIGURE 8. Comparison of the "Best Case" and "Worst Case" Gardens to the Grey Alternative. The best case (a) garden is modeled with homeowner maintenance, cheap contractor rates for construction, increased rainfall, and standard burial decommissioning. It is compared to the grey alternative at a 7% discount rate. The worst case (b) garden is modeled with maintenance visits every four months for a cumulative nine man-hours per year, standard construction rates, standard rainfall, landfill disposal, 85% underdrain escape, and a life span of 20 years. It is compared to formula estimates of the storage tunnel price under a 3% discount rate. Results are expressed as proportions. This comparison shows that there is large potential for uncertainty in rain garden implementation; plans should be thoroughly evaluated and optimized.

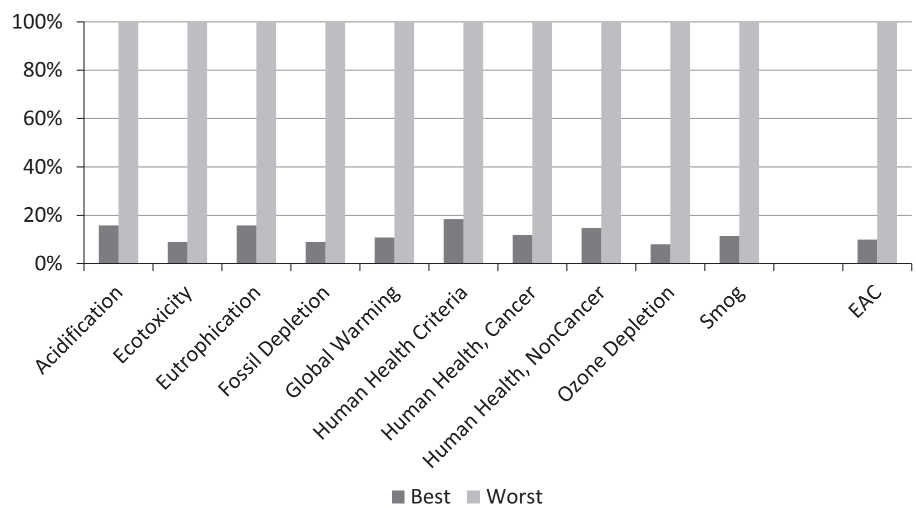


FIGURE 9. Comparison of the "Best Case" and "Worst Case" Scenario Gardens. Results are expressed as proportions. This illustrates the high uncertainty in rain garden implementation.

ous and requires replanting of the garden, a significant expense comparable to total reinstallation.

Under less costly contractor rates, as may be seen in areas with established GI programs and competition between experienced contractor groups, the gardens compare very well to the grey alternative as seen in Figure 6f, even with contractor maintenance.

As seen in Figure 7, cost differences changed very little with the addition of an underdrain while environmental benefits were gradually lost. By 85% escape, benefits to human health (noncancerous), ozone formation, and smog depletion were nearly lost. Eutrophication benefits, global warming benefits, and cost savings remained high, but were diminished by high escape.

Figure 8 shows two representative aggregations of scenarios that illustrate the uncertainty in a rain garden implementation program, a "Best Case" scenario, and a "Worst Case" scenario. Our best case scenario gardens (Figure 8a) show the possibilities of a garden plan with cheap installation, increased rainfall, and homeowner-provided maintenance adjusted for a high discount rate; our model shows them to be safely preferable to the grey alternative in every way. Our worst case scenario gardens (Figure 8b) show a garden that requires high maintenance and landfill disposal while experiencing 85% underdrain escape and an average lifetime of 20 years in an area where storage tunnel construction may have been more competitive, adjusted for a low discount rate; the garden still reaps eutrophication benefits, but the plan is otherwise highly unfavorable. Comparing the best and worst case scenarios, as in Figure 9, illustrates the uncertainty that can exist in rain garden implementation.

CONCLUSIONS AND FUTURE GOALS

We present one of the first LCAs of rain gardens based on actual large-scale field data on garden construction and maintenance. Using an LCA perspective, the baseline model for the Shepherd Creek rain gardens shows them to be highly favorable compared to the grey infrastructure alternative. They dramatically reduce environmental impacts in every impact category (with the possible exception of ecotoxicity). Of greatest interest are their benefits to both eutrophication and global warming, which they achieve by intercepting nutrient pollution before it can reach the wastewater and by reducing the use of electricity for wastewater treatment.

Garden implementation is heavily favored by higher discount rates due to its cost amortization versus that of the grey alternative. Whereas standard infrastructure requires a large upfront investment and relatively minor maintenance afterward, rain gardens require a proportionally smaller initial investment but (with required upkeep) can include a relatively higher lifetime maintenance cost; this maintenance cost is, however, more straightforward than the unevenly distributed tunnel maintenance. This relationship between cost and discount rate is exacerbated by the long construction time of a storage tunnel compared to the very short startup time of a rain garden.

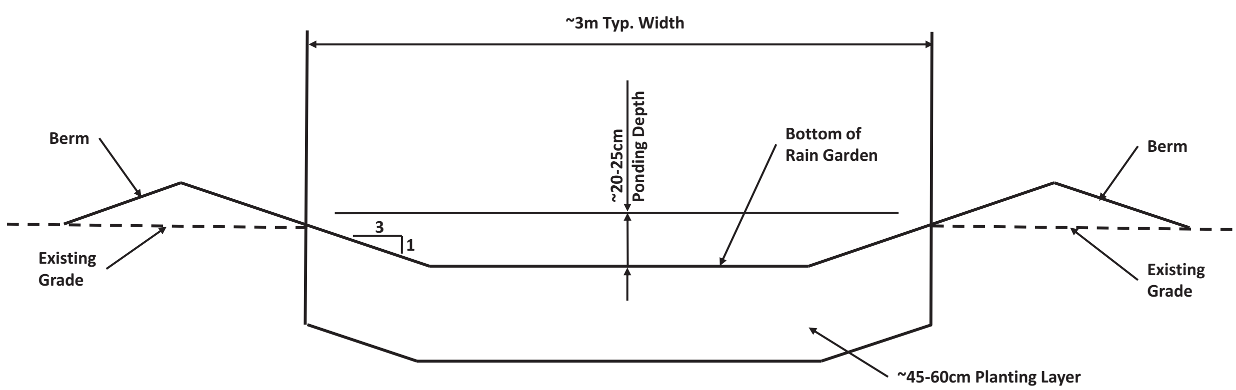
It may be possible that rain garden use can create jobs, as their installation and maintenance require relatively large amounts of unskilled labor over an extended period of time. This is opposed to the grey alternative, which requires proportionately less labor (and labor is of a higher skill level) and also requires large material and energy inputs. Contracting for rain garden construction may be less likely to draw skilled construction organizations away from other projects.

Unfortunately, as shown above, there can be a large degree of cost and performance uncertainty in rain garden implementation. For this reason, we recommend making a thorough investigation into the local soil hydrology and contracting organizations to create a well-defined implementation plan with accurate cost estimates before beginning any rain garden project. Garden installation and maintenance should be overseen by experienced or knowledgeable organizations, which can ensure the proper continued performance of the gardens.

Rain gardens have been demonstrated to create hydrologic flow patterns more like undeveloped watersheds (Davis, 2008) in headwater areas, particularly in delaying the intensity of runoff to receiving bodies. Evaluating the green and grey infrastructure approaches based on their effects on local hydrology was beyond the scope of this study, but should play a role in supporting decision making between these options.

In order to assist local governments with assessing rain garden plans, we recommend future researchers monitor existing rain garden projects to catalog maintenance costs and long-term garden performance, as these values are still sparse in the literature. Published examples of rain garden decommissioning impacts and methodologies would be another great asset in economic and environmental impact projections. Life cycle assessments of the difference in treatment between stormwater runoff and standard sewage would allow much more accurate assessment of the LCA output offset by GI in a combined sewer system. Finally, if local governments would begin to publish the construction and maintenance costs of their current infrastructure systems (such as storage tunnels), it would allow other governments to learn from their examples and better inform their own decisions.

APPENDIX



APPENDIX A. Cross Section of a Typical Shepherd's Creek Rain Garden (TetraTech, 2007).

APPENDIX B. Environmental Impacts and Financial Costs by Life Cycle Stage for Both Green and Grey Infrastructure. Values listed are for the base case analysis. Financial costs are discounted at a 5% rate.

	Acidification kg SO_2 eq	Ecotoxicity CTUe	Eutrophication kg N eq	Fossil Depletion kg oil eq	Global Warming kg CO_2 eq	Respiratory Effects kg PM2.5 eq	Human Health, Cancer CTUc	Human Health, Noncancer CTUnc	Ozone Depletion kg CFC11 eq	Smog kg O_3 eq	Equivalent Annual Cost 2013 USD
Green											
Installation	0.57	16.43	0.14	20.54	216.96	2.90E-02	8.00E-09	9.97E-09	1.06E-05	10.50	$289.91
Operation	—	—	—	—	−132.79	—	—	—	—	—	—
Decommissioning	0.03	1.19	0.01	1.45	4.12	1.06E-03	4.41E-10	4.52E-10	7.19E-07	0.89	$4.86
Grey											
Construction	1.17	34.43	0.53	55.13	273.99	1.49E-01	2.35E-08	1.33E-08	1.77E-05	18.08	$499.37
Treatment	1.48	28.81	7.15	93.61	640.13	2.46E-01	5.67E-08	9.14E-08	3.12E-05	25.02	$7.49

APPENDIX C. Master List of Alternative Scenarios and Their Inclusion in Aggregate Scenarios.

	Base Case	Low Contractor Price	Best Case Scenario	Worst Case Scenario
Base construction	X			X
Homeowner maintained	X		X	
35-Year life span	X	X	X	
Standard rainfall	X	X		X
No underdrain escape	X	X	X	
Burial decommissioning	X	X	X	
Standard tunnel alternative	X	X	X	
5% Discount rate	X	X		
3% Discount rate				X
7% Discount rate			X	
Reduced price tunnel alternative				X
Reduced construction		X	X	
20-Year life span				X
One visit/yr		X		
Three visits/yr				X
Reduced maintenance cost		X	X	
Increased maintenance cost				X
Landfill decommissioning				X
Increased rainfall			X	
85% Underdrain escape				X

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LITERATURE CITED

Andrew, R. and E.-T. Vesely, 2008. Life-Cycle Energy and CO_2 Analysis of Stormwater Treatment Devices. Water Science & Technology 58:985-993.

Angrill, S., R. Farreny, C.M. Gasol, X. Gabarrell, B. Viñolas, A. Josa, and J. Rieradevall, 2012. Environmental Analysis of Rainwater Harvesting Infrastructures in Diffuse and Compact Urban Models of Mediterranean Climate. The International Journal of Life Cycle Assessment 17:25-42.

Arnold, C.L., Jr. and C.J. Gibbons, 1996. Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. Journal of the American Planning Association 62:243-258.

Asleson, B.C., R.S. Nestingen, J.S. Gulliver, R.M. Hozalski, and J.L. Nieber, 2009. Performance Assessment of Rain Gardens. Journal of the American Water Resources Association 45:1019-1031.

Bare, J., 2011. TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Technologies and Environmental Policy 13:687-696.

Bedan, E.S. and J.C. Clausen, 2009. Stormwater Runoff Quality and Quantity from Traditional and Low Impact Development Watersheds. Journal of the American Water Resources Association 45:998-1008.

Brander, K.E., K.E. Owen, and K.W. Potter, 2004. Modeled Impacts of Development Type on Runoff Volume and Infiltration Performance. Journal of the American Water Resources Association 40:961-969.

Brown, R.A. and W.F. Hunt, 2012. Improving Bioretention/Biofiltration Performance with Restorative Maintenance. Water Science & Technology 65:7.

Cameron, R.W., T. Blanuša, J.E. Taylor, A. Salisbury, A.J. Halstead, B. Henricot, and K. Thompson, 2012. The Domestic Garden–Its Contribution to Urban Green Infrastructure. Urban Forestry & Urban Greening 11:129-137.

CRWD, 2012. BMP Performance and Cost-Benefit Analysis: Arlington Pascal Project 2007-2010. Capitol Region Watershed District, St. Paul, Minnesota.

CWP, 2007. National Pollutant Removal Performance Database. Center for Watershed Protection, Ellicott City, Maryland.

Davis, A.P., 2008. Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering 13:90-95.

Davis, A.P., W.F. Hunt, R.G. Traver, and M. Clar, 2009. Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135:109-117.

De Sousa, M.R., F.A. Montalto, and S. Spatari, 2012. Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies. Journal of Industrial Ecology 16:901-913.

Dietz, M.E., 2007. Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water, Air, and Soil Pollution 186:351-363.

Dietz, M.E. and J.C. Clausen, 2005. A Field Evaluation of Rain Garden Flow and Pollutant Treatment. Water, Air, and Soil Pollution 167:123-138.

Dietz, M.E. and J.C. Clausen, 2006. Saturation to Improve Pollutant Retention in a Rain Garden. Environmental Science & Technology 40:1335-1340.

Dorfman, M., N. Stoner, and M. Merkel, 2004. Swimming in Sewage. Natural Resources Defense Council and the Environmental Integrity Project, New York, NY. http://www.nrdc.org/water/pollution/sewage/sewage.pdf, *accessed* October 2014.

Dussaillant, A.R., C. Wu, and K. Potter, 2004. Infiltration of Stormwater in a Rain Garden: Richards Equation Numerical Model and Field Experiment. Journal of Hydrologic Engineering 9(3):219-225.

ENR, 2014. Building Cost Index History. Engineering News Record, Cincinnati, Ohio.

EPRI, 2013. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. The Electric Power Research Institute and The Water Research Foundation, Palo Alto, California.

Flower, D.J. and J.G. Sanjayan, 2007. Green House Gas Emissions due to Concrete Manufacture. The International Journal of Life Cycle Assessment 12:282-288.

Flynn, K.M., 2011. Evaluation of Green Infrastructure Practices Using Life Cycle Assessment. Villanova University, Villanova, Pennsylvania.

Ghimire, S.R., J.M. Johnston, W.W. Ingwersen, and T.R. Hawkins, 2014. Life Cycle Assessment of Domestic and Agricultural Rainwater Harvesting Systems. Environmental Science & Technology 48:4069-4077.

Ghimire, S.R., D.W. Watkins, and K. Li, 2012. Life Cycle Cost Assessment of a Rain Water Harvesting System for Toilet Flushing. Water Science & Technology: Water Supply 12:12.

Google and Sanborn, 2014. Google Maps Cincinnati.

Hallmann, M., T. Grant, and N. Alsop, 2003. Life Cycle Assessment and Life Cycle Costing of Water Tanks as a Supplement to Mains Water Supply. Centre for Design at RMIT University, for Yarra Valley Water, Melbourne, Australia.

Holman-Dodds, J.K., A.A. Bradley, and K.W. Potter, 2003. Evaluation of Hydrologic Benefits of Infiltration Based Urban Storm Water Management. Journal of the American Water Resources Association 39:205-215.

Hood, M.J., J.C. Clausen, and G.S. Warner, 2007. Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development. Journal of the American Water Resources Association 43:1036-1046.

Houdeshel, C.D., C.A. Pomeroy, and K.R. Hultine, 2012. Bioretention Design for Xeric Climates Based on Ecological Principles. Journal of the American Water Resources Association 48:1178-1190.

ISO, 2006. 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Standards Organization, Geneva.

Jacob, J.S. and R. Lopez, 2009. Is Denser Greener? An Evaluation of Higher Density Development as an Urban Stormwater-Quality Best Management Practice. Journal of the American Water Resources Association 45:687-701.

Jenkins, J.K.G., B.M. Wadzuk, and A.L. Welker, 2010. Fines Accumulation and Distribution in a Storm-Water Rain Garden Nine Years Postconstruction. Journal of Irrigation and Drainage Engineering 136:862-869.

Komlos, J. and R. Traver, 2012. Long-Term Orthophosphate Removal in a Field-Scale Storm-Water Bioinfiltration Rain Garden. Journal of Environmental Engineering 138:991-998.

Mayer, A.L., W.D. Shuster, J.J. Beaulieu, M.E. Hopton, L.K. Rhea, A.H. Roy, and H.W. Thurston, 2012. Environmental Reviews and Case Studies: Building Green Infrastructure via Citizen Participation: A Six-Year Study in the Shepherd Creek (Ohio). Environmental Practice 14:57-67.

Montalto, F., C. Behr, K. Alfredo, M. Wolf, M. Arye, and M. Walsh, 2007. Rapid Assessment of the Cost-Effectiveness of Low Impact Development for CSO Control. Landscape and Urban Planning 82:117-131.

Morgan, J., R.M. Hozalski, and J.S. Gulliver, 2010. When Do We Need to Replace Bioretention Media? 9th Annual StormCon, San Antonio, Texas.

Morzaria-Luna, H.N., K.S. Schaepe, L.B. Cutforth, and R.L. Veltman, 2004. Implementation of Bioretention Systems: A Wisconsin Case Study. Journal of the American Water Resources Association 40:1053-1061.

MSD Cincinnati, 2012. Lower Mill Creek Partial Remedy Default Plan & Modified Default Plan Costs. Metropolitan Sewer District of Greater Cincinnati, Cincinnati, Ohio.

Murphy, S.P. and T. Moore, 2007. Operations and Maintenance Requirements for Storage Tunnels and In-System Storage Facilities. Proceedings of the Water Environment Federation 2007:613-631.

Narayanan, A. and R. Pitt, 2006. Costs of Urban Stormwater Control Practices, University of Alabama, Tuscaloosa, Alabama.

Nestingen, R., B. Asleson, J. Gulliver, R. Hozalski, and J. Nieber, 2007. Techniques to Assess Rain Gardens as Stormwater Best Management Practices. Modeling of Urban Water Systems, Monograph 16, Computational Hydraulics International, Ontario.

Neukrug, H.M. and D. Camp, 2009. A Triple Bottom Line Assessment of Traditional and Green Infrastructure Options for Controlling CSO Events in Philadelphia's Watersheds: Final Report. Stratus Consulting Incorporated, Boulder, Colorado.

Nowak, D.J., D.E. Crane, and J.C. Stevens, 2006. Air Pollution Removal by Urban Trees and Shrubs in the United States. Urban Forestry & Urban Greening 4:115-123.

Odefey, J., S. Detwiler, and K. Rosseau, 2012. Banking on Green: A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community-Wide. A Joint Report by American Rivers, the Water Environment Federation, the American Society of Landscape Architects and ECONorthwest.

Olson, N.C., J.S. Gulliver, J.L. Nieber, and M. Kayhanian, 2013. Remediation to Improve Infiltration Into Compact Soils. Journal of Environmental Management 117:85-95.

Opperman, J.J., A. Warner, E. Girvetz, D. Harrison, and T. Fry, 2011. Integrated Floodplain-Reservoir Management as an Ecosystem-Based Adaptation Strategy to Climate Change. *In*: Proceedings of the American Water Resources Association 2011 Spring Specialty Conference. http://www.awra.org/meetings/Baltimore2011/doc/abs/Sess, *accessed* October 2014.

PGC, 1999. Low-Impact Development Design Strategies: An Integrated Design Approach. Department of Environmental Resources, Programs and Planning Division, Prince George's County, Maryland.

Roy, A.H. and W.D. Shuster, 2009. Assessing Impervious Surface Connectivity and Applications for Watershed Management. Journal of the American Water Resources Association 45:198-209.

Ryberg, M., M.D. Vieira, M. Zgola, J. Bare, and R.K. Rosenbaum, 2013. Updated US and Canadian Normalization Factors for TRACI 2.1. Clean Technologies and Environmental Policy 16:1-11.

Schulz, M., M.D. Short, and G.M. Peters, 2012. A Streamlined Sustainability Assessment Tool for Improved Decision Making in the Urban Water Industry. Integrated Environmental Assessment and Management 8:183-193.

Scientific Applications International Corporation and M.A. Curran, 2006. Life-Cycle Assessment: Principles and Practice. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, Ohio.

Shuster, W., R. Gehring, and J. Gerken, 2007. Prospects for Enhanced Groundwater Recharge via Infltration of Urban Storm Water Runoff: A Case Study. Journal of Soil and Water Conservation 62:129-137.

Shuster, W.D., D. Lye, A. La Cruz, L.K. Rhea, K. O'Connell, and A. Kelty, 2013. Assessment of Residential Rain Barrel Water Quality and Use in Cincinnati, Ohio. Journal of the American Water Resources Association 49:753-765.

Steffen, J., M. Jensen, C.A. Pomeroy, and S.J. Burian, 2013. Water Supply and Stormwater Management Benefits of Residential Rainwater Harvesting in US Cities. Journal of the American Water Resources Association 49:810-824.

Stephens, D.B., M. Miller, S.J. Moore, T. Umstot, and D.J. Salvato, 2012. Decentralized Groundwater Recharge Systems Using Roofwater and Stormwater Runoff. Journal of the American Water Resources Association 48:134-144.

Suter, P.Z.P., 1996. Ökoinventare von Entsorgungsprozessen: Grundlagen zur Integration der Entsorgung in Ökobilanzen. ETH, Zürich, ISBN 3952066109, 9783952066102.

Swarr, T.E., D. Hunkeler, W. Klöpffer, H.-L. Pesonen, A. Ciroth, A.C. Brent, and R. Pagan, 2011. Environmental Life-Cycle Costing: A Code of Practice. The International Journal of Life Cycle Assessment 16:389-391.

TetraTech, 2007. Report on Installations of Raingardens and Rainbarrels. STREAMS Task Order 8.

Torno, H., 1984. The EPA Nationwide Urban Runoff Program (NURP). *In*: Proceedings of the Third International Conference on Urban Storm Drainage, P. Balmer, P.A. Malmqvit, and A. Sjöberg (Editors). Göteborg, Sweden, vol. 4, pp. 1465-1474.

Tzoulas, K., K. Korpela, S. Venn, V. Yli-Pelkonen, A. Kaźmierczak, J. Niemela, and P. James, 2007. Promoting Ecosystem and Human Health in Urban Areas Using Green Infrastructure: A Literature Review. Landscape and Urban Planning 81:167-178.

USBLS, 2010. Consumer Price Index, US Bureau of Labor Statistics. Washington, D.C. http://www.bls.gov/cpi, *accessed* October 2014.

USEPA, 1994. Combined Sewer Overflow (CSO) Control Policy; Notice. United States Environmental Protection Agency, Federal Register, Washington, D.C.

USEPA, 2004. Impacts and Control of CSOs and SSOs. United States Environmental Protection Agency Office of Water, Washington, D.C.

USEPA, 2011. Evaluation of Urban Soils: Suitability for Green Infrastructure or Urban Agriculture. United States Environmental Protection Agency Region 5, Cincinnati, Ohio.

USEPA, 2013a. Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs. United States Environmental Protection Agency, Washington, D.C.

USEPA, 2013b. Rainwater Harvesting: Conservation, Credit, Codes, and Cost Literature Review and Case Studies. United States Environmental Protection Agency, Washington, D.C.

USEPA, 2014a. EPA Water Cluster Report. United States Environmental Protection Agency, Washington, D.C.

USEPA, 2014b. State and Local Climate and Energy Program: Water/Wastewater. United States Environmental Protection Agency. http://www.epa.gov/statelocalclimate/local/topics/water.html, *accessed* October 2014.

USEPA, 2014c. What Is Green Infrastructure? United States Environmental Protection Agency. http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm, *accessed* October 2014.

Wadzuk, B.M., M. Rea, G. Woodruff, K. Flynn, and R.G. Traver, 2010. Water-Quality Performance of a Constructed Stormwater Wetland for All Flow Conditions. Journal of the American Water Resources Association 46:385-394.

Wang, R., M.J. Eckelman, and J.B. Zimmerman, 2013. Consequential Environmental and Economic Life Cycle Assessment of Green and Gray Stormwater Infrastructures for Combined Sewer Systems. Environmental Science & Technology 47:11189-11198.

Weiss, P.T., G. LeFevre, and J.S. Gulliver, 2008. Contamination of Soil and Groundwater due to Stormwater Infiltration Practices, A Literature Review. St. Anthony Falls Laboratory, St. Paul, Minnesota.

Wise, S., J. Braden, D. Ghalayini, J. Grant, C. Kloss, E. MacMullan, S. Morse, F. Montalto, D. Nees, and D. Nowak, 2010. Integrating Valuation Methods to Recognize Green Infrastructure's Multiple Benefits. Center for Neighborhood Technology, San Francisco, California. April.

Wolf, K.L., 2003. Ergonomics of the City: Green Infrastructure and Social Benefits. *In*: Engineering Green: Proceedings of the 11th National Urban Forest Conference, C. Kollin (Editor). American Forests, Washington, D.C., pp. 141-143.

WWQA, 2000. Wet Weather Quality Act of 2000. *In*: Section 112 of Division B.