# Benefit-cost analysis of stormwater green infrastructure for Grand Rapids, Michigan

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## Abstract

Grand Rapids, Michigan, USA is a medium-sized city located within the Lake Michigan watershed, one the five North American Great Lakes. Like many cities, Grand Rapids spends considerable money managing stormwater. Impervious surfaces collect and concentrate volumes of water and associated sediments and pollutants. This creates flooding, erosion, and pollution problems especially for downstream communities. However, stormwater quantity can be reduced and quality can be improved by, for example, mimicking natural hydrology, enhancing biodiversity, linking ecological and economic sustainability, taking an integrated approach at manageable scales, and viewing stormwater as a resource. Evidence is mounting that onsite stormwater management systems can be cost-effective, but the detailed benefit-cost analyses are still lacking. Therefore the West Michigan Environmental Action Council, together with researchers from Grand Valley State University, estimated the economic benefits and costs of various "green infrastructure" (GI) practices. Each GI practice was standardized to treat 3,000 ft$^3$ of stormwater per 1.0-inch event plus the first inch of stormwater from larger events. This equates to about 113,000 ft$^3$ of stormwater per year. The economic analysis used a benefit transfer approach to estimate the net present value (NPV) of capital, operations, and maintenance costs as well as the direct and indirect benefits. The suite of benefits varied for each GI practice and included flood risk reduction ; reductions in stormwater volume, phosphorus, total suspended solids (TSS), and air pollution; scenic amenity value; and CO$_2$ storage. A 3.5 percent discount rate was applied to all costs and benefits, and each practice was analyzed over 50 years. Conserved natural areas had the largest net present value at $\$3.10/\text{ft}^3$, followed by street tree planters at $\$1.48/\text{ft}^3$, rain gardens at $\$1.12/\text{ft}^3$, porous asphalt at $\$0.68/\text{ft}^3$, and infiltration bioretention basins at $\$0.03/\text{ft}^3$. Green roofs had a negative net present values of $\$-1.12/\text{ft}^3$ suggesting their lifetime costs exceed their benefits, at least in Grand Rapids where ground-level open space is plentiful. If the green roof is used to attain certification such as Leadership in Energy and Environmental Design (LEED), which has a high amenity value, then the net benefits turn positive ($\$0.16/\text{ft}^3$). Rain barrels are another small-scale green infrastructure practice that can be useful and cost-effective at the household scale ($\$1.06/\text{ft}^3$). However, there is a lot of variability in the costs and benefits associated with each of these GI practices, which will affect the net present value; we utilized likely values for the region. No one GI practice is appropriate for all situations. Rather the choice of GI practice will be driven by the site and budget. This benefit-cost analysis of GI practices has policy implications for Grand Rapids and other small to mid-size Midwestern cities. With the array of options available to manage stormwater on site, municipalities like Grand Rapids are well-positioned to adopt the GI practices that are most appropriate.

## Introduction

Local government units, including villages, cities, and counties, expend significant resources to manage stormwater. The City of Grand Rapids, Michigan, USA, for example, operates stormwater infrastructure valued at $533 million (City of Grand Rapids, 2014). These government entities have a strong incentive to reduce expenditures by reducing the volume of stormwater they manage. Reducing runoff volumes also reduces both the risk of floods and the amount of pollution entering the water courses.

The dominant paradigm in stormwater management for most of the 20th century was to move the water offsite as quickly as possible through ditches and pipes, so-called “gray infrastructure”, and into the nearest stream or river. While effective at preventing ponding, moving large quantities of water, with its sediments and pollution, into water bodies resulted in flooding, erosion, and pollution problems for downstream communities. Since the 1990s an ecological paradigm has emerged that places stormwater quantity and quality within the context of integrated watershed management and low impact development. Stormwater quantity can be reduced and quality can be improved by, for example, mimicking natural hydrology, enhancing biodiversity, linking ecological and economic sustainability, taking an integrated approach at manageable scales, and viewing stormwater as a resource (Debo and Reese, 2002).

The gray infrastructure paradigm emphasizes public infrastructure built, maintained, and operated by the municipality. Stormwater infrastructure is a pure public good; that is, it is non-rival and non-exclusive, which mean that under normal circumstances, everyone can benefit from it without “using it up” and once it is built, the municipality cannot exclude anyone from enjoying its benefits, respectively (Weimer and Vining, 2010). There is little incentive for private landowners to invest in stormwater management practices because the benefits of their actions would largely accrue to their neighbors. The ecological paradigm based on onsite management and low impact development, however, requires significant investments on private property such as rain gardens, green (vegetated) roofs, and permeable pavement. The misalignment of incentives results in a market failure. In the absence of policy, actors in the marketplace will underprovide onsite stormwater management systems and practices. This will be the case even if onsite management is less expensive than the traditional sewer infrastructure. It’s not just about the costs; it’s about who pays them.

Evidence is mounting that onsite stormwater management systems can be cost-effective. The Center for Neighborhood Technology found that a municipal level green infrastructure plan could have significant net benefits for the community by reducing gray infrastructure capital costs by $120 million and providing more than $4 million in energy, air quality, and climate benefits annually (Center for Neighborhood Technology, 2014). If the net benefits of green infrastructure are positive, there is a compelling case that municipalities could save money and provide better environmental outcomes by providing incentives for private investment in onsite stormwater management through green infrastructure.

This paper analyzes the benefits and costs of stormwater management using green and gray infrastructure in the City of Grand Rapids, Michigan, USA. Specifically, it addresses seven green infrastructure practices: porous asphalt; green roofs; rain gardens; bioretention infiltration ponds; conservation of natural areas; street trees, which include tree planters and tree pits; and rain barrels. This benefit-cost analysis is part of the Rainwater Rewards project which includes a web-based stormwater value calculator that estimates the baseline stormwater runoff quantity, the reduced runoff quantity after the adoption of green infrastructure systems, and the net economic benefit of those systems (http://www.RainwaterRewards.com). The Rainwater Rewards calculator is an accessible tool for citizens, landowners, and policy makers to calculate the public benefits of green infrastructure and craft policy instruments, such as refunds or tax credits, to encourage private investment in green infrastructure.

The research team began working on valuation of ecosystem services associated with different types of green infrastructure since 2005. The INtegrated Valuation of Ecosystem Services Tool (INVEST) was developed to educate community planners and landowners about the value of ecosystem services associated with non-urban land uses in West Michigan. However, it was difficult to translate regional values for use in parcel-based decision making (Isely et al., 2010a) In 2010, INVEST was expanded and applied to a single parcel to help resolve a land use dispute between the property owner and Blue Lake Township. A calculator template was put together to demonstrate the ecosystem services associated with that parcel (Isely et al., 2012).

The team's work on quantifying the costs and benefits of stormwater management practices, specifically, began with an integrated assessment project in the Spring Lake Watershed in 2007. The team calculated direct, indirect, and opportunity costs and benefits, and performed cost effectiveness and cost-benefit analyses of bioretention/rain gardens, vegetated bio-swales, pervious pavement, constructed wetlands, and stormwater retrofits (Isely et al., 2010b). In 2013, team members completed a review of best practices in incentivizing the implementation of stormwater green infrastructure (Isely, 2014). The new Rainwater Rewards calculator has updated cost and benefit information for stormwater green infrastructure practices most likely to be found in small- to medium urban centers in the Great Lakes basin – Grand Rapids and Muskegon, Michigan. The Rainwater Rewards calculator will be the centerpiece of a community engagement curriculum on stormwater management through green infrastructure.

What we call green infrastructure in the remainder of this paper goes by many names: low impact development (LID), stormwater best management practices (BMPs), stormwater management practices (SMPs), and others. While their definitions may differ slightly, they all refer to decentralized practices that reduce the quantity of stormwater entering watercourses. For the sake of consistency, we will simply refer to all of these practices as green infrastructure (GI).

## Literature review

The most comprehensive and accessible resource to date is the Green Values Stormwater Toolbox Calculator from the Center for Neighborhood Technology (CNT) (Center for Neighborhood Technology, 2007). The CNT calculator used a relatively simple web interface that allows users to enter lot-specific information. It calculated the stormwater runoff volume under typical circumstances and estimates the reduction through the use of green infrastructure. Costs estimates considered both construction and operation and maintenance costs. The calculator estimated the following benefits: reduced air pollutants, carbon dioxide, compensatory value of trees, groundwater replenishment, reduced energy use, and reduced treatment benefits. Not every GI practice, however, delivers each of these benefits. CNT currently offers three versions of the calculator: the original, one for Chicago, and a national calculator.

Beauchamp and Adamowski (2012) used the CNT calculator and other valuation tools to estimate the value of GI compared to conventional infrastructure. GI development included reduced pavement designs, separate potable and non-potable water systems, greywater and blackwater sewage systems, and stormwater management using bioswales, wetlands, green roofs, and rain gardens. The planned development in the Montreal suburb of Vaudreuil-Dorion based on GI would cost 11-29 percent more than a conventional design. Housing values, however, are expected to increase by 15-27 percent which would offset the initial cost gap.

The Water Environment Research Foundation (WERF) developed a suite of spreadsheet-based best management practice and low impact development whole life cost models (Moeller and Pomeroy, 2009). The cost tool includes nine different practices, including permeable pavements, green roofs, rain gardens, and in-curb tree planter vaults. The cost models allow practitioners to estimate the capital, operations, and maintenance costs for each practice and compare the cost-effectiveness of each. The default spreadsheet is populated with standard values but allows the user to input locally-appropriate information about project costs, timelines, wages, and discount rates.

A locally important cost analysis was that of Clark et al. (2008) who assessed the net present value of green roofs compared to those of conventional roofs. The study site was the University of Michigan campus in Ann Arbor. The mean cost of a conventional flat roof was \$167/m$^2$ in 2008 (\$17.14/ft$^2$ in 2015). The mean capital cost of a green roof (including the conventional roof underneath) was 39 percent higher than the conventional roof alone. The researchers tallied the benefits of green roofs, including stormwater fee reductions where the city implements a stormwater charge based on impervious surfaces), energy savings, air pollution reduction, and a longer lifespan for the conventional roof. The amenity value of green roofs was not included, nor were the operation and maintenance costs for green or conventional roofs. Rather than using a standard real discount rate in their economic analysis, Clark et al. multiplied the annual benefits and costs by a three percent inflation rate and then divided by a nominal five percent interest rate. This results in an effective discount rate of less than two percent. The net present value analysis showed that, over the life of the roof, green roofs cost 25-40 percent less than conventional roofs. Energy savings and pollution reduction benefits were greater than the avoided stormwater fees. Despite the higher capital costs, the lifetime benefits outweighed the green roof's higher capital costs. However this finding is very likely due to the use of a low effective discount rate of less than two percent.

Bianchini and Hewage's (2012) also reported a positive net benefit for green roofs. Their probabilistic assessment of green roof costs and benefits found the most likely scenario produced a net benefit of \$37/ft$^2$. Like Clark et al. (2008) their economic analysis included both a 1-4 percent inflation rate and a 2-8 percent discount rate. The results were highly sensitive to the choice of inflation and discount rates. Other researchers have found negative net benefits for green roofs. For example, Carter and Keeler (2008) found that the present value costs of a green roof in Georgia was 10-14 percent higher than that of a conventional roof. They used a four percent real discount rate in their benefit-cost analysis. Likewise, Sproul et al. (2014) found that green roofs have a higher net cost over their lifetime. Sproul et al. used a three percent real discount rate. Neither of these studies, however, included amenity values for green roofs in their analyses. All of these studies suggest that a green roof's economic efficiency is highly sensitive to the choice of discount rate. Low discount rates tend to result in positive NPVs while higher discount rates of three percent or higher tend to result in negative NPVs.

Researchers at the University of New Hampshire's Stormwater Center assessed the cost and performance of several low impact development practices including porous asphalt. They found that, contrary to conventional wisdom, porous asphalt had the lowest maintenance burden in terms of staff hours and the second lowest in annual costs. Porous asphalt also performed well in removing both total suspended solids and phosphorus (Houle et al., 2013).

The Forest Service analyzed the costs and benefits of street trees in Midwestern cities. They found that, for public street trees, the benefits outweigh the costs over a forty-year period. For small trees like a crabapple the net benefit was $160 (in 2005), while for medium and large trees the benefits were $640 and $2,320, respectively. The Forest Service analysis did not, however, use discounting when assessing these benefits. Street trees provide heating and cooling energy savings, increase property values, reduce stormwater volumes by intercepting rainfall, and reduce air pollution (McPherson et al., 2006).

Economists use property value models, also known as hedonic models, to estimate the effect of housing attributes on sales prices. The housing attributes can include environmental variables and several studies have focused on GI. Hellman (2011) used a hedonic model to study the effect of stormwater volumes on housing prices in the Rochester, New York suburb of Brighton. Hellman found additional stormwater quantities negatively affect property values and that the marginal abatement costs are less than the marginal damage. Holding all other attributes constant, a one percent increase in stormwater volume leads to approximately a one percent decrease in a home's assessed value.

Another hedonic model investigated the effect of green roofs on apartment rents in New York City (Ichihara and Cohen, 2010). The presence of a green roof added 16 percent to the rental price. Though the green roof variable was statistically significant, the number of observations (44) was relatively small and the findings should be viewed with caution. The study site was a heavily urbanized area where green space is scarce. In the context of high wealth and scarce open space, residents may be willing to pay a high premium for a green roof. A hedonic analysis from Taiwan, however, found the opposite – that green roofs (as well as other GI practices like porous pavement and a balcony garden) have a negative effect on residential property prices. The authors assumed this was due to perceptions of higher maintenance costs (Chen et al., 2014). As green roofs become more common and start to feature in the property market there should be more definitive studies on their property value effects.

Green infrastructure practices can help a building earn a certification such as Energy Star or Leadership in Energy and Environmental Design (LEED). One analysis of certified commercial buildings found that such certifications command rent premiums of 3.1 percent for Energy Star and 7.0 percent for LEED. LEED buildings were also found to reduce operating costs by about 5.4 percent per year. No decrease in operating costs, however, were observed for Energy Star certified buildings (Reichardt, 2013).

Barnhill and Smardon (2012) facilitated a focus group around GI in Syracuse, New York, USA. They found three major barriers currently limit green infrastructure implementation. First is the homeowner financial cost. The costs of, for example, a residential rain garden are borne by the homeowner while the stormwater abatement benefits accrue to the community at large, especially downstream property owners – a classic market failure. The second barrier is a lack of knowledge about GI benefits, maintenance issues including costs, and the use locally-appropriate practices. The third barrier is a failure to properly frame the issue. Framing GI in terms of neighborhood regeneration and sustainability can lead to more effective engagement. Engaging local stakeholders in developing GI can improve social equity.

## Benefit transfer

The demand for environmental valuation information has outpaced research and funding for valuation projects. Consequently, many projects make up for the lack of data by using benefit transfer. Freeman (2003, p. 453) defines benefit transfer as “the practice of applying nonmarket values obtained from primary studies of resource or environmental changes undertaken elsewhere to the evaluation of a proposed or observed change that is of interest to the analyst.” The location presently under investigation is commonly called the “policy site” and the location from which the values are drawn is the “study site.”

The policy and study sites may differ for a variety of reasons, such as differences in income or preferences among the populations at the sides (demand side factors) or variation in the environmental attributes being valued (supply side factors). The benefit transfer process adjusts the study site values to reflect these differences. Benefit transfer is simpler and more accurate if the policy and study sites are relatively similar (Freeman, 2003).

Johnston et al. (2015) reviewed the generally accepted methods of benefit transfer. They described several types of benefit transfer techniques: unit value transfer and benefit function transfer, the latter of which includes structural benefit transfer and meta-analysis. Unit value transfer, though the simplest, has several drawbacks which make it less desirable for policy applications. Unit value transfer applies a single, unadjusted willingness-to-pay (WTP) value from the study site to the policy site. This may be appropriate if the study and policy sites are nearly identical. In most cases, however, unit value transfers result in unacceptably high errors and are usually not recommended.

Rather than simply transferring the WTP number from study to policy sites, benefit function transfer applies the mathematical function, including all or a subset of variables, to the policy site. Applying the function allows the researchers to adjust for differences between the sites and reduce errors. The adjustment also allows a wider range of contexts to serve as study sites. This is important where few, or no, study sites are sufficiently similar to the policy site.

In structural benefit transfer, also known as preference calibration, the researcher defines the utility or preference function that describes an individual’s choices over a range of market and non-market goods. One study site is typically used as the source of the preference function. The variables used in the preference function that were developed at the study site are measured at the policy site and an empirical relationship is established. This approach is consistent with the budget-constrained utility-maximization foundations of standard economic theory. The drawback, however, is its complexity and the expertise in mathematical economics required to employ the technique (Johnston et al., 2015).

Meta-analysis is an alternative form of benefit function transfer. Meta-analysis is “the quantitative synthesis of evidence on a particular outcome, with evidence gathered from prior primary studies” (Johnston et al., 2015, p. 26). The quantitative synthesis is most often accomplished using a meta-regression model in which the dependent variable is that of the primary studies, e.g. housing price, fecal coliform count. The independent variables are observable factors that influence the dependent variable at the various study sites. These can include, for example, economic, demographic, and resource characteristics of the study and policy sites. Though meta-analysis, and especially meta-regression models, can improve the accuracy of benefit transfers compared to unit value transfers, meta-analysis is not as rigorous or accurate as structural benefit transfer/preference calibration. Meta-analyses are most appropriate when a substantial amount of studies on that topic have been published, there is no single study that closely matches the policy site, and there is a desire to estimate benefits under different policy contexts (Johnston et al., 2015).

Johnston et al. (2015) presented a ten-step procedure for conducting a benefit transfer. First is to define the benefit transfer context such as the circumstances, the environmental resources, the current and proposed policies, and the uses for the value estimates. Second is to establish the need for benefit transfer. If sufficient resources are available, primary valuation studies are preferable over benefit transfers. Third is to define the policy, environmental goods, and population of the policy site. Fourth is to define and quantify the policy options and changes in the environmental goods. This includes determining the baseline levels and marginal changes in the provision of environmental goods and services. Fifth is to gather and evaluate valuation data and evidence through a comprehensive review of literature, both peer-reviewed and so-called "gray literature." The researchers must screen the documents for quality and relevance to the policy site. The sixth step is to determine the method of benefit transfer. As discussed above, benefit function transfers, such as meta-analysis and preference calibration, are generally preferred over unit value transfers. Seventh is to design and implement the benefit transfer. Eight is to aggregate the values over populations, areas and time. The benefit transfer results in a per-unit value. The per-unit value must be aggregated across the policy site. The ninth step is to conduct a sensitivity analysis and to test reliability. This may include conducting the transfer using a range of discount rates or changing the functional form. Cross-validation methods can be used to test the performance of meta-regression models. The tenth and final step is to report the results. This ten-step process was used to estimate the benefits and costs of GI in Grand Rapids, Michigan.

## Methods

### Runoff estimation

The New York State Department of Environmental Quality created the Construction Stormwater Toolbox to assist owners and operators with compliance with planning requirements under the New York State Pollutant Discharge Elimination System (SPDES). The Toolbox includes a design manual and a set of Excel-based runoff reduction worksheets (NYS Dept. of Environmental Conservation, 2014). The worksheets are rigorous enough for SPDES compliance, yet flexible enough to be adopted in many circumstances. Much of upstate New York lies within the Great Lakes basin and has a climate similar to that of Michigan's Lower Peninsula. After careful review, the project team deemed the New York State runoff reduction worksheets suitable for use in Michigan. The runoff reduction worksheets were used to establish baseline runoff volumes and to calculate the runoff reduced by implementing particular GI systems.

The project's unit of analysis was the 2010 census block. Census blocks were chosen because they are well-established, publicly available, and are small enough for fine scale analysis. Individual parcels were not used because the project team did not want to give individual landowners the idea that they would be compensated for the estimated market and non-market benefits of green infrastructure on their properties. The census block provides the minimum level of aggregation necessary while enabling fine-scale analysis.

The Toolbox, as well as other studies (e.g. Houle et al., 2013), use the 90th percentile 24-hour rain event as the design criterion for stormwater management. In Michigan, the 90th percentile ranges from 0.8

inches to 1.0 inches (Kuhns and Ulasir, 2015). We chose to use the upper bound (1.0 inches) as the design criterion. We assumed that the GI practices would prevent all stormwater runoff for rain events up to and including 1.0 inches. Ten years (2006-2015) of rainfall data from the Gerald R. Ford Airport in Grand Rapids were analyzed (Weather Underground 2016). The ten-year average annual rainfall in Grand Rapids was 40.0 inches and ranged from 32.4 (2007) to 48.8 (2008). The sum of rainfall events up to and including 1.0 inches as well as the first inch of events greater than 1.0 inches averaged 37.75 inches per year.

## Economic valuation

The installation, maintenance, and opportunity costs of the GI practices will be compared to the benefits of avoided stormwater runoff costs, pollution reduction, and aesthetic enhancement. These costs and benefits will be apportioned over the expected life of the system and analyzed using net present value:

$$\sum_{i=0}^{n} \frac{B_i}{(1+r)^i} - \frac{C_i}{(1+r)^i}$$

Where green infrastructure is compared to "gray infrastructure," the net cost of green infrastructure was calculated by:

$$\frac{C_i}{(1+r)^i} = \frac{C_i^{green}}{(1+r)^i} - \frac{C_i^{gray}}{(1+r)^i}$$

The direct benefits include reduced maintenance from avoided stormwater and reduced environmental and health costs related to water pollution. Green infrastructure also has indirect benefits. Street trees, rain gardens, and green roofs enhance a neighborhood's aesthetic quality and may be measured through home prices. Street trees also remove air pollution and reduce energy costs by shading buildings. A green roof may also extend the life of the conventional roof underneath and provides energy-saving insulation.

Where possible, the value estimates were taken from projects in Grand Rapids and adjusted for inflation. In other cases, the values reported in peer-reviewed and gray literature from other locations were used. These values were adjusted to the present Grand Rapids context using benefit transfer methods.

## Value of avoided runoff

The project assessed the costs and benefits of stormwater management through gray and green infrastructure. The benefits transfer approach was used to modify cost and benefit values from different times and locations. Costs for both types of systems were cataloged through literature review and conversations with local governments and service providers.

The direct cost of stormwater management was estimated from government documents. The City of Grand Rapids completed a sustainability plan which included a Stormwater Asset Management and Capital Improvement Plan (City of Grand Rapids, 2014). The projected annual cost to provide the existing "level of service" for stormwater management, including both fixed and variable costs, was $3.60 million in 2014. Stormwater reduction practices, however, only reduce variable costs. Fixed costs, such as system renewal or end-of-life replacement, inspections, and regulatory costs, were not included. Therefore only the annual variable costs of corrective and preventative maintenance were used to estimate the value of avoided runoff. The city recognized that the existing level of service is inadequate. After careful review of three additional "level of service" scenarios which provide increasing levels of annual spending requirements for basic stormwater management services, the city recommended pursuing Level of Service C which would increase the annual budget for stormwater management to $10.38 million. This level of service focuses on maintaining critical infrastructure and high priority areas. The budget for inspections of catch basins and detention basins in Level of Service C includes $639,000 and $6,500, respectively. Unlike the inspection definition for other assets, inspection of catch and detention basins includes cleaning. Cleaning activities were listed under maintenance for the existing level of service. Therefore catch basin and detention basin inspections were included in the variable costs (Table 1). The city's report used 2014 dollars. After adjusting for inflation to 2015 dollars using the Consumer Price Index (CPI), the total annual maintenance cost is $2,898,804.

*Table 1: Annual maintenance costs for stormwater management under Level of Service C (lower estimate).*

| **Asset / Activity** | **Annual maintenance cost (2014 dollars)** |
|---|---:|
| Gravity mains | $946,000 |
| Manholes | $40,000 |
| Laterals | $73,000 |
| Catch basins | $677,000 |
| Culverts | $43,000 |
| Open channels | $3,000 |
| Discharge points | $67,200 |
| Detention basins | $6,500 |
| Street sweeping | $1,020,000 |
| Total | $2,875,700 |
| **Total in 2015 dollars** | **$2,898,804** |

The stormwater management system processes runoff from the city's impervious surfaces. A feature extraction process using Landsat imagery with a ground sample distance of 30 m x 30 m found 12,671 acres of impervious surface in the city (Xian et al., 2011). That is 44% of the entire city area. At the average 40 inches of annual rainfall, each acre generates 137,940 ft$^3$/year of runoff, or 1,747,837,740 ft$^3$/year for the whole city. Under Level of Service C, the annual maintenance cost per unit of stormwater treated is $0.0017/ft$^3$/year.

Table 2 shows the present value of 50 years of avoided stormwater at a discount rate of 3.5%.

*Table 2: Value of avoided stormwater (2015 $/ft$^3$)*

| Level of Service | Unit cost of avoided stormwater | Present value cost of avoided stormwater (50 years) |
|---|---|---|
| Current | $0.00090/ft$^3$/year | $0.023/ft$^3$ |
| C | $0.00017/ft$^3$/year | $0.040/ft$^3$ |
| A | $0.00444/ft$^3$/year | $0.108/ft$^3$ |

## Standardizing the green infrastructure practice

Each GI practice was standardized based on a water-quality volume (WQv) reduction of 3,000 ft$^3$ for a 1.0 inch rain event using the NYS Stormwater Construction Toolbox. The tool calculates the size of the GI practice needed based on the area's rainfall regime, total area, and impervious area. Asphalt and building roofs are typically 100% impervious surface. Rain gardens are assumed to be placed in residential areas. Analysis of Landsat imagery showed that residential areas in Grand Rapids have an average of 41 percent impervious surface. The corresponding areas that produce 3,000 ft$^3$ WQv (actually 3,002 ft$^3$) is a total area of 2.0 acres and an impervious area of 0.8 acres. Residential areas, on average, have 5.8 residences per acre or just over 11 for 2.0 acres (0.2 acres per residence). If each of the 11 houses had a rain garden, each garden would need to have an area of 195 ft$^2$. The bioretention-infiltration basin was sized for a 0.9 acre parking lot, which is roughly equivalent to the porous asphalt parking lot, plus an additional area for the basin. Conserving natural areas would reduce the total area that would generate runoff. We assumed that the conserved area would be replaced by an impervious surface. The street tree (tree planter/pit) calculator requires a maximum of 33% impervious surface. The corresponding acreage producing 3,000 ft$^3$ WQv is 2.4 total acres and 0.8 impervious acres. The base case street tree was assumed to be a medium-sized deciduous tree, such as a red oak (McPherson et al., 2006) (Table 3).

Rain barrels were calculated separately and were not standardized to 3,000 ft$^3$. Rain barrels are a household scale practice and we assumed a house would install two 55-gallon barrels. As noted above, residential lots have an average impervious cover of 41 percent. The average residential lot size in Grand Rapids is 0.17 ac. The impervious surface in a residential lot, most of which is assumed the be the roof, is 0.07 ac. Two rain barrels with a combined storage of 110 gallons (14.67 ft$^3$) can capture the runoff from a typical residential lot up to a 0.055 in event. We assume that events larger than that will be stored up to the maximum capacity and the remainder will overflow. Two rain barrels can avoid 1,625 ft$^3$ of runoff per year. The results for rain barrels should not be directly compared to the other GI practices because of the different methodology.

*Table 3: Amount of green infrastructure required to reduce 3000 ft$^3$ of runoff per 1" rain event.*

| SMP | Total area (acres) | Impervious area (acres) | Amount required to reduce 3,000 ft$^3$ WQv per 1" event | Annual runoff avoided (all events ≤ 1.0" plus 1.0" from larger events) |
|---|---|---|---|---|
| Porous asphalt | 0.87 | 0.87 | 0.87 ac | 113,257 |
| Rain garden | 1.96 | 0.81 | 0.04 ac | 113,326 |
| Green roof | 0.87 | 0.87 | 0.85 ac | 113,257 |
| Infiltration bioretention | 1.00 | 0.86 | 0.07 ac | 113,248 |
| Conservation of natural areas* | 0.87 | 0.00 | 0.87 | 113,257 |
| Street tree (tree pit)** | 2.40 | 0.79 | 342 trees | 113,257 |
| Rain barrel*** | 0.17 | 0.07 | N/A | 1,625 |

*reduced total area by 0.87 ac, not actual stormwater volume

**reduced impervious surface area by 0.79 ac, not actual stormwater volume

***Stores rain events up to 0.05", not comparable in scale to other green infrastructure practices

Once the size of the green infrastructure practice was determined, the cost for each was estimated using the Low Impact Development (LID) Cost Tools from the Water Environment Research Foundation (WERF). The LID Cost Tools are Excel-based spreadsheets that have default parameters but can be modified for particular situations. The default case was modified to fit the Grand Rapids study area, including local and current wages and, where possible, cost estimates from local service providers. Each GI practices' size was adjusted based on the desired 3,000 $ft^3$ WQv reduction per 1.0 inch event. The default costs were adjusted for inflation to 2015 from 2005 using the Consumer Price Index from the US Bureau of Labor Statistics. Maintenance costs were scaled to the project size where appropriate. The City of Grand Rapids expects that its detention basins and rain gardens to have a 50 year life span. The city plans to replace porous pavement after 25 years (City of Grand Rapids, 2014). We used these life span estimates in our model.

The capital (installation) and periodic operations and maintenance (O&M) costs were combined into a present value calculation. A 3.5 percent discount rate was used for all present value calculations. This rate is appropriate for environmental projects with a lifespan of 30-75 years (Almansa and Martínez-Paz, 2011). The City of Grand Rapids uses a 50-year infrastructure planning horizon which is replicated in this analysis.

## Pollution and flood risk reduction

In addition to reducing stormwater volumes, GI practices reduce pollution entering waterways. The annual pollution load from a particular site can be estimated using the following formula (Landphair et al., 2000):

$$Load(lbs) = 0.2266 * Area\ (ac) * Rainfall\ (in) * R_v * C\ ({}^{mg}/_{L})$$

Where $R_v$ is the runoff to rainfall ratio and *C* is the pollution coefficient. The rainfall amount was the annual total for events ≤ 1.0 inches which totaled 27.95 inches. $R_v$ was calculated for each GI practice using the NYS Stormwater Toolbox. Weiss et al. (2007) reviewed several sources and found that contaminant loads were fairly consistent. Reported values for *C* averaged 131 +/- 77 mg/L (ppm) with a 67% confidence interval for total suspended solids (TSS) and 0.55 +/-0.41 mg/L (ppm) with a 67% confidence interval for total phosphorus. These average values were used in the calculations. All of the GI practices, except rain barrels, were sized to treat 3,000 $ft^3$ WQv for a 1.0 inch event. The Minnesota Stormwater Manual reported the pollution reduction efficiency for various GI practices (Table 4). Note that green roofs do not remove phosphorus from stormwater (Minnesota Pollution Control Agency, 2015).

*Table 4: Pollution reduction from green infrastructure SMPs.*

| | Pollution reduction efficiency | |
|---|---|---|
| SMP | Total suspended solids | Phosphorus |
| Porous asphalt | 74% | 45% |
| Green roof | 85% | 0% |
| Rain garden | 85% | 100% |
| Bioretention infiltration | 85% | 100% |

| | | |
|---|---|---|
| Tree pit | 85% | 80% |

The economic value of removing TSS and phosphorus was estimated from the treatment cost from a wastewater treatment plant. A 2007 report estimated that TSS removal costs $5.70/lb and phosphorus removal costs $220/lb (WSB & Associates, 2008). Adjusted for inflation to 2015 using the CPI, these costs are $5.93/lb and $251.25/lb, respectively. These values were based on the treatment plant's 30-year life cycle cost including capital and O&M costs. Multiplying the pollutant reduction amount (lb) by the unit cost ($/lb) resulted in the value of stormwater removal for each ft$^3$ of WQv avoided per year (Table 5). We assumed that rain barrels would have the same pollution reduction effect as rain gardens.

*Table 5: Unit price of pollution reduction.*

| GI practice | Annual pollution reduction (lbs/ft$^3$ WQv/year) | | Economic value of avoided pollution ($/ft$^3$ WQv/year) | |
|---|---|---|---|---|
| Porous pavement | TSS | 0.00818 | TSS | $0.036 |
| | P | 0.00003 | P | $0.004 |
| Green roof | TSS | 0.00818 | TSS | $0.041 |
| | P | 0.00000 | P | $0.000 |
| Rain garden | TSS | 0.00692 | TSS | $0.041 |
| | P | 0.00003 | P | $0.009 |
| Bioretention infiltration | TSS | 0.00692 | TSS | $0.041 |
| | P | 0.00003 | P | $0.009 |
| Tree planter / tree pit | TSS | 0.00686 | TSS | $0.041 |
| | P | 0.00003 | P | $0.007 |
| Rain barrel | TSS | 0.00692 | TSS | $0.041 |
| | P | 0.00003 | P | $0.009 |

Reducing the volume of stormwater entering area lakes and rivers also reduces the risk of flooding in downstream locations. In 2013, the Grand River, which flows through downtown Grand Rapids, flooded, causing an estimated $450 million in damages. The total water volume over the 18-foot flood stage for the Grand River for the entire two-week flood period in April 2013 was 3.9 billion ft$^3$ (USGS 2016). This comes out to $0.11/ft$^3$ of flood water. Though this was a large flood, it was not record setting. A flood of this magnitude has a 10 to 25-year recurrence time. That is, a given year has a 4-10 percent chance of a flood of this size. Assuming a 25-year recurrence time the annual expected damage would be $0.11/ft$^3$ * 0.04 = $0.005/ft$^3$. Reducing one cubic foot of stormwater volume is expected to avoid $0.005 in damages each year. This is the conservative estimate. Using the ten-year recurrence time (ten percent annual chance) would result in higher damage estimates.

## Other benefits from specific GI practices

### Green roofs

Researchers at the University of Michigan documented the benefits of green roofs on campus buildings (Clark et al., 2008). Using the US Environmental Protection Agency's (EPA) EnergyPlus 2.0 simulator, they found that the insulating properties of green roofs saved $0.36/m$^2$ (2006 dollars) or $0.04/ft$^2$ in 2015 dollars. This equates to $0.013/ft$^3$ WQv/year. The analysts also found that the green roof's growing plants took up the air pollutant $NO_2$ at a rate of 0.27 $kg/m^2$/year (0.06 $lb/ft^2$/year). The economic benefits from the pollution reduction were estimated at $1,680-6,380/Mg ($0.76-2.89/lb) in 2006 ($1,982-$7,526/Mg ($0.90-3.41/lb) in 2015). Applying these rates to the 37,200 $ft^2$ of green roof under the GI practice scenario yields a benefit of \$0.016-0.062/$ft^3$ WQv/year. The more conservative, lower-bound estimate of \$0.016/$ft^3$/year was used in our analysis.

Green roofs also provide a scenic amenity value when they are visible from upper floors or adjacent buildings. Ichihara and Cohen (2010) used a hedonic model to estimate the amenity value of green roofs in New York City. They found that, all else being equal, the presence of a green roof added about 16 percent to a residence's sales price. The coefficient for the green roof indicator variable was 0.1496 +/- 0.0729 which yields a lower bound of eight percent. The study's New York City location is not a close analog for Grand Rapids where housing values are much lower and access to ground-level green space is plentiful. The Ichihara and Cohen paper is, to date, the only hedonic model that considers the amenity value of green roofs. Sander et al. (2010), for comparison, found that a ten percent increase in street tree canopy raised property values in Minnesota by 0.29-0.48 percent. This effect held up to 40 percent tree cover. A green roof substitutes vegetated cover for an entirely impervious surface. Assuming that the effect of a green roof is similar to street trees, then a green roofs amenity value could be in the range for a 40 percent increase in tree canopy (1.16-1.92 percent). Given the lack of solid regional data for the amenity value of green roofs, our best judgment is it lies between zero for roofs lacking visibility and access to 2.0 percent for highly visible roofs with easy access.

Most green roofs in Grand Rapids are on office buildings, are highly visible, and are accessible (Greenroofs.com, 2015) . Therefore we used the high-end estimate of a 1.9 percent property value amenity. The average asking price of office property in Grand Rapids is \$71.26/$ft^2$ (LoopNet, Inc., 2015) which yields a capitalized amenity value for green roofs in Grand Rapids of \$1.35/$ft^2$. The annualized amenity value of green roofs at a 3.5 percent discount rate is \$0.06/$ft^2$/year or \$0.019/$ft^3$ WQv/year of WQv reduced.

Green roofs protect the conventional roofs underneath them. Analysts report that green roofs can double the life the conventional roof and eliminate the need for a full roof replacement after twenty-five years. Since a new roof costs about \$10/$ft^2$ (K. Menard, personal communication), this is a substantial benefit.

### Rain gardens and infiltration bioretention basins

Rain gardens also provide a scenic amenity. Polyakov et al. (2015) studied the amenity value of rain gardens placed at street intersections in Sydney, Australia. Rain gardens were found to increase the median property value by six percent for those within 50 m (164 ft) and four percent between 50 m and 100 m (164-328 ft) from the rain garden. Applying the six percent rate to Grand Rapids median sales price of \$129,900 results in an effect of \$7,794. At a 3.5 percent discount rate, the annualized value of a rain garden is \$332 or \$0.032/$ft^3$ WQv/year of runoff reduced. Stormwater infiltration bioretention basins also can, if carefully designed, have an amenity value. Lee and Li (2009) found that in Texas, ordinary (single use) detention basins had no influence on residential housing prices. Multi-use detention basins, on the other hand, include recreation amenities in their design. Homes closer to the multi-use basins sold for higher prices than those further away, all else being equal. For our analysis, we conservatively assumed that the infiltration-bioretention practice was similar to the ordinary, single-use detention basin and provides no amenity value.

## Street trees and conserved open space

Urban trees provide many ecosystem services beyond stormwater mitigation. The Midwest Community Tree Guide documented and quantified the benefits provided by urban trees (McPherson et al., 2006). The guide lists the benefits of street trees by unit (kWh of electricity saved, pounds of air pollutants avoided, etc.) as well as the price ($/unit) of each. The magnitude of the benefits changes as the tree grows in size and maturity. For this analysis, we used the guide's units and updated them with current and locally appropriate prices. In addition to the benefits described by McPherson et al., we also include the reduced flooding risk, reduction in total suspended solids, and reduction in phosphorus. Table 6 below shows the units, prices, and sources for each benefit. The avoided runoff volume estimates reported by McPherson et al. were higher than those resulting from the NYS Stormwater toolbox. The volume reduction estimated by McPherson et al. was based mostly on rainfall interception. The volume reduction estimated by the NYS Stormwater toolbox focused mostly on capturing runoff in the pervious area under the tree. After some deliberation, the team decided to use the McPherson runoff reduction estimates in the benefit calculation. The NYS Stormwater toolbox was used, however, to determine the size of the GI practice (number of trees) to be consistent with the other GI practices.

*Table 6: Benefits of street trees (based on McPherson et al. 2006).*

| Benefit | Price ($/unit) | Source |
|---|---|---|
| Avoided runoff | $0.0002/gallon | City of Grand Rapids data ($0.0017/ft$^3$/year WQv) |
| Electricity savings | $0.126/kWh | 2014 EIA East North Central residential, adjusted for inflation |
| Heating savings | $0.009/kBtu | 2014 EIA Michigan average residential natural gas price |
| CO2 sequestered | $0.018/lb $CO_2$ | EPA social cost of carbon for 2015, $40/ton $CO_2$ |
| Air pollution avoided | Various | McPherson et al. values adjusted for inflation using CPI |
| Aesthetic value | 0.81% of residential housing price | McPherson et al. percentage applied to Grand Rapids average housing sales price, $129,900 |
| Flood risk reduction | $0.005/ft$^3$ WQv/year | Current analysis |
| Total suspended solids | $0.041/ft$^3$/year | Current analysis |
| Phosphorus | $0.007/ft$^3$/year | Current analysis |

Conserved natural areas have been shown to increase the property values of the adjacent lots. Thorsnes (2002) used a hedonic model of the Grand Rapids, Michigan area and found that forest preserves add 19-35% to the selling price of lots adjacent to the preserve. With average Grand Rapids homes selling for $129,900 in 2015, the 19% premium is $24,681. Annualized over 50 years at a 3.5 percent discount rate, the value is $1,052 per home per year. We also assume that the preserved natural area would be adjacent to 12 lots. The total amenity value is therefore $12,627. Our analysis assumes that the conserved natural area would otherwise be converted to 0.9 acres of 100 percent impervious surface, which would generate 3,000 ft$^3$ WQv for a one-inch rain event. The resulting amenity value is $0.111/ft$^3$ WQv/year. Many of the services provided by mature (25+ year old) street trees were adapted for the conserved natural area green infrastructure practice, including the following: carbon dioxide storage at $0.029/ft$^3$/year; reduced air pollution at $0.004*342 trees = $0.013/ft$^3$/year; avoided stormwater at

$0.0017/ft$^3$/year; flood risk reduction at $0.005/ft$^3$/year; reduced total suspended solids at $0.041/ft$^3$/year; and reduced phosphorus at $0.007/ft$^3$/year. The total annual benefit from conserved natural areas was $0.208/ft$^3$/year.

The benefits from all GI practices are summarized in Table 7 and Figure 1.

*Table 7: Summary of benefits from GI practices.*

| | **Unit price of stormwater mitigation benefits (\$/ft$^3$ WQv/year)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **GI practice** | **Porous asphalt** | **Green roof** | **Rain garden** | **Street tree (medium)*** | **Infiltration bioretention** | **Conserve natural area** | **Rain barrel** |
| Avoided volume | 0.0017 | 0.0017 | 0.0017 | 0.0017 | 0.0017 | 0.0017 | 0.0017 |
| Flood risk reduction | 0.0051 | 0.0051 | 0.0051 | 0.0051 | 0.0051 | 0.0051 | 0.0051 |
| TSS pollution | 0.0359 | 0.0412 | 0.0410 | 0.0407 | 0.0410 | 0.0407 | 0.0410 |
| Phosphorus pollution | 0.0039 | 0.000 | 0.0086 | 0.0068 | 0.0086 | 0.0068 | 0.0086 |
| Amenity value | 0 | 0.0190 | 0.0323 | 0.0116 | 0 | 0.1115 | 0 |
| Energy savings | 0 | 0.0132 | 0 | 0.0243 | 0 | 0 | 0 |
| Air pollution reduction | 0 | 0.0163 | 0 | 0.0034 | 0 | 0.0126 | 0 |
| CO$_2$ storage | 0 | 0 | 0 | 0.0066 | 0 | 0.0292 | 0 |
| **Total annual benefits** | **0.0466** | **0.0965** | **0.0887** | **0.10-0.25** | **0.0564** | **0.2077** | **0.0564** |

* Benefits during first five years and increases thereafter.

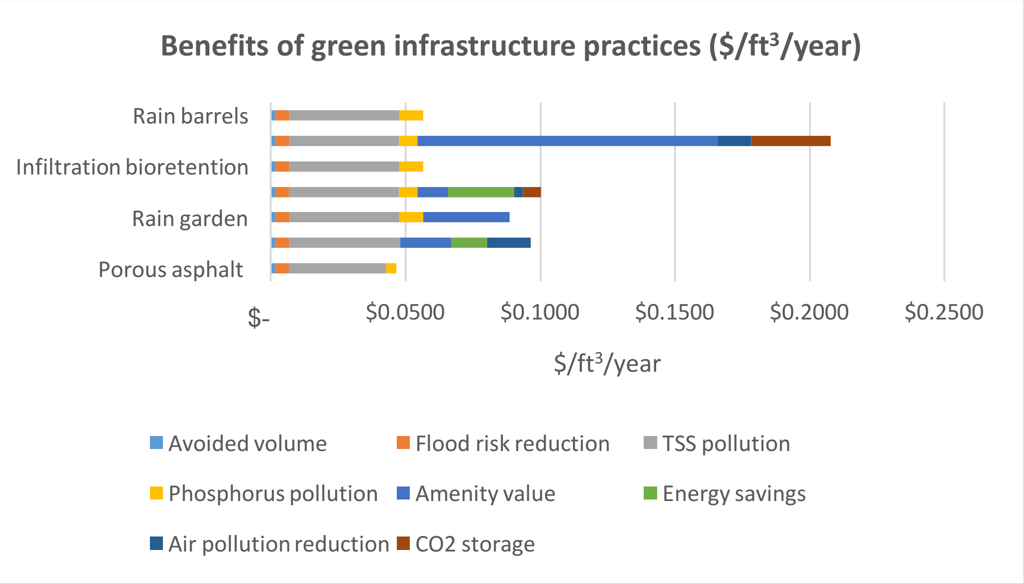

*Figure 1: Benefits of various GI practices. *Street tree benefits for the first five years, benefits increase with tree size.*

## GI costs

Green infrastructure costs were estimated using the WERF LID spreadsheet tools as a starting point and adjusted for inflation, technological advancements, and location-specific data.

### Porous asphalt

Century West Engineering compared, side-by-side, the capital costs of conventional and porous asphalt for a 3,200 ft$^2$ parking lot. The conventional asphalt lot cost \$23,680 to construct (\$7.40/ft$^2$) while the porous asphalt cost \$25,960 (\$8.11/ft$^2$). The comparison was conducted in Portland, Oregon in 2013. According to the Bureau of Labor Statistics, Portland's mean construction wage is \$25.64/hour and Grand Rapids' is \$21.04. This ratio (0.8) was used to adjust the Portland asphalt construction costs to Grand Rapids and the costs were adjusted for inflation to 2015 using the CPI. The adjusted capital costs were \$6.20/ft$^2$ for conventional asphalt and \$6.79/ft$^2$ for porous asphalt.

The figures were entered into the WERF LID cost model which includes 10% for engineering and planning and 20% for contingency. The total capital costs, including construction and development costs, were \$8.19/ft$^2$ (\$2.74/ft$^3$/year WQv) for conventional asphalt and \$8.96/ft$^2$ (\$3.00/ft$^3$/year WQv) for porous asphalt.

Both conventional and porous asphalt have maintenance costs. It was assumed that porous asphalt would have all the maintenance of conventional asphalt plus its own specialized maintenance. The Whitestone Facilities Maintenance and Repair Reference and the Operations Reference list recommended maintenance hours for specific tasks related to facilities management including parking lots (Abate et al., 2009). The schedule for each task is listed in the table below. The Bureau of Labor Statistics reports that the average construction wage in Grand Rapids was \$19.86 in 2015. This wage was used to calculate the cost for each task (Table 7).

*Table 8: Operations and maintenance costs for conventional asphalt.*

| O&M task | Frequency | Hours/ft$^2$ | Materials cost \$/ft$^2$ | Total cost \$/ft$^2$ | Total cost \$/ft$^3$/year WQv |
|---|---|---|---|---|---|
| Patch and seal | 5 years | 0.0006 | 0.07 | 0.09 | 0.03 |
| Resurface | 15 years | 0.0127 | 0.46 | 0.76 | 0.26 |
| Repair | 25 years | 0.0073 | 0.80 | 1.04 | 0.35 |
| Snowplow and sweep (weekly) | Annual | - | 0.03 | 0.03 | 0.01 |

Houle et al. (2013) estimated the maintenance costs for porous asphalt in New Hampshire. New Hampshire's cold climate is similar to that of Grand Rapids and thus is an appropriate comparison. Houle et al. estimated that the personnel costs would be \$939/ha/year (\$380/acre/year) and subcontractor costs would be \$1730/ha/year (\$700/acre/year). These values were adjusted to fit the Grand Rapids area by scaling them by the average construction and extraction occupation wages from the two cities as reported in the US Bureau of Labor Statistics' Occupational Employment Statistics. The figures were also adjusted for inflation to 2015 using the CPI. The additional maintenance costs for porous pavement were estimated at \$0.02/ft$^2$ (\$0.008/ft$^3$ WQv). The present value cost over fifty years comes out to \$3.54/ft$^3$ WQv for conventional asphalt and \$3.99/ft$^3$ WQv for porous asphalt (Table 9).

## Green and conventional roofs

A Michigan-based roofing contractor estimated the cost of a conventional commercial roof (2,000-10,000 $ft^2$) with a 25 year lifespan at roughly $10/$ft^2$ (K. Menard, Bloom Roofing, personal communication). Mr. Menard also estimated maintenance costs at about $0.05/$ft^2$/year. The Whitestone Facilities Maintenance and Repair Reference listed a specific schedule for roof maintenance over its lifetime. Annual maintenance tasks were $0.06/$ft^2$ ($0.07 in 2015 dollars) with more substantial periodic tasks at a cost of $0.11/$ft^2$ every five years and $3.15/$ft^2$ in year 15 (Abate et al., 2009). The entire roof would be replaced at the initial cost in year 25. For our analysis, we substituted Menard's local estimate for routine maintenance ($0.05/$ft^2$) in the Whitestone reference manual, keeping the periodic maintenance the same. Standardized by WQv, a conventional roof costs $3.31/$ft^3$ WQv in the first year with maintenance costs $0.02/$ft^3$ WQv/year.

A green roof requires the installation of a conventional roof underneath it. Therefore the cost of a green roof is additional to the conventional roof. Local refinements in the green roof estimates were provided by a local green roof company (J. Aleck, Live Roof, personal communication). In the Grand Rapids area, a delivered green roof systems costs $9-20/$ft^2$ plus installation costs of about $3/$ft^2$. For this project, we used an estimated installed cost of $15/$ft^2$. Green roofs require some maintenance which varies by the local environment, soil system, and type of plants used. A standard green roof with routine maintenance performed by in-house staff costs about $0.13/$ft^2$/year and about double that if the maintenance is outsourced to the green roof installer. Our analysis assumed that the maintenance would be done in-house. A green roof may extend the life of the conventional roof underneath it (Clarke et al. 2008). We assumed that the presence of the green roof would eliminate the need to replace the conventional roof in year 25. Standardized by WQv, a green roof has an installation cost, including the cost of a conventional roof of $8.24/$ft^3$ and a maintenance cost of $0.04/$ft^3$/year. The present value cost for the conventional roof was estimated at $5.77/$ft^3$ WQv and $9.23/$ft^3$ WQv for the green roof (Table 9).

## Rain garden

The 2,145 $ft^2$ of rain gardens needed to mitigate 3,000 $ft^3$ of stormwater was assumed to be spread over 11 residential homes (195 $ft^2$ per rain garden). The Washington State Department of Ecology estimated the installation and maintenance costs of rain gardens under the category of bioretention basin (Herrera Environmental Consultants, 2012). The mean of the reported low and average costs were $17.95/$ft^2$ and $0.73/$ft^2$/year for capital and maintenance costs, respectively. The construction wage differential between Washington and Michigan was used to adjust for location and the costs were adjusted for inflation using the CPI. The Grand Rapids costs for 2015 were $14.00/$ft^2$ for capital and $0.57/$ft^2$/year for maintenance. The WERF LID cost tool includes other costs, such as landscape design, first-year establishment, and periodic maintenance costs. For the 2,145 $ft^2$ of rain garden GI practice, the total capital cost is $32,788 plus regular maintenance costs of $1,223/year. Periodic maintenance tasks include replacing mulch every three years ($4,605) and tilling the soil every five years ($3,105). It was assumed that the rain gardens would be installed professionally. Opportunity costs of land were included as described above. Capital and maintenance costs could be substantially lower if homeowners or volunteers did the work themselves. Standardized on a per $ft^3$ WQv basis, the total first-year cost is $0.30/$ft^3$ WQv/year with a total present value cost of $1.03/$ft^3$ WQv (Table 9).

### Infiltration bioretention

The cost of bioretention infiltration basins was based on the cost estimates from the Puget Sound green infrastructure cost database (Herrera Environmental Consultants, 2012). The average published estimate, from 2014, was \$31.61/ft$^2$ and \$1.27/ft$^2$ in construction and maintenance costs, respectively. The average construction wage as reported by the BLS Employment Survey was used to adjust the costs from the Seattle area to Grand Rapids. Construction wages in Grand Rapids are about 75.4 percent of those in Seattle. The CPI was used to adjust the costs to 2015. The cost for bioretention construction, adjusted for location and time, was \$24.02/ft$^2$ and the adjusted maintenance cost was \$0.97/ft$^2$. The bioretention infiltration basin was sized at 3,049 ft$^2$. The total present value cost for a bioretention-infiltration basin was \$1.34/ft$^3$ WQv over fifty years (Table 9).

### Conservation of natural areas

Conserving natural areas comes with a high opportunity cost – the land will never contain income-producing structures. This opportunity cost of open space was estimated using Thorsnes' (2002) hedonic analysis of open space preservation in the Grand Rapids, Michigan area. The model included a variable for lot size. Thorsnes analyzed three developments around Grand Rapids. We chose to base our calculations on the model for the development closest to the city in adjacent Plainfield Township. The hedonic model yielded an elasticity of 0.0031 for lot size; that is, a one percent change in lot size (ft$^2$) results in a 0.3 percent change in housing sales price. The average residential sales price in 2015 was \$129,900 and the average lot size for the northeastern portion of Grand Rapids was 9,148 ft$^2$. The value of an additional square foot of lot size, therefore, was \$4.40/ft$^2$. The annualized value at a 3.5 percent discount rate was \$0.24/ft$^2$. Therefore conserving 0.9 acres of natural area would have an opportunity cost of \$0.08/ft$^3$ WQv/year and a present value cost over fifty years of \$1.94/ft$^3$ WQv (Table 9).

### Street trees

The costs of street trees, planted in stormwater-retaining tree pits, was taken directly from the Midwest Community Tree Guide which lists the costs for planting and maintaining a tree for 40 years in five year increments (McPherson et al., 2006). The costs were adjusted for inflation to 2015 dollars. The guide presents small, medium, and large tree size options; we chose medium, such as red oak, which is common in the area. The cost of planting a tree was \$200 (\$244 in 2015) or \$0.74/ft$^3$ WQv. Total maintenance costs, which include pruning, removal and disposal, treating pests and disease, infrastructure repair, irrigation, cleanup, liability and legal costs, and administrative costs, were \$55.21-33.00 per year (\$18.57-40.26 per year in 2015 dollars). Standardized to WQv, the maintenance costs range from \$0.06/ft$^3$ to \$0.12/ft$^3$. Though the WERF LID cost tool includes a concrete tree vault in the default setting for street trees, the Forest Service analysis did not include a tree vault. Tree vaults, which may cost more than \$1,000, were not included in our analysis. The total present value cost of the street trees over fifty years was \$2.92/ft$^3$ WQv (Table 9).

### Rain barrels

Rain barrels are commercially available at hardware stores. A national chain was selling basic-style 55-gallon rain barrels for \$90 per barrel (The Home Depot, 2015). The rain barrels were assumed to be replaced at the same cost every ten years. There is no operation and maintenance cost for rain barrels. The total present value cost for two rain barrels was \$0.11/ft$^3$ WQv (Table 9).

## Opportunity cost of land

Green roofs and porous asphalt parking lots are co-located with existing infrastructure. Rain gardens and street trees, however, replace other valuable resources such as lawn space or sidewalks. The opportunity cost needs to be accounted for. The opportunity cost was calculated using the value of a square foot of residential lot size in the Grand Rapids metropolitan area. The opportunity cost of land for rain gardens, bioretention ponds, and street trees was calculated using the same method as that for conservation of natural areas. For the 2,145 ft$^2$ of rain garden the opportunity cost equates to \$0.0036/ft$^3$/year of WQv. This same opportunity cost was applied to the 342 street trees and the bioretention-infiltration systems. Rain barrels have no opportunity cost for land.

*Table 9: Cost for green infrastructure practices.*

| Infrastructure / GI type | GI practice size (for 3,000 ft$^3$ WQv reduction per one-inch event) | PV cost | PV cost / ft$^3$ WQv | PV cost / unit of GI practice |
|---|---:|---:|---:|---:|
| Conventional asphalt | 37,897 ft$^2$ | \$400,395 | \$3.54 | \$10.57/ft$^2$ |
| Porous asphalt | 37,897 ft$^2$ | \$451,397 | \$3.99 | \$11.91/ft$^2$ |
| Conventional roof | 37,500 ft$^2$ | \$653,062 | \$5.77 | \$17.41/ft$^2$ |
| Green roof | 37,200 ft$^2$ | \$1,045,565 | \$9.23 | \$28.11/ft$^2$ |
| Rain garden | 2,145 ft$^2$ | \$116,816 | \$1.03 | \$54.46/ft$^2$ |
| Infiltration bioretention | 3,049 ft$^2$ | \$151,447 | \$1.34 | \$49.67/ft$^2$ |
| Conserve natural areas | 37,897 ft$^2$ | \$220,017 | \$1.94 | \$5.81/ft$^2$ |
| Street tree (medium) | 342 trees | \$359,665 | \$3.18 | \$1,051.65/tree |
| Rain barrels | 2 - not standardized to 3000 ft$^3$ | \$507.66 | \$0.31 | \$253.85/barrel |

# Results

The NPV analysis shows that five of the seven green infrastructure practices have positive net present values under the base case assumptions (Table 10, Figure 2). Conserving natural areas had the highest net benefits (\$3.10/ft$^3$) followed by street trees (\$1.48/ft$^3$) and rain gardens (\$1.12/ft$^3$) and. Porous asphalt also had a positive net present value (\$0.68/ft$^3$) as did infiltration bioretention (\$0.03/ft$^3$). Rain barrels had a positive NPV (\$1.06/ft$^3$) but these were not analyzed on the same scale as the other practices and should not be directly compared. Green roofs, however, had a negative net present value of \$-1.12 under the base case assumptions. Green roofs provided the highest benefits but also had the highest costs.

Porous pavement replaces the conventional pavement “gray infrastructure.” The green roof is compared to the conventional roof it would replace. In all other cases, the green infrastructure is additional to, and does not replace, gray infrastructure. The benefits of green infrastructure in this study come primarily from avoided stormwater volumes which are associated with reduced O&M costs, flooding, and pollution as well as, in some cases, enhanced scenic amenities. New developments in which green infrastructure practices are implemented explicitly to manage stormwater on-site may reduce the capital costs of gray infrastructure. However in the City of Grand Rapids, as in most urban areas, the existing gray infrastructure will not be removed or significantly reduced.

*Table 10: Net present value for GI practices.*

| Infrastructure / GI type | GI size (for 3,000 ft$^3$ WQv per 1" event) | PV benefits ($/ft$^3$ WQv) | PV cost GI ($/ft$^3$ WQv) | PV cost of gray ($/ft$^3$ WQv) | Net Present Value ($/ft$^3$ WQv) |
|---|---|---|---|---|---|
| Porous asphalt | 37,897 ft$^2$ | $1.13 | $3.99 | $3.54 | $0.68 |
| Green roof | 37,200 ft$^2$ | $2.34 | $9.23 | $5.77 | $-1.12 |
| Rain garden | 2,145 ft$^2$ | $2.15 | $1.03 | - | $1.12 |
| Bioretention infiltration | 3,049 ft$^2$ | $1.37 | $1.34 | - | $0.03 |
| Conserve natural area | 37,897 ft$^2$ | $5.04 | $1.94 |  | $3.10 |
| Street tree (tree pit) | 342 trees | $4.66 | $3.18 | - | $1.48 |
| Rain barrel | 2 barrels* | $1.37 | $0.31 |  | $1.06 |

*Not standardized to 3,000 ft$^3$

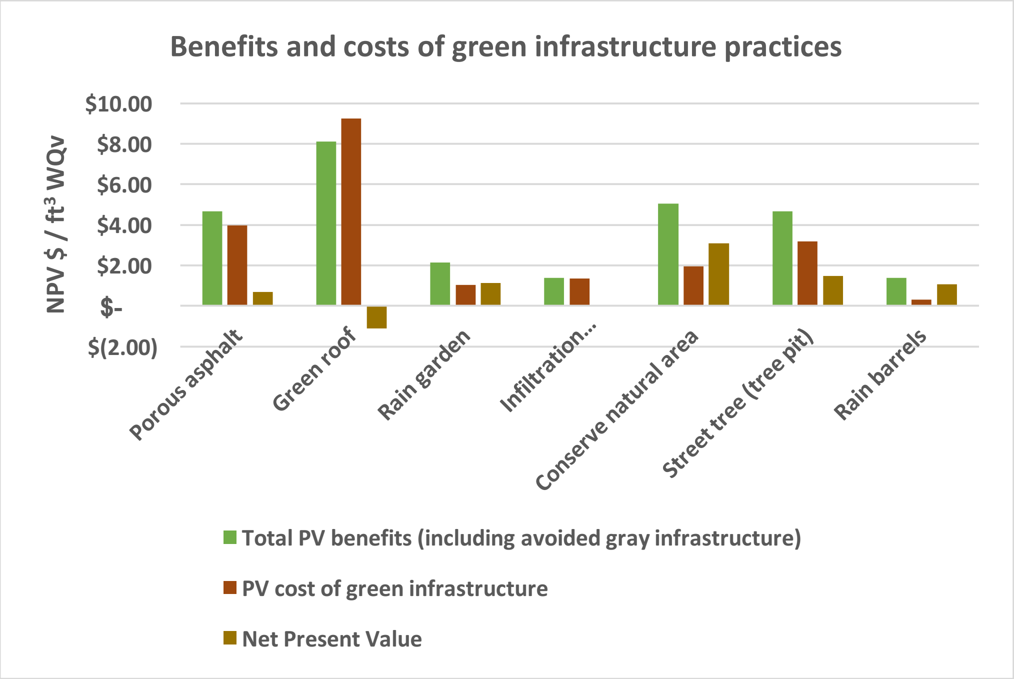

*Figure 2: Benefits, costs, and NPVs of GI practices.*

## Discussion

The GI practices showed a high degree of variability among their net present values. Conservation of natural areas owes its high NPV primarily to the amenity value it brings to a neighborhood. The scenic amenity value accounts for more than half of the total annual benefit ($0.11/ft$^3$ out of $0.21/ft$^3$). The cost of conserving natural areas comes from the opportunity cost of development. We assumed these areas would be kept in a relatively natural state without maintenance costs. While there could be some additional costs associated with this, such as deer and other wildlife eating residential garden plants, these were difficult to quantify and were not included in the analysis. The premium paid on lots adjacent to the conserved natural area, especially when combined with the suite of other ecosystem services, outweighs the opportunity cost. This suggests that low-impact development patterns that concentrate development in one area while leaving natural areas intact can be a highly cost-effective practice. It is cheaper to avoid generating stormwater runoff rather than treating it later on. This requires, however, considerable planning and long-term commitment. Natural areas are often scarce in cities like Grand Rapids so this practice may have limited potential outside of greenfield development sites.

Street trees were second in terms of net present value at $\$1.48/\text{ft}^3$ WQv. Street trees, when planted in stormwater retaining tree pits, provide substantial benefits over their lifetimes. Trees, however, take time to mature and the full benefit of street trees takes decades to be realized. Since 2006, costs for electricity and heating have increased faster than the general rate of inflation. Updating the McPherson study with current costs, as well as with additional water pollution benefits, shows that street trees are even more valuable than once thought. The present value costs are relatively low compared to porous asphalt and green roofs. Mature trees provide a high level of benefit but it takes decades for the trees to grow. Even with a reasonable discount rate, the benefits of street trees still exceed the costs. This all suggests that street tree planters are cost effective under a wide range of assumptions.

Because of the low capital and O&M costs (PV cost = $\$2.15/\text{ft}^3$ WQv), rain gardens are an attractive GI practices for homeowners and small commercial property owners. These had the third-highest NPV of the green infrastructure practices evaluated. Our analysis assumed that the rain gardens would be professionally installed. The net benefits could be even higher if the property owners install the rain garden themselves or with volunteer help. Rain gardens are also highly scalable and can be used on large or small city lots.

In our analysis, the present value cost of porous asphalt is about ten percent higher than that of conventional asphalt. Porous asphalt has positive net benefit of $\$0.68/\text{ft}^3$WQv. Studies from the University of New Hampshire's stormwater center showed that porous asphalt can be a cost-effective solution even in cold climates similar to that of Grand Rapids (Houle et al., 2013). Though porous asphalt is effective at reducing stormwater volumes and treating water pollution, it does not provide any amenity benefits like the other green infrastructure practices considered here. Parking lots are ubiquitous and, according to our results, managing stormwater from parking lots using porous asphalt results in greater overall net benefits than using bioretention infiltration systems.

We assumed that the entire impervious area would be paved with porous asphalt. That may not be necessary, however, as strategically placed areas of porous asphalt can effectively treat impervious areas that drain to it. This would reduce the needed area of porous asphalt and thus reduce the project cost. The City of Grand Rapids is already experimenting with strips of porous asphalt in the parking lanes of some city streets.

The bioretention-infiltration basin practice had a barely positive net present value ($\$0.03/\text{ft}^3$ WQv). Bioretention-infiltration basins act as large rain gardens. Unlike rain gardens, the basins are usually not planted with wildflowers and are not viewed as scenic amenities (Lee and Li, 2009). In cases where detention ponds were designed as multi-use community resources, including recreation facilities, Lee and Li did find an amenity value. Building such multi-use structures requires additional costs to achieve those benefits and those are not directly tied to the functioning of the basin itself. The net benefits of the infiltration bioretention practice could be improved if cost-effective scenic and recreational amenities are included in the design. Lee and Li found that, all else being equal, decreasing the distance to the multi-use detention basin increased home sale prices at a rate of about \$16/foot. The cost of building and maintaining a bioretention-infiltration basin was also higher than that of a rain garden because of the community-level scale of most projects.

A green roof has the highest present value cost (\$9.23/ft$^3$ WQv) of all the practices surveyed and a premium of \$4.83/ft$^3$ WQv over a standard roof. However a green roof also has substantial present value benefits (\$2.34/ft$^3$ WQv) which climb even higher when the avoided cost of roof replacement is accounted for (\$8.11). The net benefits, however, are negative (\$-1.12/ft$^3$ WQv) using the mid-range installation cost of \$15/ft$^2$. The green roof's PV cost (including the conventional roof below) is 60 percent higher than a conventional roof alone. This is considerably higher than the green roof capital cost premium (39 percent) found by Clark et al. (2008) but consistent with other estimates (Carter and Keeler, 2008, Sproul et al., 2014). The green roof installer provided a range of capital costs from \$9/ft$^2$ to \$20/ft$^2$. A capital cost of \$11.50/ft$^2$ is the break-even point. Below this cost, the green roof's net present value, all else being equal, would become positive. Note that \$11.50 /ft$^2$ is still within the quoted capital cost range. Under certain circumstances that enable a low cost installation, the green roof could be cost-effective. Alternatively, a positive NPV (\$0.25/ft$^3$ WQv) can be achieved if the amenity value is equal to or greater than seven percent of the property price. This level would be similar to the lower bound of Ichihara and Cohen's analysis of green roofs in New York City. Many small to mid-size Midwestern cities have adequate access to ground-level public green space compared to highly urban New York City. The City of Grand Rapids has eighteen buildings with green roofs (Greenroofs.com, 2015). Building owners evidently are willing to pay for green roofs, so their amenity values may be greater than the 1.9 percent of sales price higher than we estimated here.

Many of the green roofs in Grand Rapids are installed to achieve LEED certification (J. Aleck, LiveRoof, personal communication). Studies have shown that office space in LEED certified buildings rents at a premium of 4-7 percent as compared to similar buildings without such certification (Fuerst and McAllister, 2011; Reichardt, 2013). Office space in Grand Rapids rents for on average \$13.25/ft$^2$/year. The rent premium for a LEED certified building, therefore, would be about \$0.53-0.93/ft$^2$/year. If we assume that the commercial building is 37,200 ft$^2$(LoopNet, Inc., 2015) , which is the area of the green roof in our scenario, and one story, the LEED certification premium would be \$19,716-34,596/year. This premium could offset the cost of some of the more expensive green infrastructure practices, such as green roofs. A green roof can contribute up to 5 to 23 points toward the 40 points needed for basic LEED certification. Assuming all LEED points are valued equally, a green roof that contributed 8.5-15 points toward certification (21-38 percent) would have a LEED amenity value of about \$0.11-\$0.20/ft$^2$ or \$0.04-\$0.07/ft$^3$ WQv. A modest LEED amenity value of \$0.15/ft$^2$ (\$0.05/ft$^3$ WQv) would be enough to flip the green roof to a positive NPV (\$0.16/ft$^3$ WQv). This LEED amenity value of green infrastructure was not included in the analysis because not all green infrastructure practices are implemented to achieve LEED, Energy Star, or other sustainability ratings.

This benefit-cost analysis comprehensively documented the values associated with GI practices. Some values, however, are more certain than others. The amenity values for rain gardens and green roofs in particular are understudied. Our literature review found one study of rain garden amenity values (Polyakov et al., 2015) and one for green roofs (Ichihara and Cohen, 2010). Rain gardens have grown in popularity so it should be possible to see whether their presence affects housing values. Green roofs are still relatively rare but becoming more common. Grand Rapids itself is home to about one percent of all known green roofs (Greenroofs.com, 2015). Green roofs are a major investment for a commercial building so we may not expect building owners to sell them soon. In time, however, commercial buildings with green roofs should come on the market and their amenity value could be assessed.

Rain barrels do not function at the same scale as the other green infrastructure practices assessed here. For individual households, however, rain gardens are a cost effective choice for managing stormwater. Rain barrels are a low-cost option with a positive net present value (\$1.06/ft$^3$ WQv). The water from rain barrels is usually used to irrigate flower beds. This analysis did not include the economic value of the water used for this purpose which would raise the net present value further. Two rain barrels capture a small fraction of property's total runoff. Rain barrels can be used to complement other, more comprehensive green infrastructure practices.

## Validation

The estimates used in this benefit-cost analysis were validated against an actual green infrastructure project implemented in the City of Grand Rapids. Grand Rapids built the Plainfield Islands bioretention structures in 2015. It is a system of seven bioretention "islands" along a large urban road. Though it is referred to as a bioretention structure, the islands are planted with trees and flowers that add a substantial scenic amenity. In this unique case, it seems appropriate to use the costs for the infiltration bioretention practice, reflecting the highly-engineered structure, and the benefits for the rain garden, which include the scenic amenity. The total drainage area is 2.2 acres and the bioretention area is 0.1 acres. Based on the NYS Stormwater Toolbox, a 2.2 ac area would generate 286,398 ft$^3$ WQv per year in rainfall events up to one inch plus the first inch of larger events. We estimated the total present value cost of bioretention-infiltration practices at \$1.34/ft$^3$ WQv. Therefore we estimated the capital cost at \$185,013 (\$31/ft$^2$) and the total present value cost of the Plainfield Islands bioretention system at \$518,380 (\$87/ft$^2$). The actual construction cost, not including O&M costs, was \$328,000 or \$55.12./ft$^2$. Our capital cost estimate is lower than the actual cost. The Plainfield Islands structure was significantly larger and more complicated than our base case scenario of a simple infiltration bioretention basin. While imperfect, this validation exercise suggests that our cost estimates are reasonable.

## Policy

This benefit-cost analysis of green infrastructure practices has policy implications for Grand Rapids and other small to mid-size Midwestern cities. First, green infrastructure practices provide a suite of benefits including stormwater volume reduction, air and water pollution reduction, and scenic amenities. The traditional gray infrastructure provides a far more limited suite of benefits, often managing just for stormwater volumes. Therefore investments in green infrastructure practices provide far more value for each dollar invested. Second, the net benefits from green infrastructure practices, though variable, are mostly positive. Third, the benefits are largely external to the property owners. That is, the costs of green infrastructure practices are borne by the landowner but the benefits accrue to the public. This results in a market failure – fewer green infrastructure practices will be implemented than are socially optimal. There is a strong argument for public policy to provide incentives – financial, knowledge, or otherwise – for more private investment in green infrastructure practices.

A stormwater utility fee may be the most economically efficient policy to incentive green infrastructure practices. For example the City of Ann Arbor, Michigan, USA, implements a stormwater utility fee (City of Ann Arbor, 2015). The advantage of a stormwater utility is that it puts a price on runoff from impervious surfaces, thus internalizing the externality. Landowners have the flexibility to either pay the fee, or reduce their runoff by investing in the most cost-effective green infrastructure practices. Pricing stormwater runoff also fosters innovation by rewarding entrepreneurs who can invent next-generation green infrastructure practices.

Policies can also overcome knowledge and institutional barriers. Barnhill and Smardon (2012) identified three major barriers that limit investment in green infrastructure: the "public good" market failure; a lack of knowledge about the true costs and benefits; and challenges in framing the issue. The market failure could be addressed by a stormwater utility. A comprehensive outreach and education program could provide more accurate, relevant, and timely information to residents and landowners about green infrastructure. Barnhill and Smardon's work suggest the outreach will be more effective if it is framed in terms of neighborhood regeneration, sustainability, and social equity. This benefit-cost analysis was used to create a publicly available, web and mobile-based GI calculator, and to inform outreach and education campaigns in the Cities of Grand Rapids and Muskegon, Michigan. The research team is collaborating with regional partners and local government units to encourage landowners to adopt green infrastructure practices.

## Conclusions

The benefit-cost analysis for the various green infrastructure GI practice shows that porous pavement, rain gardens, infiltration bioretention, conserving natural areas, and street trees are cost-effective options. The life-cycle costs of green roofs on their own exceed their benefits but they can be cost-effective as part of a LEED certified building. No one GI practice is appropriate for all situations. Rather the choice of GI practice will be driven by the site and budget. Porous asphalt is an attractive GI practice given that parking lots are necessary and the additional capital and O&M costs over conventional asphalt are modest. Rain gardens are low-cost and attractive options for small sites like homes and street corners. Infiltration bioretention basins can be effective for treating larger areas of impervious surface. If scenic and recreational amenities are incorporated into the design they may be even more cost-effective. Conserving natural areas requires substantial up-front planning and a willingness to forgo immediate income. Over the fifty-year project life cycle, the benefits of the conserved areas more than make up for the opportunity cost of development. Street trees take time to fully provide the suite of stormwater mitigation and other ecosystem services, but their benefits are still greater than the lifetime costs. Rain barrels are a cost-effective, small-scale option for residences.

With the array of options available to manage stormwater on site, municipalities like Grand Rapids are well-positioned to adopt the GI practices that are most appropriate.

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