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

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Abstract

Grand Rapids, Michigan, USA is a medium-sized city located within the Lake Michigan watershed. Grand Rapids spends considerable money managing stormwater. Impervious surfaces collect and concentrate volumes of water and associated sediments and pollutants creating flooding, erosion, and pollution problems especially, for downstream communities. An ecological paradigm has emerged that places stormwater quantity and quality within the context of integrated watershed management. Stormwater quantity can be reduced and quality can be improved by, for example, mimicking natural hydrology. Detailed benefit-cost analyses, however, are still lacking. Therefore, the research team estimated the economic benefits and costs of various green infrastructure (GI) practices. Each GI practice was standardized to treat 84.95 m^3 (3,000 ft^3) of stormwater per 25.4 mm (1.0 inch) event plus the first 25.4 mm of stormwater from larger events. This equates to about 3,030 m^3 (107,000 ft^3) of stormwater per year. A benefit transfer approach was used 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, total phosphorus, total suspended solids, 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 NPV at \$109/m^3 of water quality volume (WQv) reduced, followed by street trees at \$46/m^3 WQv, rain gardens at \$37/m^3 WQv, and porous asphalt at \$21/m^3 WQv. Infiltrating bioretention basins and green roofs had negative NPVs of \$-3.76/m^3 WQv and \$-47.17/m^3 WQv, respectively. If the green roof is used to attain certification such as Leadership in Energy and Environmental Design, then the net benefits turn positive. This paper will help both academic researchers and stormwater managers in the Great Lakes region and beyond understand the relative benefits and costs of stormwater GI so cost-effective practices can be implemented. The calculations presented here form the basis of the www.RainwaterRewards.com stormwater GI calculator.

Keywords: green infrastructure; benefit-cost analysis; porous pavement; rain garden; urban forest; green roof

1. Introduction

Local governments 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). Governments have strong incentives to reduce expenditures by reducing stormwater volumes. Reducing runoff volumes also reduces the risk of floods and the amount of pollution entering waterways.

The dominant paradigm in stormwater management in the 20th century was moving water offsite quickly through ditches and pipes ("gray infrastructure") and into the nearest waterbody. Though effective at preventing ponding, moving large quantities of water into waterways resulted in flooding, erosion, and pollution problems for downstream communities. An ecological paradigm emerged in the 1990s that placed stormwater quantity and quality within the context of integrated watershed management and low impact development. Stormwater quantity can be reduced and water quality can be improved by 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). This ecological paradigm for onsite stormwater management goes by many names: green infrastructure, low impact development, stormwater best management practices, and others. Though their definitions may differ slightly, they all refer to decentralized practices that reduce the quantity of stormwater entering waterbodies. These practices are referred to simply as green infrastructure (GI) for the sake of consistency in this manuscript.

The gray infrastructure paradigm emphasizes public infrastructure built, maintained, and operated by the municipality. Stormwater infrastructure is a pure public good: everyone can benefit from it without using it up ("non-rival") and once it is built, the municipality cannot exclude anyone from enjoying its benefits ("non-exclusive") (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 downstream neighbors (a free-rider problem). 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, or porous pavement. The misalignment of incentives results in a market failure. In the absence of public 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 gray infrastructure. It is not just about the costs; it is also about who pays them.

Evidence is mounting that GI practices can be cost-effective. The Center for Neighborhood Technology (CNT) found that a municipal level GI 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 GI 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 GI.

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 six GI practices: porous asphalt; green roofs; rain gardens; infiltrating bioretention basins; conservation of natural areas; and street trees. 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 GI 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.

This project builds on previous work in valuing ecosystem services. The INtegrated Valuation of Ecosystem Services Tool (INVEST, http://www.gvsu.edu/wri/invest/) was developed to educate community planners and landowners about the value of ecosystem services associated with non-urban land uses in West Michigan (Isely et al., 2010a, Isely et al., 2012). The team conducted an integrated assessment of the Spring Lake (Michigan) watershed including calculations of direct, indirect, and opportunity costs and benefits for various GI practices and stormwater retrofits (Isely et al., 2010b, Isely, 2014). The new Rainwater Rewards calculator has updated cost and benefit information for stormwater GI practices most likely to be found in small and medium-size cities in the Great Lakes basin. The Rainwater Rewards calculator is the centerpiece of a community engagement strategy on stormwater management GI.

This paper is novel in several ways. First, it standardizes both costs and benefits in terms of avoided runoff (water quality volume, WQv). Most other analyses compare costs based on the area of GI, but not all GI practices are equally effective on an area basis. Second, it provides the most up-to-date estimates of GIS costs and benefits. Third, it uses economics to quantify the non-stormwater benefits of GI, such as aesthetics. Fourth, it serves as a model for benefit-cost analysis of stormwater management in other watersheds, both inside the Great Lakes basin and around the world. The paper will be of value to both academic researchers and stormwater managers.

1.1 Study area

Grand Rapids, Michigan, USA is a medium-sized city of about 200,000 residents located within the Lake Michigan watershed, one of the five North American Great Lakes (Figure 1). Green infrastructure is a key aspect of Grand Rapids' approach for sustainability. The city government has adopted both a Sustainability Plan and the Green Grand Rapids Master Plan (https://www.grandrapidsmi.gov/Government/Departments/Sustainability). The city's Environmental Services Department has constructed several rain gardens and infiltration basins within the city, including an infiltration basin underneath Mary Waters Park that will process the rainfall from a 90th percentile storm over a 34 ha drainage area. Sustainability is also part of the regional corporate culture. Grand Rapids is renowned for its office furniture industry, including Herman Miller, Steelcase, and Haworth, which has a strong commitment to sustainability and is implementing many GI practices

(Nordman et al. 2017). Grand Rapids, therefore, is an ideal location to study GI practices and serve as a model for other cities in the Great Lakes watershed and beyond.

Figure 1: Grand Rapids, Michigan, USA lies within the Lake Michigan watershed.

2. Literature review

2.1 Estimating GI costs

The most comprehensive and accessible resource on the benefits and costs of stormwater GI to date is the Green Values Stormwater Toolbox Calculator from the CNT (Center for Neighborhood Technology, 2007). The calculator uses a relatively simple web interface that allows users to enter lot-specific information and calculate stormwater runoff volume and reduction. Cost estimates considered both construction and operation and maintenance costs.

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, graywater and blackwater sewage systems, and stormwater management using bioswales, wetlands, green roofs, and rain gardens. The planned GI-based development in the Montreal suburb of Vaudreuil-Dorion would cost 11-29 percent more than a conventional design. Housing values, however, were 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 life-cycle cost models of best management practices and low impact development (Moeller and Pomeroy, 2009). The cost models allow practitioners to estimate the capital, operations, and maintenance costs for each GI 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.

Clark et al. (2008) assessed a green roof's net present value (NPV) compared to that of a conventional roof at the University of Michigan. The conventional roof's mean cost was \$167/m^2 in 2008 (\$17.14/ft^2

in 2015). A green roof's mean cost (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 (a stormwater charge based on impervious surfaces). The green roof's amenity value was not included, nor were the operation and maintenance costs for green or conventional roofs. The analysis showed that the green roof's NPV was 25-40 percent less than that of a conventional roof. Energy savings and pollution reduction benefits were greater than the avoided stormwater fees. The lifetime benefits outweighed the green roof's higher capital costs.

Bianchini and Hewage (2012) also reported a positive NPV for green roofs (\$398/m^2 (\$37/ft^2)). Other researchers have found negative NPVs for green roofs. For example, Carter and Keeler (2008) found that the present value cost of a green roof in Georgia was 10-14 percent higher than that of a conventional roof. Sproul et al. (2014) found that green roofs have a higher net cost over their lifetime. Neither of these studies, however, included scenic amenity values for green roofs. Claus and Rousseau (2012) conducted a benefit-cost analysis of green roofs in Flanders using both private and social benefits and a range of discount rates. When only accounting for the private (building owner) benefits, the green roof had a positive NPV if a low (4%) discount rate was used or if it was subsidized by the government. When the social benefits were also included, the NPV was positive under low discount rates in the base case and best case scenarios. However, it was negative in the worst case scenarios under all discount rates.

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 discount rates higher than four percent tend to result in negative NPVs.

Ichihara and Cohen (2010) used a hedonic model to investigate the effect of green roofs on apartment rents in New York City. 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). Researchers in Finland used Helsinki's small parks as a proxy for green roofs. They estimated that a view of a green roof would raise property values by up to 1.2 percent (Nurmi et al., 2016). 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.

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 total phosphorus (Houle et al., 2013). Similarly, Rodríguez-Sinobas et al. (2017) showed that porous pavement and other GI practices effectively managed urban stormwater in Madrid, Spain.

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, 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).

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 that currently limit green infrastructure implementation. First is the homeowner financial cost. The costs of 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 of 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.

2.2 Benefit transfer methodology

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. In most cases, unit value transfers result in unacceptably high errors and are usually not recommended. Benefit function transfers may be more accurate, but are also more complicated. Johnston et al.'s review also presented a ten-step procedure for conducting a benefit transfer. Our benefit-cost analysis of GI used benefit function transfer and the procedure recommended by Johnson et al. (2015).

3. Materials and methods

3.1 Runoff estimation

The New York State Department of Environmental Quality created the Construction Stormwater Toolbox to assist owners and operators in complying with planning requirements under the New York State

Pollutant Discharge Elimination System (SPDES). The Toolbox includes a set of Excel-based runoff reduction worksheets that are rigorous enough for SPDES compliance, yet flexible enough to be adopted in many circumstances (NYS Dept. of Environmental Conservation, 2014). Much of New York State lies within the Great Lakes basin and has a climate like that of Michigan's Lower Peninsula. The project team deemed the New York State runoff reduction worksheets suitable for use in Michigan and were used to establish baseline runoff volumes and calculate the runoff reduced by implementing 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. The Toolbox, as well as other studies (e.g. Houle et al., 2013), used the 90th percentile 24-hour rain event as the design criterion for stormwater management. In Michigan, the 90th percentile ranged from 19.6 mm to 25.4 mm (0.8-1.0 inches) (Kuhns and Ulasir, 2015). The upper bound (25.4 mm) was used as the design criterion. The research team assumed that the GI practices would prevent all stormwater runoff for rain events up to and including 25.4 mm as well as the first 25.4 mm of larger events. Ten years (2006-2015) of rainfall data from the Gerald R. Ford International Airport in Grand Rapids were analyzed (Weather Underground 2016). The ten-year average annual rainfall in Grand Rapids was 1,016.0 mm (40.0 in) and ranged from 823.7 mm (2007) to 1,239.3 mm (2008). The sum of rainfall events up to and including 25.4 mm, as well as the first 25.4 mm of larger events, averaged 908.1 mm (35.75 in) per year.

3.2 Economic valuation and GI practice size standardization

The installation, maintenance, and opportunity costs of the GI practices were 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 NPV equation below (Equation 1). B_i and C_i are the values of the benefits and costs, respectively, accruing in year i. The discount rate is r and the net benefits are summed over the life of the project (n). A 3.5 percent real 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) and was consistent with many of the analyses described in Section 2 Literature Review. The City of Grand Rapids uses a 50-year infrastructure planning horizon which is replicated in this analysis. All GI practices were modeled over 50 years, including appropriate replacements at intervening years (see Appendix for details). Where necessary, cost and benefit values from the literature were adjusted to the Grand Rapids policy site. The Consumer Price Index from the US Bureau of Labor Statistics was used to adjust for inflation to year 2015 dollars.

Equation 1: Calculation of net present value.

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

Where green infrastructure was compared to gray infrastructure, the net cost of green infrastructure was calculated using Equation 2:

Equation 2: Calculation of PV costs when green infrastructure replaces gray infrastructure.

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

Many studies, particularly those analyzing a single GI practice, calculate the benefits and costs on area ($\$/m^2$). However, GI practices are not equally effective at treating stormwater on an area basis. For example, one m^2 of green roof does not necessarily treat the same amount of stormwater as one m^2 of infiltrating bioretention. Street trees have large canopies to intercept rainfall, but the tree pits in which they grow occupy relatively small areas along a city sidewalk. Comparing the NPVs across GI practices therefore required the standardization based on the volume of stormwater treated. Each GI practice was standardized based on a water-quality volume (WQv) reduction of 84.95 m^3 (3,000 ft^3) for a 25.4 mm 24-hour rain event using the NYS Stormwater Construction Toolbox (Table 1). The 84.95 m^3 level was chosen to reflect the size of a GI practice that would be meaningful at the neighborhood or census block level. The toolbox calculates the size of the GI practice needed based on the area's rainfall regime, total drainage area, and impervious area. The term "reduction" refers to the reduction in stormwater entering the storm drain systems. Most GI practices slowly release the water into the ground or let it evaporate.

Once the size of the GI practice was determined, the cost for each was estimated using WERF's Low Impact Development (LID) Cost Tools. Costs and benefits were calculated in constant 2015 dollars. The paper's main body presents the summary present-value benefits and costs for each GI practice. The details of the benefit and cost calculations are presented in the Appendix.

Table 1: Amount of green infrastructure required to reduce 84.95 m^3 of runoff per 25.4 mm rain event. The total (drained) area includes the impervious area.

GI practice	Total (drained) area (ha)	Impervious area (ha)	Area (ha) required to reduce 84.95 m^3 WQv per 25.4 mm event	Annual runoff avoided (m^3) (all events $\leq$ 25.4 mm plus 25.4 mm from larger events)
Porous asphalt	0.35	0.35	0.35	3,037
Rain garden	0.79	0.33	0.02	3,039
Green roof	0.35	0.35	0.34	3,037
Infiltrating bioretention	0.40	0.35	0.03	3,037
Conservation of natural areas*	0.35	0.00	0.35	3,037
Street tree (tree pit)**	0.97	0.32	342 trees	3,037

*reduced total area by 0.35 ha, not actual stormwater volume

**reduced impervious surface area by 0.32 ha, not actual stormwater volume

3.3 Value of avoided runoff, pollution, and flood risk reduction

The project assessed the net benefits of stormwater management through gray and green infrastructure. 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, primarily through conventional gray infrastructure, was estimated from the City of Grand Rapids which completed a Stormwater Asset Management and Capital Improvement Plan (City of Grand Rapids, 2014). Only the annual variable costs of corrective and preventative maintenance were used to estimate the value of avoided runoff. After adjusting for inflation to 2015 dollars using the Consumer Price Index (CPI), the systems' total annual maintenance cost was $2,898,804.

A feature extraction process using Landsat imagery with a ground sample distance of 30 m x 30 m found 5,128 ha (12,671 acres) of impervious surface (44%) in the city (Xian et al., 2011). At the average 1,016.0 mm (40.0 in) of annual rainfall, each hectare generates 9,651.93 m^3/year of runoff, or 49,493,253 m^3/year for the whole city. The annual maintenance cost per unit of stormwater treated was estimated at \$0.0586/m^3/year (\$0.0017/ft^3/year).

In addition to reducing stormwater volumes, GI practices reduce water pollution. The annual pollution load from a particular site was estimated using the following formula for the so-called Simple Equation (Landphair et al., 2000) (Equation 3):

Equation 3: Calculation of pollution load.

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

Where R_v is the runoff-to-rainfall ratio, *C* is the pollution concentration, and 0.2266 is the units conversion factor. Weiss et al. (2007) reported pollution concentration values for total suspended solids (TSS) and total phosphorus (TP) and the Minnesota Stormwater Manual reported the pollution reduction efficiency for various GI practices (Appendix Table A1). Note that green roofs do not remove phosphorus from stormwater (Minnesota Pollution Control Agency, 2015).

The economic value of removing TSS and TP was estimated from the treatment cost from a wastewater treatment plant. Adjusted for inflation, these costs are \$5.93/lb (\$13.07/kg) for TSS and \$251.25/lb (\$553.91/kg) for TP (WSB & Associates, 2008). Multiplying the pollutant reduction amount (kg) by the unit cost (\$/kg) resulted in the value of stormwater removal for each m^3 of WQv avoided per (Appendix Table A1).

Reducing the volume of stormwater entering area lakes and rivers also reduces the risk of flooding in downstream locations. For example, Petit-Boix et al. (2017) found that GI, specifically a filter, swale, and infiltration trench, reduced flood damage from high-intensity rainfall events. In 2013, the Grand River flooded and caused an estimated \$450 million in damages to downtown Grand Rapids. Assuming a conservative 25-year recurrence time, the annual avoided flood risk was estimated at \$0.18/m^3 (\$0.0051/ft^3) (Table 2).

3.4 Other benefits from specific GI practices

3.4.1 Green roofs

Researchers at the University of Michigan documented the benefits of green roofs on campus buildings, including energy savings and NO_2 pollution uptake (Clark et al., 2008). Applying their energy savings and pollution uptake rates to our green roof scenario and adjusting for inflation leads to a lower-bound estimate of \$0.57/m^3 WQv/year. Green roofs also provide a scenic amenity value when they are visible from upper floors or adjacent buildings. Given the lack of solid regional data for the amenity value of green roofs, the team estimated a 1.9 percent property value amenity (see Appendix for full discussion). The annualized amenity value of green roofs is \$0.71/m^3 WQv/year (\$0.02/ft^3/year) (Table 2). Analysts report that green roofs can double the life of the conventional roof underneath and eliminate the need for a full roof replacement after twenty-five years. This is a substantial benefit because a new roof costs about \$107.64/m^2 (\$10/ft^2) (K. Menard, personal communication).

3.4.2 Rain gardens and infiltrating bioretention basins

Rain gardens provide a scenic amenity. Polyakov et al. (2015) found that rain gardens increased the median property value by six percent for those within 50 m (164 ft) from the rain garden. Applying the six percent rate to Grand Rapids yields an annualized amenity benefit of $1.20/$m^3$ WQV/year ($0.034/$ft^3$/year) (Table 2). For our analysis, the research team conservatively assumed that the infiltrating bioretention practice was similar to the ordinary, single-use detention basin and provided no amenity value (Lee and Li 2009).

3.4.3 Street trees and conserved natural areas

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's units were used and updated with current and locally appropriate prices. The avoided runoff volume estimates reported by McPherson et al. (which included interception by the tree canopy) were higher than those resulting from the NYS Stormwater Toolbox (which only accounted for runoff directed into the tree pit). After some deliberation, the team decided to use the McPherson runoff reduction estimates in the benefit calculation (See Appendix and Table A3 for complete details).

Conserved natural areas can increase property values of 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. The research team assumed that the preserved natural area would be adjacent to 12 lots. The resulting amenity value is $4.16/$m^3$ WQv/year ($0.112/$ft^3$/year). Many of the services provided by mature (>25 years old) street trees were adapted for the conserved natural area green infrastructure practice. The total annual benefit from conserved natural areas was $7.46/$m^3$ WQv/year ($0.21/$ft^3$/year) (Table 2).

Table 2: Benefits ($/$m^3$/year) of GI practices.

GI practice	Annual benefits ($/$m^3$ WQv/year)					
	Porous asphalt	Rain garden	Street tree planter / pit*	Conserve natural area	Green roof	Infiltrating bioretention
Avoided volume	$0.06	$0.06	$0.06	$0.06	$0.06	$0.06
Flood risk reduction	$0.18	$0.18	$0.18	$0.18	$0.18	$0.18
TSS pollution	$1.20	$1.37	$1.36	$1.36	$1.38	$1.37
TP pollution	$0.13	$0.29	$0.23	$0.23	$0.00	$0.29
Amenity value	$0.00	$1.20	$0.43	$4.16	$0.71	$0.00
Energy savings	$0.00	$0.00	$0.91	$0.00	$0.48	$0.00
Air pollution reduction	$0.00	$0.00	$0.13	$0.45	$0.57	$0.00
CO_2 storage	$0.00	$0.00	$0.25	$1.03	$0.00	$0.00
Total annual benefits	**$1.57**	**$3.10**	**$3.54-9.18**	**$7.46**	**$3.38**	**$1.90**

*Benefits during first five years and increase thereafter

3.5 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. This section reports the summary values for the costs. Full details of the calculations can be found in the Appendix.

3.5.1 Porous asphalt

Century West Engineering compared, side-by-side, the capital costs of conventional and porous asphalt for a parking lot. After adjusting for locational wage differences and inflation, the total capital costs, including construction and development costs, for Grand Rapids were estimated at \$88.11/m^2 (\$102.14/m^3 WQv/year) for conventional asphalt and \$96.41/m^2 (\$111.76/m^3 WQv/year) for porous asphalt. Maintenance estimates were obtained from Abate et al. (2009) for conventional asphalt and Houle et al. (2013) for porous asphalt and adjusted to local economic conditions. The present value cost came out to \$131.83/m^3 WQv for conventional asphalt and \$148.62/m^3 WQv for porous asphalt (Table 3).

3.5.2 Green and conventional roofs

Conventional roof costs were estimated from a local professional (K. Menard, Bloom Roofing, personal communication) and Abate et al. (2009). Standardized by WQv, a conventional roof costs \$123.47/m^3 WQv in the first year with maintenance costs \$0.62/m^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). For this project, the research team used a mid-range estimated installed cost of \$161/m^2. The present value cost, including installation and maintenance, for the conventional roof was estimated at \$215.02/m^3 WQv and \$344.26/m^3 WQv for the green roof (Table 3).

3.5.3 Rain garden and infiltrating bioretention basin

The Washington State Department of Ecology estimated the capital and maintenance costs of rain gardens and infiltrating bioretention basins (Herrera Environmental Consultants, 2012). The research team assumed that the rain gardens would be installed professionally. Opportunity costs of land were included as described above. Standardized on a WQv basis, the total first-year cost is \$11.32/m^3 WQv/year (\$0.32/ft^3/year) with a total present value cost of \$38.44/m^3 WQv (\$1.09/ft^3). The total present value cost, including capital and O&M costs, for an infiltrating bioretention basin was \$49.83/m^3 WQv over fifty years (Table 3).

3.5.4 Conservation of natural areas

Conserving natural areas comes with a high opportunity cost – the land will never contain income-producing structures. This opportunity cost 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. The calculations were based on the model for the development closest to the city in adjacent Plainfield Township. Conserving 0.35 ha (0.87 ac) of natural area would have an opportunity cost of \$2.98/m^3 WQv/year (\$0.08/ft^3/year) and a present value cost of \$72.40/m^3 WQv (\$2.05/ft^3) (Table 3).

3.5.5 Street trees

The cost of street trees 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 three tree size options – the medium tree (red oak, *Quercus rubra*), which is common in the area, was chosen. The total present value cost of the street trees was $118.42/m^3 WQv ($3.35/ft^3) (Table 3).

3.5.6 Opportunity cost of land

Green roofs and porous asphalt parking lots are co-located with existing infrastructure. Rain gardens, infiltrating bioretention basins, 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 per-area value of residential lots in the Grand Rapids metropolitan area. The opportunity cost of land for rain gardens, infiltrating bioretention basins, and street trees was calculated using the same method as that for conservation of natural areas. For the 0.02 ha (2,145 ft^2) of rain garden the opportunity cost equates to $0.13/m^3/year of WQv. This same opportunity cost was applied to the 342 street trees and the infiltrating bioretention systems (Table 3).

Table 3: Costs of conventional and GI practices.

Infrastructure / GI type	GI practice size (for 84.95 m^3 WQv reduction per 25.4 mm event)	PV cost	PV cost / m^3 WQv	PV cost / unit of GI practice
Conventional asphalt	3,520.75 m^2	$400,395	$131.83	$113.72/m^2
Porous asphalt	3,520.75 m^2	$451,397	$148.62	$128.20/m^2
Conventional roof	3,455.99 m^2	$653,062	$215.02	$187.40/m^2
Green roof	3,455.99 m^2	$1,045,565	$344.26	$302.57/m^2
Rain garden	199.28 m^2	$75,202	$38.44	$377.39/m^2
Infiltrating bioretention	283.00 m^2	$151,353	$49.83	$49.64/m^2
Conserve natural areas	3,520.75 m^2	$219,883	$72.40	$62.43/m^2
Tree planter / tree pit	342 trees	$373,386	$122.94	$1,091.77/tree

4. Results

The NPV analysis shows that four of the six green infrastructure practices have positive NPVs under the base case assumptions (Table 4). Conserving natural areas had the highest net benefits ($108.79/m^3), followed by street trees ($45.94/m^3), rain gardens ($36.87/m^3), and porous asphalt ($21.29/m^3). Infiltrating bioretention basins and green roofs, however, had negative NPVs under the base case assumptions (-$3.76/m^3 and -$47.17/m^3, respectively). Green roofs provided the highest benefits, but also had the highest costs.

Porous asphalt replaces the conventional asphalt “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 4: Net present value of six green infrastructure practices.

Infrastructure / GI type	GI size (for 84.95 m^3 WQv per 25.4 mm event)	PV benefits ($/$m^3$ WQv)	PV cost GI ($/$m^3$ WQv)	PV cost of gray ($/$m^3$ WQv)	Net Present Value ($/$m^3$ WQv)
Porous asphalt	3,520.75 m^2	$38.08	$148.62	$131.83	$21.29
Green roof	3,455.99 m^2	$82.06	$344.26	$215.02	($47.17)
Rain garden	199.28 m^2	$75.31	$38.44	-	$36.87
Infiltrating bioretention	283.26 m^2	$46.08	$49.83	-	($3.76)
Conserve natural area	3,520.75 m^2	$181.19	$72.40	-	$108.79
Street tree (tree pit)	342 trees	$168.88	$122.94	-	$45.94

Many assumptions were made in using the benefit transfer approach to estimate the GI benefits and costs. A sensitivity analysis was conducted to account for this uncertainty. In the "best case" scenario, the benefits (including the avoided cost of gray infrastructure) are ten percent higher than the base case and the costs are ten percent lower. In the "worst case" scenario, the benefits are ten percent lower and the costs are ten percent higher. In the best case scenario, all GI practices, including infiltrating bioretention and green roofs, have positive NPVs. In the worst case scenario, only rain gardens, conserving natural areas, and street trees have positive NPVs (Table 5).

Table 5: Sensitivity analysis (10%) for best and worst case scenarios.

Infrastructure / GI type	Base case NPV ($/$m^3$ WQv)	Best case scenario NPV ($/$m^3$ WQv)	Worst case scenario NPV ($/$m^3$ WQv)
Porous asphalt	$21.29	$53.14	($10.56)
Green roof	($47.17)	$16.95	($111.31)
Rain garden	$36.87	$48.25	$25.50
Infiltrating bioretention	($3.76)	$5.84	($13.34)
Conserve natural area	$108.79	$134.15	$83.43
Street tree (tree pit)	$45.94	$75.12	$16.76

5. Discussion

The GI practices showed a high degree of variability among NPVs. 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 ($4.16/m^3 out of $7.46/m^3). The cost of conserving natural areas comes from the opportunity cost of development. The research team 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 for managing stormwater. It is cheaper to avoid generating stormwater runoff rather than treating it later. 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 NPV at $45.94/m^3 WQv. Street trees, when planted in stormwater retention 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 et al. (2006) study with current costs, as well as with additional water pollution benefits, showed 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 and tree pits are cost-effective under a wide range of assumptions.

Because of the low capital and O&M costs (PV cost = $38.44/m^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.

Conserving natural areas, street trees, and rain gardens were all robust to the sensitivity analysis. Even under the worst case scenario (ten percent higher costs and lower benefits) these practices resulted in positive NPVs.

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 $21.29/m^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 infiltrating bioretention systems.

The research team 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 infiltrating bioretention basin practice had a barely negative NPV (-\$3.76/m^3 WQv). Given the various assumptions made in this analysis, it is likely that in some cases the infiltrating bioretention practice could have a positive NPV. Infiltrating bioretention 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 basins were designed as multi-use community resources, including recreation facilities, Lee and Li (2009) 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 infiltrating bioretention practice could be improved if cost-effective scenic and recreational amenities are included in the design. Lee and Li (2009) found that, all else being equal, decreasing the distance to the multi-use detention basin increased home sale prices at a rate of about \$52/m. The cost of building and maintaining an infiltrating bioretention 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 (\$344.26/m^3 WQv) of all the practices surveyed and a premium of \$129/m^3 WQv over a standard roof. However a green roof also has substantial present value benefits (\$82.06/m^3 WQv). The net benefits, however, are negative (\$-47.17/m^3 WQv) using the mid-range installation cost of \$161/m^2 (\$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 \$97/m^2 to \$215/m^2 (\$9/ft^2 - \$20/ft^2). A capital cost of \$119.48/m^2 (\$11.10/ft^2) is the break-even point. Below this cost, the green roof's NPV, all else being equal, would become positive. Note that \$119.48/m^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. This was demonstrated in the sensitivity analysis. In the best case scenario (ten percent higher benefits and lower costs), green roofs had a positive NPV of \$16.95/m^3 WQv. Alternatively, a positive NPV can be achieved if the amenity value is equal to or greater than 7.2 percent of the property price. This level would be similar to the lower bound of Ichihara and Cohen's (2010) analysis of green roofs in New York City but much higher than Nurmi et al.'s (2016) estimates from Helsinki. Many small to mid-size Midwestern cities have adequate access to ground-level public green space compared to highly urban New York City. Grand Rapids has eighteen buildings with green roofs (Greenroofs.com, 2018). 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 premium estimated here.

Many green roofs in Grand Rapids are installed to achieve LEED certification (J. Aleck, LiveRoof, personal communication). Studies have shown that LEED certified office buildings rent at a premium of 4-7 percent as compared to similar, non-certified buildings (Fuerst and McAllister, 2011; Reichardt, 2013). Office space in Grand Rapids rents for, on average \$142.62/m^2/year (\$13.25/ft^2/year). The rent premium for a LEED certified building, therefore, would be about \$5.70-10.01/m^2/year. Assuming that the commercial building is 3,456 m^2 (LoopNet, Inc., 2015), which is the area of the green roof in our scenario, and one story, the LEED premium would be \$19,716-34,596/year. This premium could offset the cost of some 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 \$1.20-\$3.80/m^2/year. A LEED amenity value of \$3.00/m^2/year (\$0.27/ft^2/year, or \$3.41/m^3 WQv) would be enough to flip the green roof to a positive NPV (\$2.08/m^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, 2018). Green roofs are a major investment for a commercial building so building owners may not be expected to sell them soon. In time, however, commercial buildings with green roofs should come on the market and their amenity value could be assessed.

The major limitation of this study was the benefit-transfer method. The estimates presented here are only as good as the data from the original studies. Although the team was as diligent and transparent as possible, transferring the values from the study site to the policy site introduces error. The sensitivity analysis suggests that conserving natural areas, street trees, and rain gardens have positive NPVs even under a worst case scenario. As Grand Rapids expands its GI practices in both public and private spaces, there will be greater opportunity to conduct original, site specific research into the benefits and costs of the GI practices.

The benefit-cost analysis described here has applications beyond Grand Rapids. The ecological and economic conditions of many cities within the Great Lakes basin, both in the US and Canada, are similar to those of Grand Rapids. With some adjustments, the values calculated here could be more broadly applied. The research team is already using the www.RainwaterRewards.com website and calculator as an educational and outreach tool in communities around the Great Lakes. The basic methodology, comparing the benefits and costs based on standardized treatment volumes, can be applied to stormwater management practices anywhere.

6. Conclusions

This paper introduced a novel approach to benefit-cost analysis of stormwater GI practices based on the volume of stormwater. The various practices can be directly compared by standardizing the practices based on how much stormwater is treated. The paper's benefit transfer methodology serves as a model for other communities around the world to estimate the net benefits of stormwater GI practices. The analysis also forms the core of the Rainwater Rewards online calculator. The calculator enables stormwater managers, policy makers, and community residents to estimate the social benefits of onsite stormwater management.

The benefit-cost analysis for the various green infrastructure practices shows that porous pavement, rain gardens, infiltrating 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 single 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. Infiltrating 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.

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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