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STORMWATER MANAGEMENT IN CHICAGO: A COST-BENEFIT ANALYSIS OF THE MCCOOK RESERVOIR, GREEN ROOFS, AND RAIN BARRELS

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Abstract

This cost-benefit analysis evaluates stormwater management options in Chicago by comparing the welfare effects of the McCook Reservoir expansion to green roofs and rain barrels, two leading forms of green stormwater management promoted by the EPA. Cook County, Illinois, has invested heavily in its Tunnel and Reservoir Plan (TARP), which serves as the region's primary means of stormwater management. Based on our findings, Chicago should invest in green stormwater infrastructure to supplement the TARP, maximize co-benefits, and proactively address climate change's intensifying impacts. First, the city should consider a subsidy program to incentivize residential green roofs. Then, if funds remain, Chicago should further research the most cost-beneficial scenarios for targeted rain barrel programs, such as a public awareness campaign on their benefits in high-risk, flood-prone areas. Expanding green roof programs to encourage broader residential implementation—ultimately, doubling the city's existing green roof space—would improve stormwater management, limit combined sewage overflows (CSOs), and better prepare Chicago for increased rainfall.

Introduction

In the summer of 2020, a First Street Foundation (2020) analysis found that 13% of Chicago properties are at substantial flood risk, and this percentage is only projected to increase. Though Chicago has long suffered from flooding, this risk still causes concern. Cook County has invested heavily in the Tunnel and Reservoir Plan (TARP), and Chicago has become a leader in green roof implementation. However, these stormwater management methods fall short of the city's needs in their current form. Moreover, the U.S. Global Change Research Program projects climate change to increase rainfall and heavy precipitation in the Midwest, stressing existing stormwater management infrastructure (Angel et al., 2018; Easterling et al., 2017). As a result, Chicago will face more intense flooding in the coming decades, levying a high cost on the city's residents.

Therefore, Chicago needs to increase its capacity to control runoff and improve its stormwater management to meet current needs and adapt to worsening climate impacts. This study conducts a cost-benefit analysis of three forms of stormwater management—green roofs, rain barrels, and deep tunnels and reservoirs—because these are standard practices with varying degrees of proactivity and sustainability in Chicago.

Environmental economics traditionally classifies stormwater management as a public good that the government must provide to its residents. For example, large-scale projects like the TARP offer no private market in which city residents can participate, and the government must use public funds and policy to provide an efficient provision of stormwater management. For low-impact development like green roofs, rain barrels, and retention ponds, stormwater management aligns with Wichman's (2016) definition of "impure public goods." These goods provide both public and private benefits, but their stormwater management outcomes are public benefits spatially linked across the watershed (Burnett & Mothorpe, 2019). For both public works and low-impact infrastructure, government action is required to influence residents' behavior and ensure an adequate level of stormwater management across the community. Not only does Chicago experience regular flooding from heavy rainfall and insufficient capacity to manage stormwater, but runoff also pollutes local waterways. This market failure, combined with the public-good nature of stormwater management, places the onus on the city to take action.

As climate change worsens, Chicago needs to promote adaptation and sustainability, especially in infrastructure. The city has an opportunity to adapt to climate change through improved stormwater management, preparing Chicago for increased rainfall, and reducing the intensity of future floods. In the face of climate change, the city can adopt or expand many forms of stormwater management to address these problems, each with varying degrees of proactivity and sustainability.

Background

Across the U.S., cities and municipalities have considered and implemented green and gray infrastructure policies to manage watersheds and stormwater runoff. Cost-benefit analysis allows policymakers to gauge whether incentivizing and subsidizing green infrastructure is a socially beneficial way to manage stormwater. This analysis can inform Chicago's design and implementation of a green infrastructure requirement.

For example, Chicago's Green Permit Program offers builders, contractors, developers, and homeowners an expedited permit process and support for planning green roof projects (Department of Buildings, 2012). Currently, Chicago has 5,564,412 sq ft of green roofs, holding an estimated 127,883,932 gallons of stormwater annually. Only Washington, D.C., a third of Chicago's size, outpaces the city in its total area of green roofs (Stand & Peck, 2019).

In 2011, Chicago's Sustainable Backyard Program provided 420 $40 rebates for rain barrels, funded by the Environmental Protection Agency's Pollution Protection Program (Department of Water Management, 2014). Though the city still encourages rain barrel use, it currently has no program to incentivize rain barrels.

The Metropolitan Water Reclamation District of Greater Chicago (MWRD) is currently constructing the McCook Reservoir expansion outside city limits as part of the TARP to decrease flooding and CSOs in the greater area. The MWRD completed the first stage of the reservoir in 2017 with a storage capacity of 3.5 billion gallons. Following its expansion, McCook Reservoir will provide "an estimated total of $143 million per year in flood reduction benefits" to the county (Fore, 2017, p. 2). The Army Corps of Engineers (USACE) and MWRD fund the project and will operate the reservoirs once completed (Chicago District, n.d.). Since the City of Chicago does not fund the TARP but reaps its benefits, our study explores whether the city can supplement TARP with cost-beneficial green infrastructure development.

Methodology

Our study compares three forms of stormwater management—green roofs, rain barrels, and deep tunnels and reservoirs—against the *status quo*. Currently, Chicago does not have established requirements or subsidies for stormwater management but utilizes the MWRD's existing deep tunnels and reservoirs to mitigate flooding and CSOs. Our population of interest is the residents of the City of Chicago, Illinois, and this study focuses on the costs and benefits within the city. However, we also discuss the social benefits of reduced pollution for the broader Lake Michigan and Great Lakes region.

The time frame for our analysis includes construction plus operation over each program's expected lifespan. Due to the different time frames of the McCook Reservoir, green roofs, and rain barrels, we calculate the equivalent annual net benefit (EANB) for each project to compare the three policy options. The EANB—calculated by dividing the net present value (NPV) by the annuity factor with the same time frame and discount rate—yields an annualized measure of a program's NPV over its lifespan. The EANB allows for the comparison of programs with different time frames on an equal measure.

Standing:

This cost-benefit analysis assesses if the McCook Reservoir Phase II, green roofs, and rain barrels improve social welfare for Chicago residents. The MWRD, a state special-district agency that serves the broader Cook County area, conducts most of Chicago's stormwater management through its TARP. Alongside funding and support from the USACE, the MRWD expects to complete its expansion of the McCook Reservoir by 2029. Because TARP serves Cook County as the region's primary means of stormwater management, we first assessed the costs and benefits of McCook Phase II for the entirety of Cook County. We then portioned these values by household to isolate the welfare effects within Chicago using data from the U.S. Census Bureau (2020b, 2020c). Isolating the effects within Chicago allows equal evaluation of all three policy options.

This analysis compares the McCook Reservoir to green roofs and rain barrels, two leading forms of green stormwater management used at EPA facilities (Office of Mission Support, 2017). In evaluating the net benefits of green roofs and rain barrels, we assume the city would subsidize their installation, which is typical for these policies across the country. City residents and homeowners receive the primary benefits of municipal green infrastructure, so we estimate the costs and benefits of green roofs and rain barrels only for Chicago residents.

Parameters:

Across this study, we used a standard marginal cost of public funds (MCPF)[1] of $1.20 to capture the real opportunity cost of government spending. We scale all costs borne by the government accordingly by a factor of 1.20. The installation cost of green roofs and the purchase cost of rain barrels fully factor in the MCPF to provide a more conservative estimate that does not hinge on the subsidy level. Notably, our analysis estimates green roofs' premium costs and benefits to isolate welfare effects independent of standard residential roofs.

Across our estimates, detailed for each policy option in the following section, we adjusted all values to 2020 U.S. dollars based on the U.S. Bureau of Labor Statistics (2021) consumer price index for all urban consumers in the Chicago metropolitan area (CPI-U Chicago). We then project the inflation-adjusted costs and benefits across the expected lifespan of each program, discounted at rates of 3% and 7% based on EPA best practices (National Center for Environmental Economics, 2014). A 3% discount rate best reflects the time preference for public and long-term projects like these stormwater management options, so we use 3% as the primary discount rate in our discussion. Our results and sensitivity analysis also include a 7% discount rate, which best reflects the time preference for private investment.

Additionally, our estimates monetize intangible[2] (i.e., non-market) social costs and benefits in several categories, including flooding and pollution reduction, homeowner installation, and upkeep. This study uses the average household willingness to pay (WTP)[3] per watershed service of $6.99 from Castro et al.'s (2016) contingent valuation to capture intangible secondary benefits, including habitat preservation, recreation, and other watershed ecosystem services. Though Chicago residents' total WTP for watershed services is imprecise relative to each program's effectiveness, including a household WTP of only one watershed service provides a more conservative estimate.

Limitations:

Stormwater management policies primarily seek to decrease flooding, making the shadow price of these benefits critical to each program's NPV. This shadow pricing requires estimating the relationship between water storage and flooding and then monetizing each program's estimated flooding reduction. We assume that annual water storage as a percentage of yearly runoff approximates the flooding reduction of green roofs and rain barrels. We calculated runoff based on the average annual rainfall in Chicago of 36.89 inches and the average lot size in Chicago (Chicago Weather Forecast Office, n.d.; Heskes, 2012). According to Festing et al. (2014), the average cost of a household flood in the Chicago area equals $4,560, with roughly 6.55% of households experiencing a flood each year, totaling $298,515,823 annually. Therefore, estimated flooding reduction multiplied by the total annual cost of household flooding monetizes this benefit for green roofs and rain barrels. Analysis by the MWRD and EPA provides the estimated flooding reduction benefit of the McCook Reservoir (Aistars et al., 1988; O'Connor, 2020).

Furthermore, climate change will increase flooding, rainfall, and heavy precipitation over the next century. However, climate projections are too varied to provide precise predictions of increased rainfall at the local level. As a result, flooding costs will likely rise, especially throughout long-term projects, but our estimates cannot adequately incorporate the expected change in these baseline costs.

Costs and Benefits

McCook Reservoir Expansion:

The TARP is a large public works project for pollution and flood control in Cook County, Illinois. The program includes four tunnel systems that capture and transport combined sewage and stormwater to the Majewski Reservoir, Thornton Composite Reservoir, and McCook Reservoir. The MWRD has completed the

[1] The *Marginal Cost of Public Funds* (MCPF) accounts for the social costs of taxation. These costs include deadweight loss, tax collection's administrative costs, the substitution effects of taxes, and inefficiencies from tax avoidance. At a MCPF of $1.20, each dollar of collected taxes carries a marginal excess tax burden (social cost) of $0.20.

[2] *Intangible* refers to impacts, goods, and services that are not sold in a market and, therefore, have no market price. Where possible, we shadow price intangible impacts to quantify their social value.

[3] *Willingness to Pay* is the maximum price that a consumer is willing to pay for a good or service, equaling the quantified value of the good. In this analysis, WTP represents the monetary value placed on the social benefits of cleaner watershed ecosystems.

TARP's preliminary tunnels and most of its reservoirs, making significant and effective progress in flood control. Therefore, policymakers must evaluate whether to continue the McCook Reservoir's expansion, especially when paired with new green infrastructure programs.

Phase II of the McCook Reservoir started construction in 2017 with planned completion in 2029 and will expand the existing reservoir through an additional 6.5 billion gallons of water storage. Given that this analysis began in 2021, we regard the expansion's already completed subprojects, like overburden removal and slope stabilization, as sunk costs. As noted in our methodology, we calculate McCook Reservoir's benefits to Chicago based on the percentage of Cook County households within Chicago, with 1,066,829 Chicago households out of 1,971,108 households across the county (U.S. Census Bureau, 2020b, 2020c).

McCook Reservoir's Phase II costs include construction, materials, labor, management, maintenance, water treatment, and the MCPF. The cost of construction, materials, and labor include the land and engineering fees of continuing programs and contracts with the USACE—such as the rock wall stabilization, Des Plaines inflow tunnel, and final reservoir preparation—totaling $361,517,145 (O'Connor, 2020). In addition, we estimate the reservoir's annual maintenance and management costs after construction based on the costs of a similar reservoir with the same capacity, equaling $892,080 per year for Chicago residents (Coates, 2012).

The TARP captures excess stormwater flow from the combined sewer system, conveying it through tunnels to storage reservoirs and then to MWRD facilities for treatment. Therefore, McCook Reservoir's water treatment costs will increase after Phase II's completion. With a metered water treatment rate of $0.004080 per gallon and 40 billion gallons of stormwater each year, we estimate the annual cost of water treatment at $105,941,354 for Chicago households.

The McCook Reservoir also has some intangible costs. As a large-scale project, its construction time is relatively long at an expected 13 years, a considerable time cost that we account for by discounting future benefits. In addition, long-term and continuing construction may have negative unquantifiable externalities such as noise and disruption in neighboring communities.

McCook Reservoir's Phase II benefits mainly come from its larger water storage capacity. The larger water storage capacity operates as a sewer backup, reducing water pollution, flooding, and CSOs. We measure this additional capacity's flooding and pollution reduction benefits using estimates from the MWRD and EPA, equaling $50,282,112 in reduced flooding and $144,119,992 in reduced water pollution each year (Aistars et al., 1988; O'Connor, 2020).

We estimate secondary benefits from watershed ecosystem services, including recreation and habitat preservation, using the household WTP for watershed services. For example, reduced wastewater into Lake Michigan and the Chicago River preserves habitats for more than 50 fish and wildlife species in the regional watershed. These ecosystem benefits further protect citizens' interests, conserve regional waters in line with state and federal law, and increase property values. In 2020, Chicago had 1,066,829 households (U.S. Census Bureau, 2020b), and assuming each household is willing to pay $6.99 for secondary watershed and ecosystem services (Castro et al., 2016), the total annual WTP equals $7,454,458. Furthermore, as a public works program, one intangible and unquantifiable benefit of McCook Reservoir's expansion is that the onus to implement and maintain the program falls solely on the city and does not require active citizen participation.

Table 1: *Costs and benefits of the McCook Reservoir Phase II.*

	Tangible	**Intangible**
Costs	• Construction • Maintenance and management • Water treatment • MCPF	• Construction time • *Unquantifiable*: Noise and disruption
Primary Benefits		• Reduced water pollution and CSOs • Reduced household flooding
Secondary Benefits		• Habitat preservation, recreation

Green Roofs:

The primary tangible costs of green roofs include installation and the subsidy's MCPF. There are two types of green roofs: multi-course and semi-intensive. Semi-intensive green roofs are deeper and allow for larger plants and more stormwater retention than multi-course roofs. Multi-course residential green roofs generally cost $11.49 to $13.94 per sq ft, and semi-intensive green roofs generally cost $18.07 to $21.97 per sq ft (Miller et al., 2011). In this analysis, we use the median cost of a multi-course green roof because the subsidy targets homeowners who would install a residential green roof, and we factor the $1.20 MCPF into these installation costs. Lastly, green roofs' primary intangible cost is the required upkeep by property owners, ranging from $0.23 to $0.35 per sq ft annually (Miller et al., 2011). Therefore, this analysis uses the median of $0.29/sq ft.

We measure the primary benefits of green roofs as their reduction in water treatment costs, longer average lifespan than a standard residential roof, reduced flooding and CSOs, and improved health from reduced pollution. Green roofs' capacity for water storage—through the capture, evaporation, and transpiration of rainwater—decreases the stormwater flowing to water treatment plants, thus reducing water treatment costs and household flooding. Based on Chicago's average rainfall, an additional 5,564,412 sq ft of green roofs would hold 63,941,966 gallons of water per year. This water storage would provide $295,466 in flooding reduction benefits and $260,883 in water treatment cost savings each year. We calculate the health benefits of reduced pollution using Miller et al.'s (2011) estimate of $0.09/sq ft, equaling $464,708 annually. Additionally, green roofs have a 40-year lifespan, compared to 20 years for a standard residential roof, providing a $4.40/sq ft benefit at year 20 (Miller et al., 2011; Technical Preservation Services, n.d.).

Green roofs also reduce the urban heat island effect, returning the tangible, secondary benefit of lower energy costs equaling $0.06/sq ft (Miller et al., 2011). The urban heat island effect will worsen with climate change, so Chicago could greatly benefit from expanded investment in green roofs in this regard. This benefit initially prompted Chicago to begin its investments in green infrastructure like green roofs; in 1995, Chicago experienced an extreme heat event that led to the deaths of several hundred people over five days. As a result, Chicago adopted a comprehensive Climate Change Action Plan that set extreme heat adaptation priorities, including green roofs (Climate Change Adaptation Resource Center, 2016).

Additionally, green roofs provide several intangible, non-market benefits, including urban green space, biodiversity, gardening, and habitat preservation opportunities. For example, some biologists believe bees are starting to fare better in urban areas than in rural areas, and green roofs offer habitat and pollination opportunities (Cameron, 2017). Our analysis uses Castro et al.'s (2016) household WTP for watershed ecosystem services to reflect these non-market benefits.

Table 2: *Costs and benefits of green roofs.*

	Tangible	Intangible
Costs	• Installation • MCPF	• Upkeep by property owners
Primary Benefits	• Reduced water treatment costs • Deferred roof replacement	• Reduced water pollution and CSOs • Reduced household flooding
Secondary Benefits	• Reduced energy costs	• Biodiversity, habitat preservation

Rain Barrels:

The primary private cost of rain barrels is the purchase of the barrel. Our study assumes an average cost of $100 for a 50-gallon barrel with a usable life of 20 years (Department of Environmental Services, 2006). Since the owner can install rain barrels, we measure the installation and annual maintenance costs with a shadow price of time using the median hourly wage in Chicago of $27.79 (Midwest Information Office, 2020). The primary public cost of rain barrels is the social cost of rebates or subsidies provided by the city, accounted for in the MCPF.

Rain barrels can reduce water treatment costs by collecting stormwater runoff in the barrel rather than municipal catch basins. Residents can use this water for gardening or car washing, decreasing the demand for potable tap water. In addition, the rain barrels divert runoff from the sewage system, reducing flooding, CSOs, and pollution deposits into the Chicago River and Lake Michigan.

This study prices the reduction in water treatment cost by multiplying the number of gallons harvested per year by the metered rate of water in Chicago (Department of Finance, 2020). Furthermore, we price the benefits of runoff diversion using the number of rain barrels and the average annual rainfall in the city. Our study assumes that each of the 554,200 single-family, attached or detached residences in Chicago has one 50-gallon rain barrel (U.S. Census Bureau, 2020a), which has the potential to harvest up to 1,752,657,500 gallons of water per year, assuming the average barrel is at 50% capacity before each day of rainfall.

Table 3: *Costs and benefits of rain barrels.*

	Tangible	Intangible
Costs	• Barrels and materials • MCPF	• Upkeep by property owners • Installation by property owners
Primary Benefits	• Reduced water treatment costs	• Reduced household flooding • *Unquantifiable:* Health benefits of reduced water pollution
Secondary Benefits		• Habitat preservation, recreation

Results

Table 4 provides the purchase and construction costs, annual costs, and annual benefits alongside the results of our cost-benefit analysis over each program's expected lifespan. The McCook Reservoir expansion produces the largest EANB for Chicago residents of $63,996,979 per year at a 3% discount rate, equaling $2,048,161,777 of total discounted net benefits over its 100-year lifespan. Moreover, the McCook Reservoir returned the highest flooding reduction benefit of all three programs in this analysis. The project's benefit-cost ratio (BCR) equals 1.69, with an internal rate of return (IRR)[4] of 14.4%.

Of the two city-level green infrastructure options assessed in this analysis, only green roofs produced positive net benefits for Chicago, with $4,114,464 in EANBs and $95,104,893 in total discounted net benefits over 40 years at a 3% discount rate. Though the BCR at a 3% discount rate is higher than that of the McCook Reservoir expansion, equaling 1.78, the project's IRR is 8.6%. Accordingly, green roofs' EANB decreased to $1,290,805 with a BCR of 1.16 at a 7% discount rate.

Rain barrels resulted in a net social loss with an EANB of –$65,155,029 and –$969,342,310 of total discounted net benefits over 20 years at a 3% discount rate. Annual upkeep costs totaled $76,997,014, accounting for the program's largest category of costs. With a BCR of 0.21, no variation in the discount rate returns a break-even NPV, resulting in the program's lack of an IRR.

[4] The *Internal Rate of Return* (IRR) is the discount rate at which the NPV equals zero.

Table 4: *Social benefits and loss table with first-year costs, annual benefits, and annual costs in 2020 USD.*

Expected Lifespan	**McCook Reservoir Phase II** *100 years*		**Green Roofs** *40 years*		**Rain Barrels** *20 years*	
(1) Costs						
(a) tangible						
Rain Barrels (*yr. 1)*					65,559,346	
Construction	361,517,145		84,889,131			
Maintenance and Management	892,080					
Water Treatment	105,941,354					
(b) intangible						
Installation *(yr. 1)*					30,798,806	
Upkeep			1,613,390		76,997,014	
(2) Benefits						
(c) tangible						
Reduced Water Treatment Costs			260,883		3,575,421	
Reduced Energy Costs			342,526			
Deferred Roof Replacement *(yr. 20)*			*25,039,854*			
(d) intangible						
Reduced Flooding	50,282,112		295,466		7,288,887	
Reduced Pollution	144,119,992		464,708			
WTP for Watershed Services	7,454,458		7,454,458		7,454,458	
Discount Rate	*3%*	*7%*	*3%*	*7%*	*3%*	*7%*
(3) Present Value of Costs	2,987,042,707	1,167,261,016	122,182,271	106,398,376	1,241,879,292	912,065,615
(4) Present Value of Benefits	5,035,204,484	1,676,385,204	217,287,164	123,607,008	272,536,982	194,069,269
(5) Net Present Value of Benefits	2,048,161,777	509,124,189	95,104,893	17,208,633	-969,342,310	-717,996,346
(6) Equivalent Annual Net Benefit	63,996,979	35,661,048	4,114,464	1,290,805	-65,155,029	-67,773,776
(7) Benefit-Cost Ratio	1.69	1.44	1.78	1.16	0.22	0.21
(8) Internal Rate of Return	0.144		0.086		*n/a*	

Sensitivity Analysis

This section contextualizes the article's main findings by examining each program's sensitivity to varied discount rates and parameters. Green roofs and the McCook Reservoir—the two cost-beneficial programs in our results—undergo further scrutiny in Monte Carlo analyses that vary critical parameters based on the expected range of values at 3% and 7% discount rates.

This study uses 3% as its primary discount rate, as it best reflects the time-preference of public and long-term investments, alongside a 7% discount rate for the time-preference of private investment. Our sensitivity analysis examines each policy's BCR, EANB, and NPV at 2%, 5%, and 8% discount rates. Finally, our break-even analyses investigate the values of given parameters necessary to return an NPV of $0 at 3% and 7% discount rates holding other parameters constant.

McCook Reservoir Expansion:

Table 5 provides the BCR, EANB, and NPV of the McCook Reservoir expansion at 2%, 5%, and 8% discount rates. Consistent with the project's 14.4% IRR, the McCook Reservoir expansion produced sizable net benefits at all three discount rates. In addition, even with an expected lifespan of 100 years, the project returned $29.6 million in EANBs and $370 million in net benefits at an 8% discount rate consistent with short-term private investment.

Table 5: *Sensitivity analysis of the McCook Reservoir Phase II at varying discount rates. EANB and NPV in 2020 USD.*

	Discount Rate		
	2%	*5%*	*8%*
Benefit-Cost Ratio	1.74	1.56	1.37
Equivalent Annual Net Benefit	$71,473,376	$49,077,552	$29,641,214
Net Present Value	$3,160,910,736	$976,739,562	$370,430,921
Internal Rate of Return		*0.144*	

To assess the McCook Reservoir expansion's break-even points, we conducted a sensitivity analysis of the annual water storage and household WTP necessary to return a break-even NPV, as detailed in *Table 6*. Given our estimates of annual water storage, annual flooding benefits, and annual pollution benefits, we assumed perfectly linear relationships between (1) water storage and reduced flooding and between (2) water storage and reduced pollution—the two criteria of the program's effectiveness. Within the range of this analysis, we expect a 1% decrease in annual water storage to produce a 1% decrease in flooding reduction benefits and a 1% decrease in pollution reduction benefits. This analysis provides a rough estimate of the break-even annual water storage, holding construction cost, maintenance and management costs, and WTP constant.

In order to break even under these assumptions, the McCook Reservoir expansion would have to collect 2.9 billion gallons annually of combined sewage-stormwater at a 3% discount rate and 12.3 billion gallons at a 7% discount rate. The MWRD estimates that the reservoir expansion will process 40 billion gallons each year—significantly higher than our break-even estimate. At a 3% discount rate, break-even corresponds to over $14 million of combined flooding and pollution reduction benefits for Chicago each year. Absent unexpected infrastructure failure over the reservoir's lifetime, these conditions are improbable considering Chicago's climate, average rainfall, and population.

Table 6: *Break-even analysis of the McCook Reservoir Phase II.*

	Discount Rate	
	3%	*7%*
Water Storage (gallons per year)	2,872,185,205	12,279,429,997
*Flooding Reduction in Chicago**	*$3,610,488*	*$15,435,892*
*Pollution Reduction in Chicago***	*$10,348,483*	*$44,242,784*
Household Willingness to Pay for Watershed Services	–$69.98	–$50.48

**Assuming a perfectly linear relationship between water storage and flooding reduction benefit*
***Assuming a perfectly linear relationship between water storage and pollution reduction benefit*

To return a $0 NPV, household WTP for watershed services would have to equal –$69.98 at a 3% discount rate. Holding all other values constant, the primary benefits of reduced flooding and decreased potable water pollution maintain a positive net benefit for the McCook expansion up to these WTP values.

As reported in *Table 7*, we conducted a Monte Carlo analysis to estimate the range of net benefits. Analysis from the MWRD and EPA provided our estimates for water pollution costs, reduced flooding benefits, and reduced pollution benefits (Aistars et al., 1988; O'Connor, 2020). Therefore, our Monte Carlo analysis varied household WTP for watershed services based on Castro et al.'s (2016) findings. We varied WTP with a triangular distribution using the WTP among city residents for recreation (the lowest WTP of a relevant watershed service) of $2.67 as the minimum, the average for watershed services at $6.99 as the mode, and the highest WTP of a relevant watershed service among city residents (habitat for species) of $18.78 as the maximum.

Table 7: *Monte Carlo analysis of the McCook Reservoir Phase II with variable WTP for watershed services (n=10,000 simulations). EANB and NPV in 2020 USD.*

	Benefit-Cost Ratio		**Equivalent Annual Net Benefit**		**Net Present Value of Benefits**	
Discount Rate	*3%*	*7%*	*3%*	*7%*	*3%*	*7%*
95% Confidence Interval	1.66 1.77	1.41 1.51	61,426,358 72,013,276	33,861,217 41,632,521	1,965,891,545 2,304,715,676	483,428,447 594,377,476
Mean	1.71	1.46	66,042,040	37,221,697	2,113,612,006	531,405,208
Standard Error	*0.0003*	*0.0003*	*28,472*	*20,991*	*911,229*	*299,681*
Median	1.70	1.45	65,672,078	36,931,782	2,101,771,711	527,266,163
Standard Deviation	*0.03*	*0.03*	*2,847,232*	*2,099,086*	*91,122,914*	*29,968,149*
Min	1.65	1.40	60,451,898	33,017,602	1,934,704,891	471,384,357
Max	1.79	1.52	73,752,162	42,860,535	2,360,367,039	611,909,535
Range	0.14	0.12	13,300,264	9,842,933	425,662,148	140,525,178
Cost-Beneficial Simulations	100%	100%	100%	100%	100%	100%

At a 3% discount rate, our Monte Carlo analysis returned a cost-beneficial outcome in 100% of the 10,000 simulations. The 95% confidence interval of the EANB ranges from $61.4 to $72.0 million. Point estimates of the EANB returned a median of $66.0 million, compared to an estimated $64 million in our primary analysis.

Green Roofs:

As detailed in *Table 8*, green roofs maintain a sizable net social benefit at 3% and 7% discount rates. However, 8% approaches the program's IRR, reducing the EANB to $502,981 and the BCR to 1.06. Under conditions at or above the standard discount rates of private investment, a city-funded green roof program of this size may return a small or slightly negative NPV.

Table 8: *Sensitivity analysis of green roofs at varying discount rates. EANB and NPV in 2020 USD.*

	Discount Rate		
	2%	*5%*	*8%*
Benefit-Cost Ratio	2.00	1.42	1.06
Equivalent Annual Net Benefit	4,705,392	2,781,265	502,981
Net Present Value of Benefits	128,718,244	47,723,965	5,997,859
Internal Rate of Return		*0.086*	

We calculated the break-even values of the program's main parameters at our principal discount rates, as reported in *Table 9*. Holding all other values constant, we estimate that a Chicago green roof program would be cost-beneficial up to 12,419,087 sq ft at a 3% discount rate and 6,729,722 sq ft at a 7% discount rate. Since our study evaluates doubling Chicago's area of green roofs with an additional 5,564,412 sq ft, a reasonable variation in the square footage is unlikely to return a net social loss.

Table 9: *Break-even analysis of green roofs.*

	Discount Rate	
	3%	*7%*
Square Feet of Green Roofs	12,419,087	6,729,722
Installation Cost Per Sq Ft	$26.96	$15.29
Upkeep Cost per Sq Ft	$1.03	$0.52
Willingness to Pay for Watershed Services	$3.13	$5.78

Upkeep and installation costs vary depending on the type of green roof (e.g., multi-course residential vs. intensive), climate, vegetation, and region, so we also conducted a break-even analysis of these costs. At a 3%

discount rate, green roofs provide a positive NPV with up to $1.03 in annual upkeep costs per square foot. The program also remains cost-beneficial at installation costs per square foot up to $26.96 at a 3% discount rate. At a 7% discount rate, our study estimates upkeep cost ($0.29) considerably below the break-even value, but the estimated installation cost of $12.71 approaches the break-even value of $15.29 at a 7% discount rate.

Additionally, we calculated the household WTP required to return a break-even NPV. Break-even WTP equals $3.13 at a 3% discount rate and $5.78 at a 7% discount rate. While $3.13 is below our estimate, $5.78 approaches our estimate of $6.99. These break-even values fall within the range of WTP per watershed service provided by Castro et al. (2016). Considering the impact of a 7% discount rate, which nears the program's 8.6% IRR, we conducted a Monte Carlo analysis to determine the probability of a cost-beneficial outcome.

The sources for upkeep cost, installation cost, and WTP for watershed services provide a range of estimates depending on the type of green roof (for upkeep and installation costs) and the type of watershed service (for WTP). Our Monte Carlo analysis varies these three parameters simultaneously over 10,000 simulations based on triangular distributions to identify the effect of variation in these estimates. *Table 10* details the descriptive statistics, point estimates, and probability results of this analysis.

We varied the installation cost with a triangular distribution based on estimates from Miller et al. (2011) at the U.S. General Services Administration. We used the median cost per square foot of multi-course residential green roofs ($12.71) as the mode, $11.49 for low-cost residential roofs as the minimum, and $21.97 for high-cost intensive green roofs as the maximum. Annual upkeep cost was also varied with a triangular distribution using the median cost per square foot of $0.29 as the mode, $0.23 for low-cost extensive roofs as the minimum, and $0.35 for high-cost intensive roofs as the maximum.

Table 10: *Monte Carlo analysis of green roofs with variable installation cost, upkeep cost, and WTP for watershed services (n=10,000 simulations).*

	Benefit-Cost Ratio		**Equivalent Annual Net Benefit**		**Net Present Value of Benefits**	
Discount Rate	*3%*	*7%*	*3%*	*7%*	*3%*	*7%*
95% Confidence Interval	0.99	0.64	–35,936	–3,713,495	–830,661	–49,507,232
	3.46	2.26	13,764,862	10,561,977	318,171,636	140,809,205
Mean	2.03	*1.30*	6,077,873	2,613,904	140,488,648	34,847,808
Standard Error	*0.007*	0.004	*37,283*	*38,091*	*861,792*	*507,824*
Median	1.94	1.23	5,607,436	2,185,657	129,614,603	29,138,536
Standard Deviation	*0.66*	*0.43*	*3,728,319*	*3,809,144*	*86,179,240*	*50,782,398*
Min	0.70	0.43	–2,167,849	–6,897,275	–50,109,331	–91,952,460
Max	4.25	2.84	16,693,722	13,646,434	385,871,571	181,930,283
Range	3.55	2.41	18,861,571	20,543,709	435,980,902	273,882,743
Cost-Beneficial Simulations	97.38%	72.03%	97.38%	72.03%	97.38%	72.03%

This analysis varied household WTP with a triangular distribution based on Castro et al.'s (2016) estimates. The minimum equals the WTP among city residents for recreation (the lowest WTP of a relevant watershed service) at $2.67, the mode was set to the average for watershed services at $6.99, and the maximum equals the highest WTP of a relevant watershed service among city residents (habitat for species) at $18.78.

The 95% confidence interval of this Monte Carlo analysis estimates the EANB would range from –$36,936 to $13.8 million at a 3% discount rate. Point estimates place the median EANB at $6.1 million, compared to $4.1 million in our main results. The probability of a cost-beneficial outcome under these assumptions equals 97.38%.

Similar to the break-even analysis, these results indicate that a municipal green roof program is highly likely to result in a net social benefit at a 3% discount rate. However, these results also suggest that green roofs are sensitive to the time-preference of costs and benefits. At a 7% discount rate, variation in WTP, installation cost, and upkeep cost returned a net social loss in 27.97% of simulations.

Rain Barrels:

Rain barrels produced a net social loss in our results, and the results at varied discount rates illustrate the impact of upkeep cost—the highest cost of rain barrels—on the program's NPV. As provided in *Table 11*, a 2% discount rate increased the program's total net social loss as future upkeep costs were discounted at a lower rate, with the inverse occurring at an 8% discount rate.

Table 11: *Sensitivity analysis of rain barrels at varying discount rates. EANB and NPV in 2020 USD.*

	Discount Rate		
	2%	*5%*	*8%*
Benefit-Cost Ratio	0.22	0.22	0.21
Equivalent Annual Net Benefit	–64,571,196	–66,410,275	–68,492,539
Net Present Value of Benefits	–1,055,831,612	–827,618,820	–672,469,840
Internal Rate of Return		*n/a*	

Though our results estimate that an extensive rain barrel program would not return a net social benefit to the city, we also conducted a break-even analysis to gauge how specific variables contribute to the program's negative NPV. Our study assessed the value of one rain barrel per residential home in Chicago, equaling over half a million barrels. However, as detailed in *Table 12*, this sensitivity analysis estimates that reducing the number of rain barrels could result in a break-even NPV, equaling 56,897 barrels at a 3% discount rate and 54,916 barrels at a 7% discount rate.

While we initially expected the average empty rate to impact the results considerably, neither the empty rate nor the water averted from city sewers has a practically significant impact on the program's NPV. For example, at a 3% discount rate, homeowners would have to catch over 354% more water than their rain barrels could accumulate annually for decreased flooding costs to bring the BCR to 1. Similarly, homeowners would have to avert 961% more water from city sewers than their rain barrels could collect annually for reduced water treatment costs to result in a break-even NPV.

Table 12: *Break-even analysis of rain barrels.*

	Discount Rate	
	3%	*7%*
Number of Rain Barrels	56,897	54,916
Hours of Upkeep	0.77	0.60
Empty Rate of Rain Barrels	354.68%	366.92%
Water Averted from Combined Sewage-Stormwater System	961.15%	997.77%
Willingness to Pay for Watershed Services	$68.06	$70.52

Compared to green roofs and the McCook Reservoir expansion, rain barrels require the most time and engagement from residents to achieve benefits—including homeowner installation, emptying barrels, and clearing debris from gutters. Even at an annual upkeep time of 5 hours per household, upkeep was the largest category of costs. In order to achieve a break-even NPV, homeowner upkeep would have to equal 0.77 hours annually at a 3% discount rate, holding all other values constant. However, reduced homeowner upkeep would decrease the empty rate and the program's overall effectiveness. Additionally, while we estimated WTP at $6.99 per household, break-even WTP equals $68.06 at a 3% discount rate. These results suggest that homeowner upkeep cost, which we shadow priced based on Chicago's average wage rate, and WTP are the two most significant variables contributing to the program's net social loss.

Policy Recommendations

This analysis primarily considers scenarios at a 3% discount rate and includes results and scenarios at a 7% discount rate. In line with our results and sensitivity analysis, we recommend that Chicago implement a subsidy program to expand green roofs by 5.5 million sq ft and supplement the net benefits of the MWRD's

McCook Reservoir expansion. In addition, if funds remain, Chicago should consider running a public awareness campaign about the benefits of rain barrels in residential areas at the highest flood risk to better prepare these areas for increased rainfall.

Considering the NPV of benefits, EANB, and BCR, our analysis fails to demonstrate a cost-beneficial result for the rain barrels subsidy. The program also has a considerable present value of upkeep costs. However, our break-even analysis finds that the quantity of rain barrels significantly impacts the program's NPV. Therefore, this program may return a net social benefit at less than 56,000 barrels. If further research supports the use of rain barrels at a smaller scale, the city can use available resources to publicize their benefits for flood control and pollution reduction to residents in flood-prone areas. Especially in flood-prone areas, information campaigns may increase public understanding of flood risk, correcting information failure and raising the WTP for rain barrels.

The McCook Reservoir expansion is cost-beneficial, with a NPV of over $2 billion. The reservoir expansion has the largest EANB of the options evaluated in this study, equaling nearly $64 million per year over its 100-year lifespan and breaking even in 2034. Moreover, the McCook Reservoir's 14.4% IRR indicates that this project can confidently withstand a higher discount rate. Additionally, our Monte Carlo analysis produced cost-beneficial outcomes in 100% of simulations at both 3% and 7% discount rates. Although the TARP has the largest net social benefits, the City of Chicago does not fund the project. Chicago can only supplement the TARP with its own city-level policies to meet the increasing demand for stormwater management.

The green roofs subsidy is cost-beneficial with an EANB of $4 million. Over a 40-year lifespan, this program would improve social welfare with over $95 million of discounted net benefits. Moreover, green roofs have the highest BCR of the three options evaluated, equaling 1.78 at a 3% discount rate with each dollar in costs associated with more benefits than the McCook expansion. Also, green roofs returned a cost-beneficial outcome in 97% of our Monte Carlo simulations. However, the IRR of 8.6% makes this project moderately sensitive to high discount rates. Therefore, the 95% confidence interval in our Monte Carlo analysis includes the possibility of a net social loss.

Considering our estimates, Chicago should implement a program to double the existing area of green roofs with an additional 5.5 million sq ft. Though it provides high net social benefits, TARP is insufficient as the only stormwater management method as the Chicago area faces an expected increase in rainfall and flooding. Chicago should consider green roofs as a supplement. Second, green roofs have unique co-benefits, such as reducing air pollution, the urban heat island effect, and household energy costs. Green roofs would not only improve Chicago's stormwater management but would also assist adaptation to broader climate impacts. Third, green roofs require some, but not extensive, resident participation. They do not require as much resident upkeep as rain barrels, and green roofs provide added incentives and positive net benefits for residents to participate.

Discussion

Although the McCook Reservoir yields the highest NPV of benefits, implementing gray infrastructure takes considerable time, money, and coordination between government agencies. Therefore, we believe city-level policymakers should supplement gray infrastructure with green infrastructure, which is less expensive, quicker to implement, and a critical adaptation to climate change. Gray infrastructure alone will likely not meet all of Chicago's needs. The future costs imposed on the city from flooding and other climate impacts could well exceed those of maximizing investments in improved stormwater management now. Green infrastructure's effectiveness and social benefits, especially rain barrels, depends on community buy-in and WTP. In Chicago, the city could focus rain barrel programs on flood-prone areas, with community education of rain barrel's benefits in those neighborhoods. Citizens willing to commit time and effort to maintain rain barrels—and therefore, with a high individual WTP—can effectively mitigate flooding.

Notably, however, this study is specific to Chicago, and results may differ in other parts of the country. For example, gray infrastructure in the greater New Orleans area includes spillways and levies; the region also sits at or below sea level, rendering deep tunnels and reservoirs infeasible. Additionally, the subtropical climate of southeastern Louisiana means temperatures rarely fall below freezing. Rain barrels are particularly susceptible to damage from freezing temperatures, thus lowering upkeep costs in warmer climates.

Moreover, we could not quantify all of green infrastructure's social benefits in this analysis. For example, the reduction in water pollution from rain barrels would improve public health. Further research should isolate and quantify the health benefits of green infrastructure and low-impact development more precisely.

Though rain barrels would likely not produce positive net benefits across Chicago, local communities can use green infrastructure to supplement large-scale gray stormwater management with adaptable small-scale initiatives that target runoff at its source. In Chicago, doubling the area of green roofs enables the city to improve the region's stormwater management efforts with positive net benefits at a roughly equivalent ratio of benefits to costs as the McCook Reservoir.

Conclusion

To better prepare Chicago for increased rainfall in the coming years and reduce flooding across the city, we analyzed three alternatives to improve stormwater management: green roofs, rain barrels, and the McCook Reservoir Phase II. Based on our results and sensitivity analysis, we recommend that the City of Chicago implement a subsidy program to expand residential green roof implementation and add 5.5 million sq ft of green roofs to double the existing space. In addition, if needed, the city can use available funds to raise public awareness about the benefits of rain barrels for residents in high-risk, flood-prone areas.

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