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Consequential Environmental and Economic Life Cycle Assessment of Green and Gray Stormwater Infrastructures for Combined Sewer Systems

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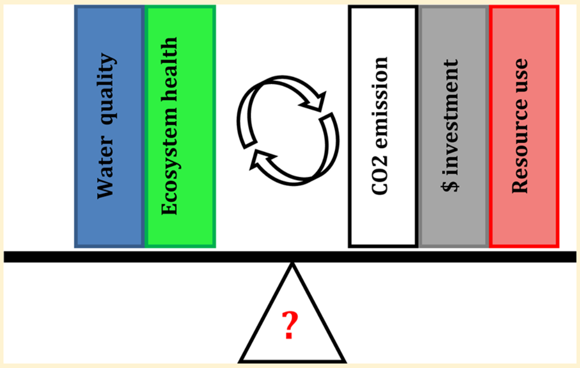
Supporting Information

ABSTRACT: A consequential life cycle assessment (LCA) is conducted to evaluate the trade-offs between water quality improvements and the incremental climate, resource, and economic costs of implementing green (bioretention basin, green roof, and permeable pavement) versus gray (municipal separate stormwater sewer systems, MS4) alternatives of stormwater infrastructure expansions against a baseline combined sewer system with combined sewer overflows in a typical Northeast US watershed for typical, dry, and wet years. Results show that bioretention basins can achieve water quality improvement goals (e.g., mitigating freshwater eutrophication) for the least climate and economic costs of 61 kg CO_2 eq. and \$98 per kg P eq. reduction, respectively. MS4 demonstrates the minimum life cycle fossil energy use of 42 kg oil eq. per kg P eq. reduction. When integrated with the expansion in stormwater infrastructure, implementation of advanced wastewater treatment processes can further reduce the impact of stormwater runoff on aquatic environment at a minimal environmental cost (77 kg CO_2 eq. per kg P eq. reduction), which provides support and valuable insights for the further development of integrated management of stormwater and wastewater. The consideration of critical model parameters (i.e., precipitation intensity, land imperviousness, and infrastructure life expectancy) highlighted the importance and implications of varying local conditions and infrastructure characteristics on the costs and benefits of stormwater management. Of particular note is that the impact of MS4 on the local aquatic environment is highly dependent on local runoff quality indicating that a combined system of green infrastructure prior to MS4 potentially provides a more cost-effective improvement to local water quality.



INTRODUCTION

Stormwater runoff and nonpoint source (NPS) pollution is a leading contributor to impairments of water quality and stream ecosystems in the United States.[1,2] By flushing NPS pollutants, stormwater runoff has the potential to contaminate both surface and groundwater, disturb aquatic ecosystems, and impact human commercial and recreational activities.[3] Mitigating these impacts is difficult due to the spatial and temporal variability of the quality and quantity of runoff flows and the impacts of continued land use change.[4] Effective stormwater management is expected to become increasingly challenging given increased precipitation intensity and variability in many areas due to climate change.[5]

Demand is expanding for water resource infrastructure,[6,7] including "green" infrastructure for stormwater management.[8,9] Conventional, single-purpose "gray" infrastructure collects and conveys stormwater runoff to centralized treatment facilities or discharges NPS polluted runoff directly to receiving bodies with little to no treatment (possibly simple detention as in the case of separated sewers).[10] In contrast, green infrastructure employs natural processes to minimize runoff quantity, reduce peak stormwater flows, and improve runoff quality, while providing additional benefits that gray infrastructure cannot, such as counteracting urban heat island effects, reducing energy costs, creating community amenities, and improving habitats.[9,11] Examples of green infrastructure for stormwater management include bioretention basins (shallow, vegetated basins that collect and treat runoff through infiltration and evapotranspiration), green roofs (covered by growing media and vegetation, which infiltrate and evapotranspire stored rainwater), and permeable pavement (pavement with sufficient voids to infiltrate and store water).[11] However, new infrastructure, both gray and green, comes at a cost of capital, materials, and energy inputs. The environmental impacts associated with these inputs are trade-offs for the benefit of

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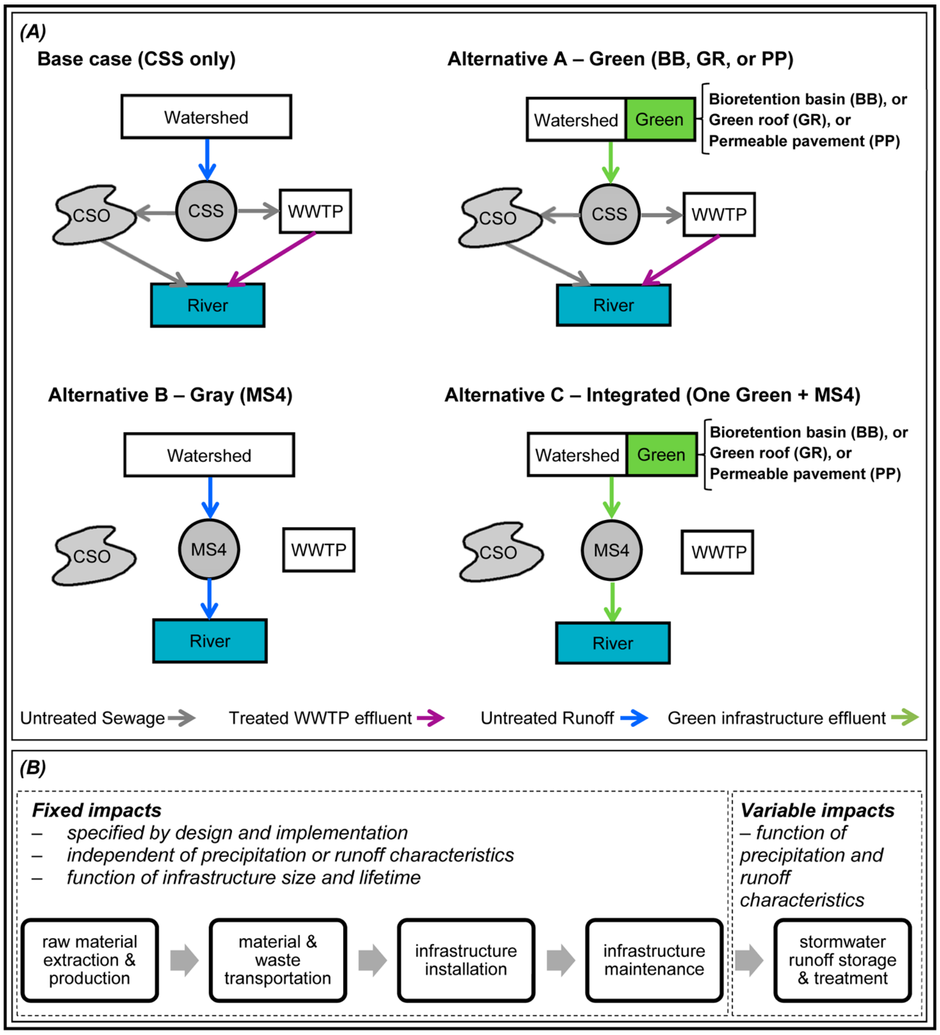

Figure 1. (A) Schematic of water flows in the base case, combined sewer system (CSS), and stormwater management alternatives where the infrastructure expansion is (a) "Green" which can be a bioretention basin (BB), a greenroof (GR), or a permeable pavement (PP), (b) a gray infrastructure solution, municipal separate storm sewer system (MS4), and (c) a combination of one of the green infrastructures with MS4. (B) System boundary for five life cycle stages modeled for each stormwater management alternative. Note that only the last stage, stormwater runoff storage and treatment, is a function of precipitation as well as runoff quantity and quality.

improved water quality and ecosystem services and new social and economic opportunities that result from improving stormwater management.[1,12]

Life cycle assessment (LCA) presents an opportunity to assess these trade-offs, compare designs, and choose the most appropriate stormwater management systems by quantifying a variety of environmental impacts and benefits. Total life cycle costing (LCC) presents a similar opportunity to determine the full economic cost of stormwater infrastructure expansion.[13,14] LCA has been effectively applied to evaluate the environmental performance of water infrastructure including the environmental impacts associated with the construction, maintenance, and disposal of various green infrastructure technologies[15−17] and the incremental life cycle impacts and benefits of adding green infrastructure on an existing stormwater management system[18−21] for a variety of environmental measures. These studies generally find that water quality can be improved with green stormwater infrastructure expansion at a potential cost of elevated greenhouse gas (GHG) emissions and resource/energy consumption. The estimates of life-cycle GHG emissions released by implementing stormwater infrastructure vary significantly depending on the type and life span of the infrastructure as well as the watershed characteristics.[17,19] However, these increased environmental impacts can be partially offset by considering the influence of vegetation on adjoining building energy use and on carbon sequestration,[15,21] as well as the energy savings achieved by reducing runoff flows to wastewater treatment plants (WWTP).[19,21] Previous studies also indicate that the construction materials (e.g., concrete and asphalt components, rock and soil aggregates, and large diameter high density polyethylene pipe) of the green infrastructure often represent the largest contributor to the environmental impacts from these systems.[18−20,22] Several of these studies included uncertainty, scenario, and sensitivity analysis demonstrating the implications of variations of infrastructure sizing[16] economic costs,[21] and land uses (i.e., imperviousness).[22] Other system conditions can also significantly affect the trade-off analysis including local climate patterns and regulatory requirements, the quality of the stormwater runoff, and the lifetime and treatment efficiency of the systems.[1,17]

Table 1. Influent and Effluent Quality for All the Water Flows Modeled in the Base Case and the Stormwater Management Alternatives As Shown in Figure 1A

		typical concentrations of the pollutants					typical treatment rates[a]	
				urban runoff				
	unit	raw sewage and CSO	secondary treated sewage effluent	typical	low	high	BB	PP
TSS	mg/L	200[30]	20[30]	80[31]	0.5[32]	4800[32]	59%[33]	89%[33]
TP	mg/L	8[30]	5[12]	0.3[31]	0.01[32]	15.4[32]	50%[34]	25%[35]
TN	mg/L	40[30]	20[12]	2[30,31]	0.02[30]	20[31]	60%[34]	25%[35]
COD	mg/L	500[36]	53.8[12]	75[30]	75[30]	275[30]		
Grease	mg/L	100[36]	0[b]	3.5[31]	3.5[31]	3.5[31]		
Chloride	mg/L	50[36]	50[12]	430[37]	44[37]	2085[37]		
Copper	ug/L	220[30]	5.09[12]	10[31]	0.6[14]	1360[14]	81%[33]	86%[33]
Lead	ug/L	100[30]	0.67[12]	18[31]	0.2[14]	1200[14]	84%[29]	74%[38]
Zinc	ug/L	280[30]	8.96[12]	140[31]	0.1[14]	22500[14]	79%[33]	66%[33]
Mercury	ug/L	5[39]	0.023[12]	0[b]	0[b]	0[b]		
Manganese	ug/L	53[39]	47.04[39]	0[b]	0[b]	0[b]		
Insecticides	ug/L	0[b]	0[b]	1.05[31]	0.1[31]	2[31]		
Herbicides	ug/L	0[b]	0[b]	3[31]	1[30]	5[30]		

[a] The treatment rates refer to the pollutant reduction from the influents to the effluents of a system. In present research, the typical treatment rates are the median or average estimates reported by previous studies and are assumed to be calculated using the event mean concentration (EMC) efficiency method. Therefore, the treatment rates remain constant under the various rainfall events simulated. [b] 0 was assumed when no estimates were readily available in the literature.

Table 2. Water Flows through the Base Case and Stormwater Management Alternatives A, B, and C (as shown in Figure 1A) under the Three Precipitation Scenarios Presented in Figure 2

			water flows (m^3/yr)							
			base case (CSS)		Alternative A (green infrastructure of bioretention basin, green roof, permeable pavement)			Alternative B (municipal separate storm sewer system)	Alternative C (integration of alternative A and alternative B)	
precipitation scenario	annual precipitation (cm/yr)	annual runoff (m^3/yr)	through WWTP to river[a]	through CSO to river[b]	to storage in green infrastructure	through WWTP to river[a]	through CSO to rive[b]	direct to river[c]	to storage in green infrastructure	through green infrastructure to river[d]
P1 (average year)	110	1012	869	142	1012	0	0	1012	1012	0
P2 (dry year)	75	786	429	357	705	46	35	786	705	81
P3 (wet year)	124	1851	699	1151	1254	179	417	1851	1254	596

[a] Discharge treated to WWTP effluent standards. [b] Direct discharge of untreated sanitary wastewater as the treatment benefits to the effluent from the green infrastructure are negated when this effluent mixes with sanitary waste in the combined sewer system. [c] Direct discharge of untreated stormwater runoff. [d] Effluent from the bioretention basin and permeable pavement assumed based on the stormwater quality and average treatment efficiencies reported. For the other green infrastructure, the green roof, no treatment benefits are realized, as discharge from the roof will result in ground-level runoff that will act like stormwater runoff in terms of transporting nonpoint source pollutants. As such, effluent from the green roof was modeled as untreated stormwater runoff.

While previous studies have evaluated the marginal environmental impacts of adding green infrastructure on existing gray systems,[18−22] to date, De Sousa et al.[21] is the only study that we are aware of that evaluated potential combinations of green and gray stormwater additions to an existing system. In their study, De Sousa et al.[21] compared the environmental performance of a portfolio of green infrastructures implemented in Bronx, NY (one of 772 U.S. cities operating combined sewer systems)[23−25] versus two scenarios of detention and treatment using gray infrastructure. The study was conducted under a single precipitation scenario and used the EPA's SWMM model to evaluate changes to hydraulic flows as well as LCA to estimate potential associated environmental impacts, though only greenhouse gas emissions were considered. The authors found that the green infrastructure scenario has 75−95% lower life cycle GHG emissions than the gray infrastructure options largely due to the latter's higher material requirements and life cycle electricity usage. The green infrastructure portfolio was sized to detain the first inch of rainfall and was found to reduce combined sewer overflow (CSO) events; however, the study did not evaluate the effects of modeled interventions on water quality.

Despite the wealth of previous work, there remains an open question regarding environmental trade-offs in the life cycle of gray and green infrastructure between water quality gains and incremental energy and material costs for green and/or gray stormwater infrastructure expansion to reduce combined sewer overflows (CSOs). The current study explicitly addresses this question for a set of infrastructure expansion options typical of those currently available to municipal agencies. The goal of the study is to quantify the marginal economic and environmental costs and benefits of expanding stormwater infrastructure under various precipitation patterns, thus advancing the knowledge needed for decision-making while considering forecasted climate change effects in rainfall intensity and frequency. Given the site-specific nature of stormwater management and to expand the applicability of the findings of the present study, sensitivity and uncertainty of the life cycle model were considered by varying critical systems variables such as infrastructure life span, stormwater runoff quality, and land imperviousness.

■ RESEARCH SCOPE AND METHOD

Overview. A consequential LCA was performed to evaluate the potential economic and environmental costs and benefits associated with alternative expansions to an existing stormwater infrastructure system, assumed to be a combined sewer system (CSS) in a typical, mixed-use urban watershed in the Northeastern US of 4047 m^2 (one acre) covered by Type B soil with 80% imperviousness.[26] Three potential stormwater infrastructure expansion alternatives were investigated to manage the impacts from stormwater runoff and CSOs in this watershed and were compared to the current baseline case (CSS/CSO): (A) one of three green infrastructures: bioretention basin (BB), green roof (GR), or permeable pavement (PP) due to their demonstrated high performance and increasing implementation in urban settings;[27−29] (B) a gray infrastructure solution, namely, municipal separate stormwater sewer system (MS4) that directly discharges stormwater runoff to receiving water bodies; and (C) a combination of one of the green infrastructures with MS4. This results in a total of seven stormwater management alternatives that were modeled: (A) BB, GR, and PP; (B) MS4; and (C) BB+MS4, GR+MS4, and PP+MS4 (Figure 1A). Depending on the configurations of each stormwater management alternative, flows of varying water quantity (Figure 1A, Table 1) and quality (Figure 1A, Table 2) are modeled.

The green infrastructures, BB and PP, can filter the runoff influents and remove the NPS pollutants at treatment rates reported in Table 2. For GR, the effluent quality depends strongly on a variety of factors (e.g., compositions of plants and substrates, the age of roof, practices of roof management, rainfall intensity), and for different pollutants, both net release and net reduction have been observed.[40−42] As a result, we conservatively assume that the GR provides no water quality improvement[43] but does divert rain from stormwater runoff through storage. GR effluent after being conveyed to the ground will mix with stormwater runoff and thus is assumed to have the same chemical compositions as urban runoff. In Alternative A, after the treated effluents from the green infrastructures are conveyed through the CSS, they are modeled as secondary treated sewage effluent or CSO assuming no dilution effects by the stormwater runoff based on data reported by previous studies[44,45] (Figure 1A). For Alternative B, MS4 is assumed to directly discharge runoff to natural water bodies without providing any water quality benefits.[46] In Alternative C, when BB or PP is integrated with MS4, the treated effluent from the green infrastructure will flow to MS4 and be discharged to rivers and streams with less concentrated NPS pollutants than the raw urban runoff due to the treatment provided by BB and PP; when GR is integrated with MS4, the final discharge to receiving water bodies is modeled as untreated urban runoff because neither GR nor MS4 reduce the mean concentration of NPS pollutants as they pass through the systems. By integrating the green and gray alternatives in Alternative C, both the benefits and costs associated with the two alternatives are integrated.

Wastewater Treatment Plant and Combined Sewer Overflows. The wastewater treatment plant (WWTP) for the CSS is assumed to be conventional with effluent of total nitrogen <20 mg/L and total phosphorus <5 mg/L,[12,30,47] average dry weather flow (ADWF) equivalent to 0.013 cm/h/acre and interceptor capacity (peak wet weather flow ratio) of 3*ADWF.[12,48,49] Exceeding the capacity of the CSS (assumed as 0.025 cm/h of stormwater runoff[48,49] or 2*ADWF) results in the direct discharge of untreated wastewater and stormwater runoff as a combined sewer overflow (CSO). For the modeled watershed, the average velocity of runoff associated with a 2.5 cm (1 in.) in 24 h rain event is ∼0.025 cm/h, and therefore it is assumed to be the minimum rainfall event to induce a CSO when there is no stormwater infrastructure expansion to the CSS. Concentrations of CSO pollutants vary significantly[45] and wastewater dilution by runoff in the CSO was only observed for the pollutants mainly originated from human activities (i.e., BOD_5, TKN, sulfate), not for other wastewater pollutants (i.e., COD, TSS, TP are hardly affected or become more concentrated).[44] As such, the untreated urban wastewater and CSOs are assumed to have the same composition (Table 2).

Effluent quality from the WWTP can significantly affect the model results since it is integral to the base case used for comparison. Of note, increasingly stringent wastewater discharge standards are being pursued to better protect aquatic and human health.[50] In order to provide insights for integrated municipal stormwater and wastewater management,[51] the effects of an enhanced effluent quality standard (TN < 3 mg/L, TP < 1 mg/L) representing tertiary nutrient removal through the use of the 5-stage Bardenpho process configuration[12] were also modeled.

Functional Unit. By design, each green infrastructure has the capacity to store the runoff associated with 2.5 cm (1 in.) of rainfall generated over the defined 1 acre watershed (79 m^3), the most common sizing criterion by many states in the US.[52−54] Accordingly, the bioretention basin, green roof, and permeable pavement were sized as 137 m^2, 1298 m^2, and 4047 m^2, respectively. The MS4 was designed to manage 10-year events (equivalent to 12.5 cm), a common minimum requirement for many States.[55] Given that the MS4 system would be significantly larger in capacity than the green infrastructure systems, a portion of the MS4 system was allocated to capacity provided by the green infrastructure (approximately 221 m of the 30 cm (12 in.) pipe in the 1 acre network). In this way, it is assumed that the green infrastructure would reduce the need to build out this additional capacity in the MS4 system, effectively increasing the capacity of the system without the need for additional or larger-diameter pipe.

Life Cycle Inventory. For the baseline CSS, only the stormwater runoff treatment was inventoried and analyzed, given that this is a consequential LCA of infrastructure that is already installed. Each of the seven alternative expansions was inventoried over five life-cycle stages (Figure 1B). Impacts of the first four stages are fixed once the infrastructure is designed and built including (1) raw material extraction and production, (2) material and waste transportation, (3) infrastructure installation, and (4) infrastructure maintenance. Impacts associated with the fifth life cycle stage, stormwater runoff storage and treatment, are variable and depend on external conditions including precipitation intensity as well as runoff quality.

The life cycle inventory (LCI) for each alternative was developed based on a hybrid framework. Background LCI data were retrieved from the databases of ecoinvent v.2.2, US Input Output, and US LCI, supplemented with other literature sources as detailed in the Supporting Information, and assembled in SimaPro 7.3.3.[56] Infrastructure material production and transportation were inventoried using a process-based approach; installation and maintenance stages as well as data gaps in the first two stages were modeled using economic input-output LCA (see SI). Details of material requirements and installation for each green infrastructure type were based on the well-defined standards by Virginia Department of Conservation and Recreation[34,43,35] supplemented with information from RSMeans,[57] while maintenance information was obtained from the Center for Neighborhood Technology's Green Values National Stormwater Calculator[14] due to the lack of information available that was specific to the Northeast in general or Connecticut in particular. For the MS4 system materials were inventoried using Connecticut Drainage Manual,[58] material acquisition and infrastructure installation were modeled from RSMeans,[57] and maintenance information was obtained from the city of Redding, California.[59] All of the materials used for constructing the Alternatives are locally available so a 16 km (10 mile) radius is assumed for transportation of those materials and solid waste disposal by truck.

Precipitation Scenarios. Precipitation data for New Haven, Connecticut[60] (typical of the Northeastern US) were used to define three precipitation scenarios (Figure 2): (P1) is designed to have the average annual rainfall volume (110 cm) with rainfall events contributing to this total precipitation occur as average rain events with the significant majority being <2.5 cm. This is an important assumption because all of the green infrastructure systems were designed to manage this exact capacity, that is, the first 2.5 cm of precipitation in any given single event; (P2) is based on 1970, representing a dry year with one of the lowest annual precipitations recorded (75 cm) and only seven events with more than 2.5 cm of precipitation that could cause CSOs; (P3) is based on 2005, a wet year of high annual precipitation (124 cm) and fourteen high precipitation events of 2.5–8 cm.

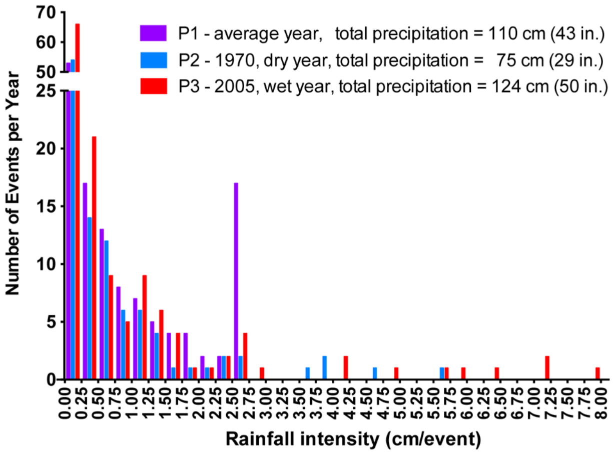

Figure 2. Number of precipitation events (>0 cm) per total rainfall intensity (inches/event) in New Haven, CT for three precipitation scenarios.

Life Cycle Impact Assessment (LCIA). Environmental impacts of the base case and the stormwater management alternatives under the precipitation scenarios were assessed for six midpoint indicators: climate change (kg CO_2 eq.), freshwater eutrophication (kg P eq.), marine eutrophication (kg N eq.), freshwater ecotoxicity (kg 1,4-DB eq.), marine ecotoxicity (kg 1,4-DB eq.), and fossil fuel depletion (kg oil eq.) using the common ReCiPe 2008 midpoint (hierarchist) method.[61,62]

Equation 1 provides the generic formula for calculating the annual impact for a given environmental midpoint i, under one of the three rainfall scenarios j, where the annual impact $E_{i,j}$ is a sum of the impacts for that environmental midpoint at each life cycle stage:

$$E_{i,j} = \frac{E_{\text{material},i}}{t} + \frac{E_{\text{transportation},i}}{t} + \frac{E_{\text{installation},i}}{t} + E_{\text{treatment},i,j} + E_{\text{maintenance},i} - E_{\text{avoided maintenance},i} \qquad (1)$$

The environmental impacts caused by the first three life cycle stages, material production, material transportation, and infrastructure installation, are amortized over the expected lifespan (t) of the infrastructure. A 30-year, 40-year, 25-year, and 50-year life span is assumed for BB, GR, PP, and MS4, respectively.[14,63] Avoided maintenance burdens associated with implementing a new stormwater management alternative were accounted for as credits (i.e., maintenance of conventional roof or conventional asphalt pavement will be avoided when a green roof or permeable pavement is implemented), assuming that conventional infrastructures (i.e., conventional roofs and road pavements) exist before implementing the stormwater expansion alternatives and that those expansions are not substituting for other new infrastructures.

Cost–Benefit Analysis. To evaluate the economic costs of water quality improvements against resulting environmental impacts (i.e., greenhouse gas emissions, resource depletion) for each stormwater management alternative, a cost–benefit ratio of water improvement can be defined as

$$\text{cost–benefit ratio of water improvement} = \frac{\Delta\$ \text{ or } \Delta CO_2 \text{ or } \Delta\text{resource}}{\Delta\text{WQI}} \qquad (2)$$

where $\Delta\$$, ΔCO_2, and Δresource are the annualized life cycle economic costs, greenhouse gas emissions, and energy consumption, respectively, of the alternative as compared to the base case. ΔWQI, a measure of the marginal benefit of water quality improvement, is the annual reduction in any of the four water-associated environmental categories (freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, and marine ecotoxicity) by a stormwater management alternative for a given precipitation scenario, as compared to the base case. All economic costs are presented in 2002 dollars and converted using US urban average consumer price index as a measure of inflation rates and an average annual discount rate of 5%.[64]

Uncertainty Analysis. Stormwater management is known to be highly site- and source-specific, so it is important to understand the implications of technical and physical variability associated with stormwater management. Given that wide ranges of expected lifetime of the infrastructures (BB: 25–50 years; GR: 25–50 years; PP: 20–40 years; MS4: 30–70 years)[14] and pollutant concentrations in urban runoff (Table 2) have been documented by previous studies[30,31,37,45] and the potentially significant implications to the results of the model, these two variables were selected to evaluate uncertainty.

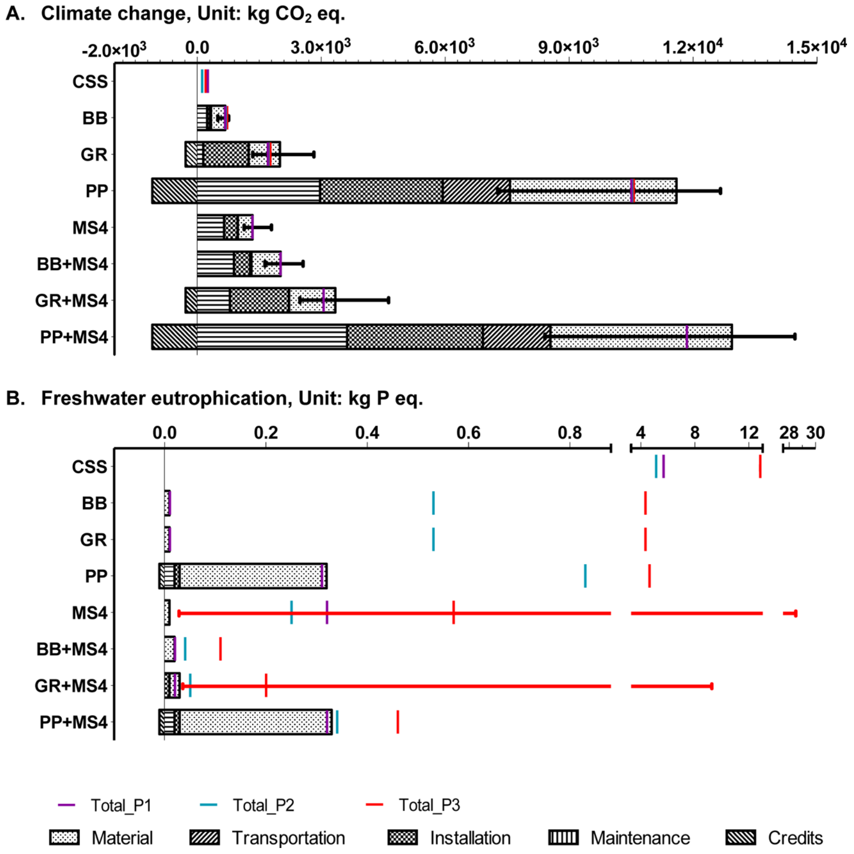

Figure 3. Colored vertical hashes corresponding to each of three rainfall scenarios (P1−P3, as described in Figure 3) represent net life cycle impacts for (A) climate change and (B) freshwater eutrophication for CSS and each of the stormwater management alternatives (Figure 1A). Patterned bars show the fixed impacts by each of the first four life cycle stage (materials processing and transportation, installation and maintenance, Figure 1B), with credits for avoided burdens shown left of the vertical axis. Black error bars on the patterned bars shown in (A) represent the impact of uncertainty in infrastructure lifetime (25−50 yrs. for BB; 25−50 yrs. for GR; 20−40 yrs. for PP; 30−70 for MS4) can have on the total fixed impacts; Red error bars shown in (B) represent the impact of uncertainty in stormwater runoff quality (Table 1) can have on the total eutrophication impacts under the most extreme precipitation scenario (P3).

Sensitivity Analysis. Land imperviousness is considered a crucial determinant for urban stormwater management and a deciding variable for selection of a stormwater management alternative,[65−68] because it directly affects the quantity of runoff generated and subsequently the designed infrastructure capacity that affects all of the life cycle environmental impacts. These impacts are expected to be nonlinear in relation to imperviousness, given the nonlinear responses of the rainfall-runoff ratio, infrastructures' engineering configurations (e.g., surface area, depth) to changes of land imperviousness, and the fixed conveyance capacity of the baseline sewer system. Model sensitivity was tested by altering the initial assumed imperviousness by ±10% to explore the implication of the results for stormwater management in watersheds during various development phases.

■ RESULTS AND DISCUSSION

The following sections present the LCA results for the representative impact categories of GHG emissions and freshwater eutrophication for each stormwater management alternative, while full results for the remaining four categories are given in the SI. Fossil fuel depletion trends with GHG emissions and are both indicative of costs from additional stormwater infrastructure. Marine eutrophication as well as freshwater and marine ecotoxicity trend with freshwater eutrophication and are indicative of water quality improvement benefits.

Environmental Cost of the Alternatives as Indicated by Greenhouse Gas Emissions. Compared to the base case of a CSS, all seven alternatives generate additional greenhouse gas (GHG) emissions since they all require some additional infrastructure; however, there are large differences in the potential climate impacts (Figure 3A). Note the colored hashes (one for each precipitation scenario) in Figure 3A represent the total life cycle GHG emissions (including credits) for all life cycle stages including runoff storage and treatment. The bioretention basin (BB) yields the lowest GHG emissions (~700 kg CO_2 eq. per year) while the integration of permeable pavement (PP) and MS4 (PP+MS4) yields the highest GHG emissions (11 860 kg CO_2 eq. per year). This large climate impact is largely caused by the production of construction materials (mainly concrete manufacturing: 3310 kg CO_2 eq. per year) as well as the relatively intensive installation and maintenance processes required for the PP.

By avoiding the annual maintenance of conventional roof or conventional asphalt pavement by implementing a green roof or permeable pavement, 280 kg CO_2 eq. and 1088 kg CO_2 eq. per year were avoided for GR and PP, respectively. These are considered as credits to total life cycle GHG emissions, depicted to the left of the *y*-axis in Figure 3. The implementation of green infrastructure and/or MS4 systems is designed to reduce or eliminate CSOs specifically, but also reduces overall flows to WWTPs. While less overall water is being treated in WWTPs in the scenarios modeled here, the reductions in WWTP chemical and energy use with these marginal reductions in flow are small, and so no credit is assumed for avoided stormwater treatment.

Overall, the four life cycle stages independent of precipitation and runoff characteristics (Figure 1B) account for the majority of GHG emissions for all seven alternatives. However, for each alternative, the life cycle GHG emissions are dominated by different life cycle stages (e.g., installation for GR and maintenance for MS4). Simulations based on the upper and lower limits of the infrastructures' life expectancies[14] (error bars in Figure 3A) indicate that while the GHG emissions of all of the alternatives are impacted, PP systems realize a reduction in ~3000 kg CO_2 eq. or 30% of PP's life-cycle GHG emissions annually if lifespan is extended from 25 years to 40 years, primarily through the reduction in effective annual material use.

Water Quality Benefits of the Alternatives as Indicated by Freshwater Eutrophication. All of the stormwater management alternatives demonstrate a considerable reduction in freshwater eutrophication over the base case (Figure 3B) with the precipitation scenario having a strong influence on the magnitude. Further, nearly all of the total life cycle eutrophication benefits (shown by hash and precipitation scenario in Figure 3B) come from a single life cycle stage, stormwater runoff storage and treatment. Further, there is clearly a wide range of uncertainty associated with the eutrophication impacts of the MS4 systems due to the significant variability in stormwater runoff quality (Table 1 − urban runoff). Not surprisingly, the base system (CSS) generates the largest freshwater eutrophication, and this is exacerbated under the most extreme precipitation scenario where there are the most rainfall events leading to CSOs. It is noteworthy that the total volume of stormwater runoff, rather than the total volume of CSOs, is the most critical determinant of the eutrophication impacts generated by the CSS (Note that for the base case, P1 caused more runoff and less CSOs than P2 as shown in Table 1, and *Total_P1* is larger than *Total_P2* as shown in Figure 3B). This is due to the only moderate nutrient removal efficiency at a conventional WWTP, so that a significant fraction of nutrients are present in the effluent and contribute directly to eutrophication;[12] further, the chemical and energy requirements during secondary treatment contribute indirectly to eutrophication via emissions from electricity generation and chemicals production. By reducing the runoff influents to WWTP, in addition to reducing CSO events, all the Alternatives achieved reductions in eutrophication impacts over the base case. Given that capacity expansion is regarded as an adaptive approach by WWTPs to protecting against increased precipitation intensity and variability due to climate change,[69] the results here indicate that capacity expansion alone is unlikely to achieve the goal.

Among the alternatives, the highest eutrophication reductions, and therefore the greatest water quality improvements, are achieved by Alternative C, the integration of green and gray systems, regardless of the type of green infrastructure that is paired with MS4. When the runoff flows are within the green infrastructure's treatment capacity (as under precipitation scenario 1), all of the green infrastructure systems (Alternative A) are able to mitigate the majority of the eutrophication impacts that would be generated in the CSS. MS4 (Alternative B)'s small eutrophication impact is a result of the relatively low pollutant concentrations in typical urban runoff as compared to those in treated secondary WWTP effluents and CSOs (Table 2). However, the concentrations of urban runoff pollutants in the United States range widely, as reported by previous studies.[45,30,31,37] Considering various runoff compositions (see Table 2), it is found that sewer separation could actually worsen water quality with the possibility of MS4 doubling life cycle eutrophication impacts annually as compared to CSS under the wettest precipitation scenario (P3). (Note that error bars for P3 in Figure 3B represent the impacts of variability in runoff quality as described in Table 2).

Cost−Benefit Analysis. As indicated by the LCIA results above, the stormwater management alternatives can help improve water quality at the cost of incremental environmental impacts (represented by GHG emissions above but similar trends are found for resource depletion (SI)). In addition, economic resources need to be invested to expand stormwater infrastructure (i.e., constructing and maintaining the infrastructures), which can be prohibitive given the increasing funding gaps for upgrading and maintaining the degrading water systems.[70] To better understand the potential trade-offs between environmental/economic costs and water quality improvements (represented here by per kg P eq. reduction), the Alternatives are compared using eq 2 from three perspectives: economic costs (US $), GHG emissions (kg CO_2 eq), and resource consumption (kg oil eq).

As shown in Figure 4, depending on which of these variables are selected as the "cost" indicator, different optimal stormwater management alternatives are suggested. For example, BBs are generally the most financially cost-effective ($98 per kg P eq. reduction) and demonstrate the smallest climate footprint (61 kg CO_2 eq. emitted per kg P eq. reduction). MS4 is the most effective in eutrophication reduction for the least amount of resource depletion (42 kg oil eq. consumed per kg P eq. reduction). For comparison, the operational cost of removing 1 kg of phosphorus at a WWTP is ~420 US $ on average and $2000−3000 when the capital costs are taken into account.[71,72] Results indicate that both green and gray alternatives are efficient in phosphorus reduction in terms of life cycle economic costs (84−1642 US $ per kg P eq. reduction). Of all the alternatives considered, PP demonstrates the highest environmental costs to reduce phosphorus, over 1.2 ton CO_2 eq. or 375 kg oil eq. per kg P eq. reduction, as compared to 21.1

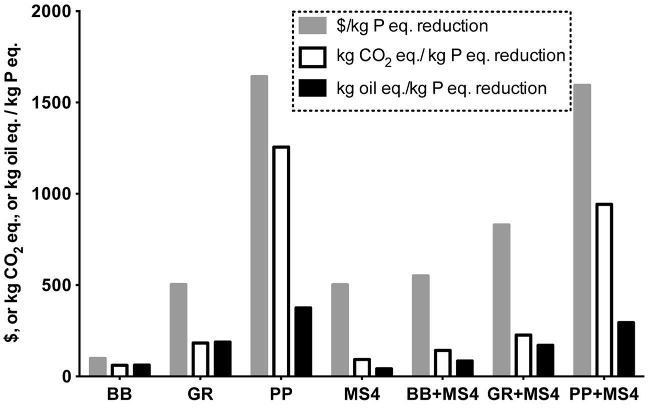

Figure 4. Cost−benefit ratios of water improvement: reduction of freshwater eutrophication impacts at the expenses of economic costs ($/kg P eq), climate impacts (kg CO_2 eq/kg P eq), and energy consumption (kg oil eq/kg P eq).

ton CO_2 eq. emitted and 7069 kg oil eq. consumed per person in the US in 2011.[73,74]

Impact of More Stringent WWTP Effluent Standards. Realizing water quality benefits through improved WWTP effluent quality as an alternative to managing stormwater runoff was modeled (note that this only affects the base case and Alternative A, Figure 1A). Unlike freshwater eutrophication, GHG emissions of Alternative A (green infrastructure options of BB, GR, and PP) are not significantly affected by enhanced WWTP treatment (an increase of 0.5−7.4% CO_2 eq.). Tertiary treatment at WWTPs can reduce Alternative A's eutrophication impacts by ~21% (Figure 5). The low climate cost of water quality improvement through enhanced WWTP effluent for the most extreme precipitation scenario (P3), 78 kg CO_2 eq. emission per kg P reduction, as compared to 61−1257 kg CO_2 eq. emission per kg P reduction by the seven alternatives considered (assuming secondary treatment at the WWTP, Figure 4), further supports the integration of stormwater and wastewater practices to simultaneously advance water and climate benefits. In addition, the small differences between the overall life cycle eutrophication impacts and those directly on the receiving water environment indicate that WWTP tertiary system upgrade itself caused minimal eutrophication effects. It is noteworthy that the implementation of green infrastructure can significantly improve water quality by reducing the total eutrophication impacts by more than 40% even when compared to a WWTP with advanced treatment. This is related to urban runoff tending to have lower nutrient concentrations than WWTP effluents because the WWTP is treating both municipal sewage as well as stormwater.

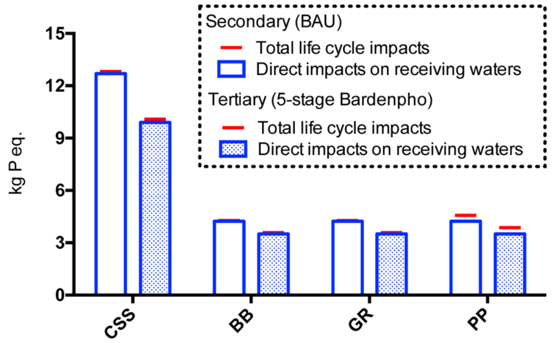

Figure 5. Effects of enhancing wastewater treatment standards from secondary (TN < 20 mg/L, TP < 5 mg/L) to tertiary (TN < 3 mg/L, TP < 1 mg/L) on freshwater eutrophication impacts associated with stormwater management while no infrastructure or green infrastructures are implemented. Horizontal hashes show the impacts generated through all life cycle stages; bars show the direct eutrophication impacts on the receiving waters.

Sensitivity to Imperviousness Analysis. When imperviousness increases, the volume of runoff generated by the same precipitation event increases exponentially.[75] The changes of runoff volume affect all of the water flows in the system directly impacting the environmental impacts associated with the stormwater storage and treatment life cycle stage. To evaluate the implications of imperviousness, a critical parameter, the LCA was repeated for the wettest precipitation scenario (P3) when the original imperviousness (80%) was increased and decreased by 10% respectively (Figure 6). Since the green infrastructures were sized to capture the volume of runoff associated with the first 2.5 cm (1 in.) of rainfall, the size, and therefore the material inputs, for the bioretention basin, green roof, and permeable pavement were increased to account for the altered runoff now associated with this same rainfall. Sizing of MS4 were not modified in this sensitivity analysis because it was sized based on the minimum regulatory requirement.

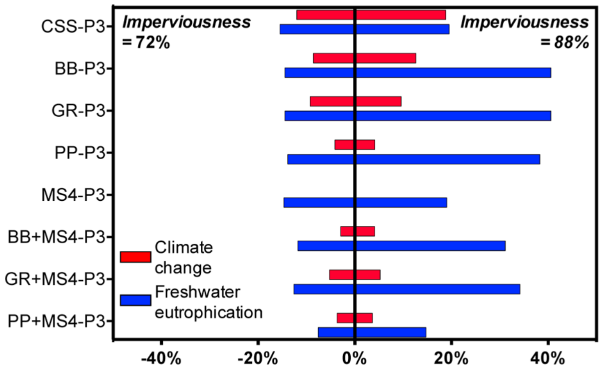

Figure 6. Effects of increasing and decreasing the watershed imperviousness by 10% (initial imperviousness = 80%) on climate change (red bars) and freshwater eutrophication (blue bars) under the wettest precipitation scenario, P3. Lower imperviousness (Imperviousness = 72%) results in lower climate change and freshwater eutrophication impacts (shown on *x*-axis as negative percentage changes from the initial results), and higher imperviousness (Imperviousness = 88%) results in higher climate change and freshwater eutrophication impacts (shown on *x*-axis as positive percentage changes from the initial results).

With greater imperviousness, climate impacts increased (by 0−18%) for the CSS and the stormwater management alternatives because the capacity of the green infrastructure needs to be increased to manage the additional runoff from the same precipitation event and additional treatment is required at the WWTP. Similarly, less imperviousness reduces the climate footprints of those systems (by 0−12%), because there will be less runoff and infrastructures can be downsized. Given the climate impact is largely generated by the four fixed life-cycle stages, the climate footprint of MS4, whose size was not altered with the changes of land imperviousness, was insignificantly affected.

As expected, water quality declines as indicated by increased eutrophication when imperviousness increases and vice versa. Due to the exponential relationship between runoff−rainfall ratio and watershed imperviousness, increasing the imperviousness by 10% leads to more significant eutrophication impacts (15−41%) than the decreases in P loading (8−15%) observed when imperviousness is decreased by 10%. The larger sensitivity of freshwater eutrophication to changes in imperviousness indicates that "water quality benefits" are more susceptible to land use changes than GHG emissions are. The significant increases of climate and eutrophication impacts associated with the stormwater management alternatives suggest that they will have limited water quality improvement benefits at a higher GHG emission cost in a more impervious watershed.

■ IMPLICATIONS

The trade-offs between environmental improvement and potentially substantial economic costs are known to confront public and private investment and regulatory decisions for stormwater management.[1] By conservative estimate, the total water infrastructure needs for CSO control and stormwater management in the United States were \$63.6 billion and \$42.3 billion, respectively, in 2008.[11] The environmental costs of stormwater infrastructure expansion have received little attention since runoff management is generally assumed to generate net environmental benefits_ENREF_18.[17] To our knowledge, the present study is the first to assess the environmental and economic cost-effectiveness of using green, gray, and integrated green and gray stormwater infrastructures to achieve water improvement goals from a life cycle perspective. The optimal stormwater management alternatives were illuminated by the *cost-benefit ratio of water improvement*, which takes into account the trade-offs between the environmental benefits and environmental and economic costs of implementing stormwater management alternatives. Realizing water quality benefits through green infrastructure are shown to be reliant on local rainfall intensity and land imperviousness. With more extreme precipitation events over an increasingly imperviousness landscape expected, the benefits achievable by green infrastructures will be constrained. Of additional significance, the goal of installing MS4s for improved water quality over CSOs is highly dependent on local runoff quality. Results of this research indicate that MS4 could realize even greater eutrophication impacts than conventional CSS/CSO if the runoff is heavily polluted. This becomes more significant as precipitation frequency and intensity are projected to increase under certain climate change scenarios. Although this research investigated multiple environmental costs as well as the economic costs associated with green and gray stormwater infrastructures through their life cycles, the benefits considered were constrained to the water quality improvement through runoff management, leaving out the potential GHG mitigation effects, other ecosystem services, and social benefits of green infrastructure.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional figures and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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