

The Greatest Opportunity for Green Stormwater Infrastructure Is to Advance Environmental Justice

Gregory H. LeFevre,^{*} Marccus D. Hendricks,^{*} Maya E. Carrasquillo,^{*} Lauren E. McPhillips,^{*} Brandon K. Winfrey,^{*} and James R. Mihelcic^{*}



Cite This: <https://doi.org/10.1021/acs.est.3c07062>



Read Online

ACCESS |



Metrics & More



Article Recommendations

SCIENTIFIC
OPINION
NON-PEER
REVIEWED



KEYWORDS: green stormwater infrastructure, environmental justice, water quality, pluvial flooding, sustainable development, equity, climate resilience, nature-based solutions

■ INTRODUCTION AND MOTIVATION

In 2021, *Environmental Science & Technology* convened an ACS Global Webinar^a on green stormwater infrastructure (GSI) as a tool for environmental justice. Since then, we researchers have continued to discuss advancing GSI science, practice, and priorities. The U.S. Environmental Protection Agency¹ describes green infrastructure as “the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspire stormwater and reduce flows to sewer systems or to surface waters.” GSI systems use a variety of names both within the United States and worldwide (e.g., low-impact development, sponge cities, water sensitive cities) and encompasses concepts from physical stormwater design/management practices to sustainable urban planning and urban ecology.^{2,3} GSI and, more broadly, other nature-based solutions offer possibilities for

improving urban hydrologic function and water quality while providing multiple co-benefits;⁴ however, we contend the most important benefit is as a tool to advance environmental justice (EJ). Indeed, if these benefits lack intentionality in process and placement to repair past harms, we miss the greatest opportunity of all. Here we present summarized thoughts concerning strengths, weaknesses and threats, and opportunities for GSI (Figure 1).





Figure 1. Current strengths, weaknesses and threats, and opportunities in green stormwater infrastructure (GSI), including water quality improvement, climate resilience, and environmental justice. We argue GSI offers multifaceted opportunities for urban water sustainability, including valorizing stormwater for reuse; however, the single most important, pressing opportunity is as a tool for environmental justice (background photo by G.H.L.).

■ EXISTING STRENGTHS

Fundamentally, GSI are naturally resilient systems that serve multiple functions. Decreasing stormwater runoff and improving water quality may be primary and more obvious design goals, but ecosystem services,⁵ including urban habitat provision (e.g., pollinator microhabitats and connectivity), heat island mitigation, and aesthetic improvements, are important co-benefits. Plant and microbial communities help maintain functionality; e.g., roots improve hydraulic conductivity, and microbes biodegrade many contaminants.⁶ GSI practices have demonstrated removal of many important stormwater contaminants (e.g., sediments, nutrients, heavy metals, PAHs) at the lab, pilot, and field scale. The diversity and distributed nature of GSI practices provide fit-for-purpose flexibility (e.g., rooftop capture, infiltration trenches, bioretention cells, greenroofs, treatment wetlands) and can lower barriers to adoption by siting at private homes and businesses or public parks and right-of-ways.

■ WEAKNESSES AND THREATS

Many of the weaknesses that we articulated related to managing expectations for GSI and the need to not “oversell” what GSI cannot do. Specifically, GSI systems are not (typically) designed to mitigate extreme rain events or remove highly soluble contaminants. Most GSI practices are intended to capture and infiltrate high-frequency, low-intensity events. GSI practices can help “flatten the curve” off peak stormflow and decrease total discharge volumes, but additional storage is required for extreme events or to optimize groundwater recharge.⁷ Although capture spaces can have dual usages for much of the time (e.g., sports fields), green infrastructure cannot fully replace gray infrastructure for managing flood hazards and a hybrid approach is needed.⁸ Real and perceived “parallel infrastructure” requirements (i.e., needing both GSI and gray systems) can create implementation/management barriers. Highly soluble contaminants, including many trace organic contaminants (TORCs) and deicing salts, are poorly removed in GSI systems and threaten underlying groundwater in systems containing high-infiltration, sand-based media. GSI benefits from regular maintenance (e.g., pruning, trash removal, unclogging) to maintain function and prevent an “unkempt” aesthetic. GSI

can suffer from the assumption that no or minimal maintenance is required of nature-based treatment systems. Improving GSI maintenance is often ignored as a viable research question (and adequate resources are not directed). Distributed/decentralized GSI maintenance may require time and/or specialized skills lacking in an existing municipal workforce. GSI assets on private property may be critical for meeting watershed-scale stormwater needs, but ensuring affordability of capital costs and maintenance (or who pays) presents challenges for public–private integration. Indeed, GSI affordability on private property presents a very real barrier to implementation equity. For example, many “cost-share” programs inherently benefit wealthy communities with greater capital.⁹ GSI practices may also not be “recognized” across political/jurisdictional boundaries; likewise, critical perception gaps exist between residents and asset managers concerning stormwater infrastructure “amenity” value.¹⁰ “Green” redevelopment into existing cityscapes without active social justice considerations can pave the way for gentrification.¹¹

■ OPPORTUNITIES

We believe that there are substantial opportunities to improve GSI. Innovations in GSI infiltration media (e.g., mineral-enhanced sands, black carbon) are improving rapid sorption and/or transformation of more challenging dissolved phased contaminants (e.g., TORCs). For example, GSI can effectively remove some emerging toxicants like 6-PPDq.¹² Biological processes (bacteria, plants, and fungi) synergized with rapid abiotic capture are increasingly being leveraged for the removal of contaminants.^{6,13} For example, development of novel materials that rapidly sorb TORCs during storm event infiltration while supporting subsequent biodegradation between events could effectively decouple (short) stormwater hydraulic residence time (HRT) from (longer) contaminant biodegradation contact time, much like how activated sludge revolutionized wastewater treatment by decoupling HRT from solids residence time. Small-scale practices are scaling into stormwater capture–treatment–recharge (CTR) systems for managed aquifer recharge.¹⁴ The expanding Internet-of-things and smart sensors/controls are better managing legacy stormwater issues (e.g., combined sewer overflows) and could revolutionize synergized green–gray infrastructure systems to markedly improve climate resilience.¹⁵ With the growing interest in impacts beyond the improvement of water quantity and quality, there is a need to optimize GSI design for inclusive provision of multiple co-benefits.

We contend that the most important opportunity in GSI is as a tool to advance social and environmental justice. Pluvial flooding has long differentially impacted socially vulnerable groups who have borne the burdens of concomitant public health and property damage.¹⁶ Predominantly Black, Latine, Indigenous, and other marginalized neighborhoods in the United States have experienced systematic underinvestment in public green spaces and tree cover while being fractured by forced gray infrastructure projects (e.g., interstate highways, railroads) through historically divisive (i.e., eminent domain) and racist (e.g., redlining, housing covenants) practices. Greening urban water infrastructure can increase access equality at a variety of spatial scales and reconnect residents with local water.¹⁷ GSI vegetation improves pollutant removal and contributes to heat mitigation and cultural services by improving a sense of place.¹⁸ Urban green/blue spaces improve community mental health.¹⁹ GSI, as part of a layered flood-mitigation

system, facilitates multiuse public health infrastructure (e.g., decorative gardens, local food production, active areas) and can encourage community science participatory research. Indeed, stormwater agencies adopting green infrastructure approaches are often more attuned to social concerns and equity compared to those using conventional storm sewer plans.²⁰ A recent analysis of U.S. green infrastructure plans, however, underscored that the majority of municipal green infrastructure plans systemically failed to centralize principles of equity or justice,^{9,20} presenting both a critical gap and major future opportunity. Poorly implemented GSI without intentionality toward EJ, early community involvement, or recognition of historically racist policies' long shadow can deepen environmental inequities.^{9,11} We see transforming and deploying GSI for environmental justice and community empowerment as the singular, foremost opportunity, and that the time is now.²¹

There is growing interest in lower- and middle-income countries for GSI as a sustainable development tool.²² UN-Habitat²³ acknowledges the important role that green infrastructure can play as an option for climate adaptation in the world's cities while also providing other benefits such as restoring and regenerating natural ecosystems. However, the UN Environmental Programme (UNEP) has recognized the bulk of green infrastructure investments have occurred in higher-income countries; therefore, supporting economic analysis of implementation in a low- and middle-income country context is less common.²⁴ Cost is often a key factor in less developed countries; thus, making use of appropriate design, including the use of existing nature-based solutions and conservation practices, can often be more attainable and cost-effective than more "engineered" forms of GSI.⁴ One strength of the environmental science and engineering community is that we have the ability to quantify real or perceived health benefits from improvements in water quality and quantity and access to green space.^{25–27} We also posit that promoting GSI in lower- and middle-income countries is entirely consistent with GSI as a tool to support environmental justice. One such example is the Revitalising Informal Settlements and their Environments (RISE) program in Indonesia and Fiji that focuses on using GSI approaches to integrate urban water management in informal settlements. The lack of infrastructure in informal settlements can be addressed with constructed treatment wetlands, rainwater capture, and formalizing drains. The program launched in 2018 and is currently evaluating environmental and public health outcomes in 24 settlements undergoing these interventions.²⁸

CONCLUSIONS AND RECOMMENDATIONS

GSI has expanded in recent decades from "fringe" to increasingly accepted; the recent Bipartisan Infrastructure Law specifically highlights nature-based solutions.²⁹ GSI cannot solve all water challenges—it is critical to calibrate expectations—but can help secure a more resilient water future, transforming stormwater from a rapidly expelled waste to a valorized, valued resource. There are critical areas where we can improve GSI from a hydrologic/contaminant removal standpoint, but we argue significantly greater strides must be made toward integrating the social and public health elements into holistic GSI design and management for securing multifaceted, equitable community resilience in the ways the communities see fit. We contend engineers and planners who design infrastructure—and indeed faculty who train these professionals—using the same tired and exclusionary approaches from the past hundred years are actively

perpetuating the structural racism manifested in much of our nation's legacy infrastructure. Green infrastructure offers an opportunity to cast a new collective vision, provided that justice is unequivocally tethered to our water quantity and quality aspirations.

The following recommendations should be used to prioritize future research, investment, and policy.

1. Prioritize (and therefore fund) the public health and environmental justice potential of GSI as an approach to healing land, water, and communities. Frame GSI as a multifaceted component of the environmental social determinants of health through a focus on equitable accessibility, connection, and multiple benefits for people. Specifically, the planning process for GSI should be more inclusive and requires enhanced coordination among municipal divisions responsible for planning, designing, and maintaining GSI. GSI practices must recognize indigenous connections, past and present, to the land and incorporate indigenous knowledge whenever possible. Community self-determination is a cornerstone of environmental justice and should be a required component of the participatory planning process to ameliorate past harms of infrastructure to historically marginalized communities. GSI approaches must be made accessible to countries in which little or no public infrastructure exists, including lower- and middle-income countries where GSI can achieve multiple sustainable development goals.
2. GSI should focus on improving resilience in a climate of increasing extremes. GSI design should help protect communities from future pluvial flooding, with efforts directed toward socially vulnerable communities. Even in temperate regions, GSI should valorize stormwater by recharging dwindling groundwater supplies. The climate benefits of GSI, including urban heat mitigation, should be prioritized as public health infrastructure. Finally, we must recognize the limits to GSI in mitigating flood hazards under future climate extremes and that hybrid green–gray infrastructure is often necessary.
3. Fund research for improving maintenance and longevity of GSI. Maintaining GSI should be considered an active (and supported) research topic—it is hardly solved nor merely an "implementation issue"—and deserves a holistic problem-solving planning and engineering approach. Research support for understanding the ecosystem services benefits of GSI beyond water-focused function will be critical. There should also be significant federal funding support for GSI workforce development training (both construction and maintenance) to support local under-resourced municipalities.
4. Every STEM course taught at universities should have an inherently integrated environmental and/or social justice component. The future leaders of tomorrow who design infrastructure that impacts peoples' lives (e.g., students studying engineering, design, chemistry, urban planning, public health, environmental science) must be trained to think holistically with environmental and social justice as a central pillar of education and professional practice, not as a separated afterthought.

AUTHOR INFORMATION

Corresponding Authors

Gregory H. LeFevre — Department of Civil and Environmental Engineering and IIHR—Hydroscience & Engineering, University of Iowa, Iowa City, Iowa 52242, United States; orcid.org/0000-0002-7746-0297; Email: gregory-lefevre@uiowa.edu

Marccus D. Hendricks — School of Architecture, Planning & Preservation, University of Maryland, College Park, Maryland 20742, United States; Email: mdh1@umd.edu

Maya E. Carrasquillo — Department of Civil & Environmental Engineering, University of California—Berkeley, Berkeley, California 94720, United States; Email: mcarrasquillo@berkeley.edu

Lauren E. McPhillips — Department of Civil and Environmental Engineering and Department of Agricultural and Biological Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, United States; orcid.org/0000-0002-4990-7979; Email: lxm500@psu.edu

Brandon K. Winfrey — Department of Civil Engineering, Monash University, Clayton, Victoria 3800, Australia; Email: brandon.winfrey@monash.edu

James R. Mihelcic — Department of Civil & Environmental Engineering, University of South Florida, Tampa, Florida 33620, United States; orcid.org/0000-0002-1736-9264; Email: jm41@usf.edu

Complete contact information is available at: <https://pubs.acs.org/10.1021/acs.est.3c07062>

Notes

The authors declare no competing financial interest.

Biographies



Gregory H. LeFevre is an associate professor in the Department of Civil and Environmental Engineering and IIHR—Hydroscience & Engineering at the University of Iowa. He is a member the inaugural *ES&T* Early Career Board.



Marccus D. Hendricks is an associate professor of Urban Studies & Planning and Director of Stormwater Infrastructure Resilience and Justice (SIRJ) Lab in the School of Architecture, Planning & Preservation at the University of Maryland.



Maya E. Carrasquillo is an assistant professor in the Department of Civil & Environmental Engineering and PI of the Liberatory Infrastructures Lab (LiL) at the University of California—Berkeley.



Lauren E. McPhillips is an assistant professor in the Department of Civil and Environmental Engineering and the Department of Agricultural and Biological Engineering at The Pennsylvania State University.



Brandon K. Winfrey is a lecturer in the Department of Civil Engineering at Monash University.



James R. Mihelcic is the Samuel L. and Julia M. Flom Professor in the Department of Civil & Environmental Engineering at the University of South Florida. He is an associate editor at *ES&T*.

ACKNOWLEDGMENTS

G.H.L. was supported by a National Science Foundation (NSF) CBET CAREER grant (1844720). Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

ADDITIONAL NOTE

^aThe recording of the ACS Global Webinar “Green Stormwater Infrastructure: Opportunities and Challenges in the Era of Climate and the Pursuit of Justice” is available on demand at <https://www.acs.org/events/all-events/green-stormwater-infrastructure-opportunities-and-challenges-in-the-era-of-climate-and-the-pursuit-of-justice.html>.

REFERENCES

- (1) U.S. Environmental Protection Agency. What is Green Infrastructure? <https://www.epa.gov/green-infrastructure/what-green-infrastructure> (accessed 2023-10-06).
- (2) Fletcher, T. D.; Shuster, W.; Hunt, W. F.; Ashley, R.; Butler, D.; Arthur, S.; Trowsdale, S.; Barraud, S.; Semadeni-Davies, A.; Bertrand-Krajewski, J.-L.; Mikkelsen, P. S.; Rivard, G.; Uhl, M.; Dagenais, D.; Viklander, M. SUDS, LID, BMPs, WSUD and More - The Evolution and Application of Terminology Surrounding Urban Drainage. *Urban Water J.* **2015**, *12* (7), 525.
- (3) Matsler, A. M.; Meerow, S.; Mell, I. C.; Pavao-Zuckerman, M. A. A ‘Green’ Chameleon: Exploring the Many Disciplinary Definitions, Goals, and Forms of “Green Infrastructure.”. *Landsc. Urban Plan.* **2021**, *214*, 104145.
- (4) McPhillips, L.; Wu, H.; Rojas Quezada, C.; Rosenzweig, B.; Sauer, J. R.; Winfrey, B. Nature-Based Solutions as Critical Urban Infrastructure for Water Resilience. In *Nature-Based Solutions for Cities*; Edward Elgar Publishing, 2023; pp 146–166.
- (5) Hoover, F.-A.; Hopton, M. E. Developing a Framework for Stormwater Management: Leveraging Ancillary Benefits from Urban Greenspace. *Urban Ecosyst.* **2019**, *22* (6), 1139–1148.
- (6) Muerdter, C. P.; Wong, C. K.; LeFevre, G. H. Emerging Investigator Series: The Role of Vegetation in Bioretention for Stormwater Treatment in the Built Environment: Pollutant Removal, Hydrologic Function, and Ancillary Benefits. *Environ. Sci. Water Res. Technol.* **2018**, *4* (5), 592–612.
- (7) McPhillips, L. E.; Matsler, M.; Rosenzweig, B. R.; Kim, Y. What Is the Role of Green Stormwater Infrastructure in Managing Extreme Precipitation Events? *Sustain. Resilient Infrastruct.* **2021**, *6* (3–4), 133–142.
- (8) Hendricks, M. D.; Dowtin, A. L. Come Hybrid or High Water: Making the Case for a Green-Gray Approach toward Resilient Urban Stormwater Management. *J. Am. Water Resour. Assoc.* **2023**, *59*, 885.
- (9) Hoover, F.-A.; Meerow, S.; Grabowski, Z. J.; McPhearson, T. Environmental Justice Implications of Siting Criteria in Urban Green Infrastructure Planning. *J. Environ. Policy Plan.* **2021**, *23* (5), 665–682.
- (10) Carrasquillo, M. E. Black Lives Matter in Engineering, Too! An Environmental Justice Approach towards Equitable Decision-Making for Stormwater Management in African American Communities. University of South Florida, 2020.
- (11) Walker, R. H. Engineering Gentrification: Urban Redevelopment, Sustainability Policy, and Green Stormwater Infrastructure in Minneapolis. *J. Environ. Policy Plan.* **2021**, *23* (5), 646–664.
- (12) Rodgers, T. F. M.; Wang, Y.; Humes, C.; Jeronimo, M.; Johannessen, C.; Spraakman, S.; Giang, A.; Scholes, R. C. Bioretention Cells Provide a 10-Fold Reduction in 6PPD-Quinone Mass Loadings to Receiving Waters: Evidence from a Field Experiment and Modeling. *Environ. Sci. Technol. Lett.* **2023**, *10* (7), 582–588.
- (13) Wiener, E. A.; LeFevre, G. H. White Rot Fungi Produce Novel Tire Wear Compound Metabolites and Reveal Underappreciated Amino Acid Conjugation Pathways. *Environ. Sci. Technol. Lett.* **2022**, *9* (5), 391–399.
- (14) Luthy, R. G.; Sharvelle, S.; Dillon, P. Urban Stormwater to Enhance Water Supply. *Environ. Sci. Technol.* **2019**, *53* (10), 5534–5542.
- (15) Kerkez, B.; Gruden, C.; Lewis, M.; Montestruque, L.; Quigley, M.; Wong, B.; Bedig, A.; Kertesz, R.; Braun, T.; Cadwalader, O.; Poresky, A.; Pak, C. Smarter Stormwater Systems. *Environ. Sci. Technol.* **2016**, *50* (14), 7267–7273.
- (16) Hendricks, M. D.; Van Zandt, S. Unequal Protection Revisited: Planning for Environmental Justice, Hazard Vulnerability, and Critical Infrastructure in Communities of Color. *Environ. Justice* **2021**, *14* (2), 87–97.
- (17) Wendel, H. E. W.; Downs, J. A.; Mihelcic, J. R. Assessing Equitable Access to Urban Green Space: The Role of Engineered Water Infrastructure. *Environ. Sci. Technol.* **2011**, *45* (16), 6728–6734.
- (18) Rippey, M. A.; Krauss, L.; Pierce, G.; Winfrey, B. Plant Functional Traits and Viewer Characteristics Co-Regulate Cultural Services Provisioning by Stormwater Bioretention. *Ecol. Eng.* **2021**, *168*, 106284.
- (19) White, M. P.; Elliott, L. R.; Grellier, J.; Economou, T.; Bell, S.; Bratman, G. N.; Cirach, M.; Gascon, M.; Lima, M. L.; Löhmus, M.; Nieuwenhuijsen, M.; Ojala, A.; Roiko, A.; Schultz, P. W.; van den Bosch, M.; Fleming, L. E. Associations between Green/Blue Spaces and Mental Health across 18 Countries. *Sci. Rep.* **2021**, *11* (1), 8903.
- (20) Grabowski, Z. J.; McPhearson, T.; Pickett, S. T. A. Transforming US Urban Green Infrastructure Planning to Address Equity. *Landsc. Urban Plan.* **2023**, *229*, 104591.
- (21) Bozeman, J. F.; Chopra, S. S.; James, P.; Muhammad, S.; Cai, H.; Tong, K.; Carrasquillo, M.; Rickenbacker, H.; Nock, D.; Ashton, W.; Heidrich, O.; Derrible, S.; Bilec, M. Three Research Priorities for Just

and Sustainable Urban Systems: Now Is the Time to Refocus. *J. Ind. Ecol.* **2023**, *27* (2), 382–394.

(22) Valente de Macedo, L. S.; Barda Picavet, M. E.; Puppim de Oliveira, J. A.; Shih, W.-Y. Urban Green and Blue Infrastructure: A Critical Analysis of Research on Developing Countries. *J. Clean. Prod.* **2021**, *313*, 127898.

(23) Envisaging the Future of Cities. United Nations Human Settlements Programme (UN-Habitat). https://unhabitat.org/sites/default/files/2022/06/wcr_2022.pdf (accessed 2023-10-18).

(24) United Nations Environmental Programme. *Green Infrastructure Guide for Water Management: Ecosystem-Based Management Approaches for Water-Related Infrastructure Projects*; 2014.

(25) Fry, L. M.; Cowden, J. R.; Watkins, D. W. J.; Clasen, T.; Mihelcic, J. R. Quantifying Health Improvements from Water Quantity Enhancement: An Engineering Perspective Applied to Rainwater Harvesting in West Africa. *Environ. Sci. Technol.* **2010**, *44* (24), 9535–9541.

(26) Yessoufou, K.; Sithole, M.; Elansary, H. O. Effects of Urban Green Spaces on Human Perceived Health Improvements: Provision of Green Spaces Is Not Enough but How People Use Them Matters. *PLoS One* **2020**, *15* (9), e0239314.

(27) Wu, L.; Qiu, X.-W.; Wang, T.; Tao, K.; Bao, L.-J.; Zeng, E. Y. Water Quality and Organic Pollution with Health Risk Assessment in China: A Short Review. *ACS ES&T Water* **2022**, *2* (8), 1279–1288.

(28) Leder, K.; Openshaw, J. J.; Allotey, P.; Ansariadi, A.; Barker, S. F.; Burge, K.; Clasen, T. F.; Chown, S. L.; Duffy, G. A.; Faber, P. A.; Fleming, G.; Forbes, A. B.; French, M.; Greening, C.; Henry, R.; Higginson, E.; Johnston, D. W.; Lappan, R.; Lin, A.; Luby, S. P.; McCarthy, D.; O'Toole, J. E.; Ramirez-Lovering, D.; Reidpath, D. D.; Simpson, J. A.; Sinharoy, S. S.; Sweeney, R.; Taruc, R. R.; Tela, A.; Turagabeci, A. R.; Wardani, J.; Wong, T.; Brown, R. Study Design, Rationale and Methods of the Revitalising Informal Settlements and Their Environments (RISE) Study: A Cluster Randomised Controlled Trial to Evaluate Environmental and Human Health Impacts of a Water-Sensitive Intervention in Informal Settlements in Indonesia and Fiji. *BMJ Open* **2021**, *11* (1), e042850.

(29) White House Council on Environmental Quality, White House Office of Science and Technology Policy, White House Domestic Climate Policy Office. Opportunities to Accelerate Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, & Prosperity. 2022. <https://www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf> (accessed 2023-08-07).