

## COMMENTARY

# Come hybrid or high water: Making the case for a Green–Gray approach toward resilient urban stormwater management

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## Abstract

120 years or more of unsustainable urban development has damaged the natural environment and disrupted essential ways to stabilize water body overflow and even mitigate pluvial flooding. In light of catastrophic flooding that has occurred globally, a renewed commitment to transforming built surfaces and incorporating more green infrastructures (GIs) has emerged. In fact, one could argue that an overcommitment to GI is being touted in the literature, but largely disconnected from more real-world possibilities, considering all things. In this commentary, we make the case that as cities transition from development patterns of the past and even considering climate-induced storm characteristics of the future, a hybridized solution (e.g., Green–Gray) should be considered. Smaller approaches to urban greening have been implemented in areas that need larger-scale restorations, thus proving to be insufficient. Likewise, the uncertainty surrounding rainfall and storm events has forced us to be more strategically balanced in our efforts to achieve resilience in our stormwater infrastructure. Hybridized solutions that include a diverse set of systems, anchored in local conditions, position us best for effective urban stormwater management. In the absence of such solutions, runoff volumes will continue to rise, flooding will prevail, and disenfranchised communities will remain disproportionately impacted by these impacts of urbanization.

## KEYWORDS

green infrastructure, flooding, resilience, sustainable development, urban drainage, land change, climate

## 1 | INTRODUCTION

As the global population shifts toward predominant settlement in urban areas (United Nations Department of Economic and Social Affairs, 2012), the deleterious impacts of extensive development remain evident in population centers around the world. Cities are often characterized by heat islands, degraded air quality, fragmented natural landscapes, and reduced habitat for varied floral and faunal communities

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### Research impact statement

This research argues that considering development patterns of the past and climate-induced storms of the future, a hybridized solution (e.g., Green–Gray) is needed for urban stormwater management.

(Carlyle-Moses et al., 2020; Han et al., 2014; Heisler & Brazel, 2010; Nowak & Greenfield, 2012; Oke, 1982; Smith et al., 2005; Stagoll et al., 2010; Van Metre et al., 2019). Urbanization also has notable impacts on municipal and regional water resources, as extensive impervious cover in cities often results in decreased infiltration, elevated runoff volumes, and compromised water quality in local and downstream surface water bodies (Leopold, 1968). These impacts of urbanization on water quality and quantity in cities are likely to be amplified under predicted amplifications of regional hydroclimate, such as modified frequency and intensity of storm events (Miller & Hutchins, 2017), especially in the presence of climate change and the absence of strategic intervention.

To efficiently manage the stormwater running off of impervious materials used for above ground urban development, cities have traditionally engineered structural systems for surface and subsurface stormwater control using many of the same industrial materials. Cement, concrete (e.g., prestressed and reinforced), cast iron, polyvinyl chloride, and steel, among others, have been the preferred materials; hence, the emergence of “gray” infrastructure. Gray infrastructure by definition are human-engineered structural systems such as curb and gutter, pipelines, levees, dams, culverts and cross-drain pipes, and ditches, among others that are installed with the purpose to collect and convey stormwater runoff from impervious surfaces. Over the years, especially more recently, this engineered gray infrastructure has proven to be insufficient for a number of reasons, including stationarity and retrofit costs. In addition, in many older cities, the existing gray stormwater infrastructure was built during times in which impervious cover and stormwater volumes were lower than current levels, and urban populations were not as high. At present, increased development activity and modified climate patterns have resulted in these systems having to manage higher runoff volumes than they were initially designed for (Kessler, 2011). Given the pressure these gray infrastructure systems are under, cities have begun to review and include alternatives to urban stormwater management.

Local, national, and inter-governmental land managers, planners, and policymakers are now exploring the development, promotion, and implementation of nature-based solutions to correct or reverse traditional urban stormwater challenges as well as address emerging environmental issues that have been introduced under climate change (Escobedo et al., 2019). These solutions include the design and continuous use of living, natural materials and features to address societal challenges in a manner that is environmentally, economically, and socially beneficial (European Commission, 2015). Under the umbrella of nature-based solutions, green infrastructure (GI), defined as “strategically planned networks of high quality natural, semi-natural, and cultivated areas designed and managed to deliver a wide range of ecosystem services ... in urban and peri-urban settings,” is often regarded as an effective tool with which to achieve these goals (FAO, 2016). Indeed, the use of GI has been linked to environmental benefits such as local air quality improvement (Jayasooriyah et al., 2017), urban heat island mitigation (Sanchez & Reames, 2019), and strategic expansion of vegetation in densely developed areas (Huang et al., 2017); and to improving physical (Dalton & Jones, 2020), social (Jennings & Bamkole, 2019), and psychological (Berman et al., 2008) health outcomes for urban residents. It has also been linked to stormwater mitigation. While these benefits of GI are important, these nature-based-solutions also have their fair share of limitations, and this is especially true of their ability to facilitate stormwater management in urban environments.

In this commentary, we utilize knowledge of the strengths and limitations of gray and green stormwater infrastructure to present an argument that favors a very intentional Green–Gray hybrid approach, rather than the more ad hoc Green–Gray management that is currently underway. We define hybrid as a system that consists of the purposive joining of Green and Gray assets for the capture and dispersal of stormwater runoff. Considering the limitations of both systems individually, coupled with the looming uncertainty of climate change, cities should make a deliberate effort to implement a hybrid Green–Gray approach to urban stormwater management. We believe that a conscious hybrid Green–Gray approach is more efficient, effective, and resilient across a wider range of stormwater scenarios than leaving such design to chance as a result of an ever-dynamic urban setting. To make this case, we begin with more context on the history of urban development with a specific focus on stormwater infrastructure. We then introduce a more detailed discussion of GI and link it to stormwater mitigation. Ultimately, we make the case for hybrid in the core of this commentary. We ground all of the above in equity and restorative justice in the advancement of hybrid approaches prior to concluding with some final thoughts in favor of a purposeful hybridized effort for urban stormwater management.

## 2 | THE HISTORY OF URBAN DEVELOPMENT AND STORMWATER INFRASTRUCTURE

Cities have grown indefinitely in land area, population size, and development, particularly in terms of paving over what was once natural land cover with impervious surfaces (Vogler & Vukomanovic, 2021). Thus, stormwater systems in urbanized areas are currently designed and

installed purely for the purpose of managing stormwater runoff as a result of losses in natural ways of treating and draining water (Grigg, 2012; van Vliet, 2019). Stormwater runoff is rainfall, snowmelt, or overflow that moves across built surfaces or oversaturated soils and does not permeate into the ground (Elmer & Leigland, 2013). Rapid urbanization during the industrial era and over subsequent years has further contributed to more intense and faster runoff from paved surfaces such as roof tops, parking structures, and streets (Smith et al., 2005). In many urban areas, large percentages of natural land cover are nonexistent. Wetlands and riparian zones have been filled in with concrete and asphalt, underground aquifers have been pumped out and replaced with basements and foundations, and streams and tributaries have also been lined and covered with flood control intentions, but this process too has ultimately disrupted natural systems and processes for managing stormwater (Gori et al., 2019; Peng et al., 2015).

Conventional stormwater systems transitioned from naturally lined ditches and channels to paved gutters and channels, to eventually include underground pipes. However, this conventional system coupled with other forms of impervious urban development is unsustainable and has largely contributed to the elevated amount of greenhouse gas emissions resulting in global climatic change. Given the non-stationarities resulting from climate change, existing gray infrastructure may be under-designed for future climate. In addition to the impending threat of larger storms due to climate change, current gray stormwater infrastructure is also susceptible to failing when inundated, causing flooding that can be life threatening and economically challenging to residential stakeholders and municipalities that are impacted by system failure (Obropta, 2017). Repairs to these systems are often costly, and can take years to complete (Kessler, 2011), delaying the time within which they are addressed, and often leaving community members vulnerable to high stormwater volumes. While extensive in their coverage, these gray solutions to stormwater management can be limited in their prolonged capacity to effectively manage stormwater. However, including diverse sets of GI (e.g., size and type) to complement existing gray infrastructure can provide a way of increasing stormwater management across a watershed without having to entirely retrofit the original gray infrastructure.

### 3 | LINKING GI AND STORMWATER MITIGATION

Green infrastructure notably aids in the enhancement of urban stormwater mitigation efforts. Frequently used green stormwater infrastructure includes bioswales, rain gardens, downspout disconnections, permeable pavements, planter boxes, rainwater harvesting practices, stormwater detention basins and urban forests (USEPA, 2022). Both independently and collectively, these green stormwater infrastructure techniques have been found to have measurable impacts on runoff reduction (Armson et al., 2013; Li et al., 2020).

Traditionally, stormwater detention basins have been a widely used best management practice for green stormwater infrastructure. Often comprised of a mix of flood tolerant vegetative species planted within an engineered drainage basin, these structural solutions aid in reducing runoff volumes and stormwater pollutant loads (Fletcher et al., 2015). In recent years, there has been growing emphasis on the use of entirely natural and non-structural best management practices for urban stormwater management. For example, urban forests (e.g., trees and shrubs in developed areas) represent some of the most highly studied (Badiu et al., 2019) and widely utilized (Gavrilidis et al., 2019; O'Brien et al., 2017) forms of GI, as they provide nature-based solutions to larger-scale climate issues such as urban heat islands while aiding in reducing runoff volumes. It is thus important to understand their relative contributions to urban stormwater management.

Urban trees contribute to stormwater mitigation through three key processes: interception of precipitation on foliar and woody surfaces, promotion of infiltration via drainage through soil macropores, and uptake of soil water via transpiration (Carlyle-Moses et al., 2020; Guo et al., 2017; Johnson & Lehmann, 2006; Livesely et al., 2016; Phillips et al., 2019). The impacts of these processes are both quantifiable and scalable. For isolated urban trees, interception has been found to be notable. Canopy interception can significantly contribute to runoff reduction by urban trees, as isolated trees have been found to intercept from 20% to 80% of incident precipitation on average (Asadian & Weiler, 2009; Nytych et al., 2019; Xiao & McPherson, 2011). Armson et al. (2013) found that for isolated street trees in Manchester, United Kingdom, related interception and infiltration processes yielded runoff reductions of approximately 62%, relative to sites on which no trees were present.

For closed-canopy components of urban forests (e.g., woodlots, forest fragments), approximately 25% of precipitation may be intercepted (Dowtin et al., 2021), preventing a sizable proportion of incident precipitation from reaching urban surfaces and becoming runoff. Water uptake by urban trees can also be substantial, with variation common among trees of differing size and species (Gotsch et al., 2018). Modeled municipal-scale estimates of runoff reduction by urban tree cover have been sizeable, with an estimated 187,000 m<sup>3</sup>/year and 3.37 million m<sup>3</sup>/year of annual avoided runoff due to tree cover in Lisbon, Portugal and New York City, New York, respectively (Peper et al., 2007; Soares et al., 2011). These estimates of runoff reduction by urban trees have been valued at \$1.97–\$33.6 million USD in savings of municipal water treatment costs in these cities (Peper et al., 2007; Soares et al., 2011).

While it is evident that urban trees play an integral and economically important role in local stormwater mitigation efforts, there are limitations to their efficacy in providing this ecosystem service; this is also true for other forms of GI. For structural stormwater BMPs such as detention basins, poor management can result in system failure, whereby proper drainage of water from these systems is hindered and excessive nutrients are not adequately removed from runoff diverted to the systems, leading to localized water quality issues such as algal

blooms (Shammaa & Zhu, 2001). For urban forests, the foliar and woody surfaces upon which precipitation is intercepted have limited storage capacity (Xiao & McPherson, 2016). Once this capacity is reached, precipitation is more effectively drained, rather than retained by the canopy, allowing a greater proportion of precipitation to be funneled to urban ground surfaces where it can become stormwater runoff (Berland et al., 2017; Xiao et al., 1998). This can happen during high-intensity or high-magnitude storm events during which the canopy may become saturated and storage capacity met. Furthermore, the capacity of urban trees to facilitate infiltration is limited by the hydraulic conductivity of the soils in which they have been planted and established (Weiliang et al., 2021; Yang & Zhang, 2011). In areas in which trees are planted in compacted soils, drainage efficiency is low, and ponding, rather than infiltration of precipitation is more likely to occur. It is thus beneficial to provide simultaneous acknowledgment of the contributions and limitations of trees and other green stormwater infrastructure, while strategically planning for their optimal use in conjunction with gray systems.

While urban forests and other vegetation display these limitations to reducing stormwater, these restraints can be overcome, in part, by inclusion of engineered solutions. The use of engineered soils can aid in increasing the stormwater mitigation capacity of urban forests and other forms of green stormwater infrastructure. For some engineered soils, bulk density is often lower than that of the highly compacted soils characteristic of urban areas, and available water-holding capacity (i.e., the amount of water soil can store for plant use) tends to be higher (Sax et al., 2017). These modified soil conditions help to infiltrate stormwater and decrease runoff volumes beyond what would be reduced through interception by the urban tree canopy alone. Woody vegetation planted in engineered soils can also achieve deep rooting depths, which allows roots to remove water from deep soil reservoirs via transpiration (Bartens et al., 2009). This uptake of deep soil water by tree roots increases soil water storage capacity, thereby facilitating both subsequent runoff drainage and reduced stormwater volumes in areas where these soils are used to support vegetation cover. The combined use of engineered soils and vegetation guides the application of bioretention technologies and other forms of green stormwater infrastructure (Thompson et al., 2008; Tirpak et al., 2018). It also provides a blueprint for how best to shape and prioritize hybrid approaches to urban stormwater management.

## 4 | MAKING THE CASE FOR HYBRID

Development patterns of the past and potential climate-induced storm characteristics of the future suggest that thoughtful considerations should be given to how we adapt stormwater management practices moving forward. As detailed above, green and gray stormwater infrastructure have an array of both strengths and limitations of their capacity to reduce runoff. Forthcoming initiatives to effectively manage urban stormwater should thus prioritize a combined use of both approaches to stormwater mitigation, so as to ensure maximal runoff reduction across urban areas. To optimize the impacts of this hybrid approach, weather, development, and social patterns in the areas in which they will be established must be accounted for in their design and installation.

### 4.1 | Storm event types, Stormwater runoff characteristics, and GI performance

Rainfall and storm events vary depending on their origin/causes (e.g., ocean or continent), temperature, duration, intensity, season (e.g., summer or winter), propagation speed, cyclogenesis (development patterns), spontaneity, coverage area, and wind involvement at the surface and aloft, among many other factors (Emmanuel et al., 2012; Prein et al., 2017). Climate change impacts and atmospheric transitions will only increase the uncertainty of storm characteristic types and parameters (Wang et al., 2013). Likewise built environments and urban landscapes are ever-changing as well. Thus, the characteristics of stormwater runoff and surface-level interactions also vary tremendously and will continue to do so under different storm events, over time, and across different built environments (Arnbjerg-Nielsen et al., 2013; Liu et al., 2013; Qin et al., 2013). Shorter, slower, smaller, and less intense (e.g., small peak flows and less volume) stormwater runoff may be well managed by GIs (Damodaram et al., 2010). Performance, however, can still vary significantly (Hendricks et al., 2018). On the contrary, storms that produce longer, faster, larger, or more intense stormwater runoff might interact differently with GI systems, rendering them less effective in performance and management of that runoff (Ashley et al., 2018; McPhillips & Matsler, 2018; Taguchi et al., 2020). Therefore, future stormwater systems or a combination of them must take changing weather patterns into account to be effective across various scenarios.

### 4.2 | Viability of GI in urban environments

Further considering the promise of GI as discussed above, implementing these systems as retrofits can assist in supporting stormwater management and other hydrological targets at various scales. These systems and development forms can help to reduce peak flow volumes and return baseflow to predevelopment conditions (Golden & Hoghooghi, 2018). They also significantly aid in improving water quality by reducing the concentration of pollutants such as nutrients, metals, and total suspended solids from runoff (Liu et al., 2014). However, the literature on

GI performance is mixed across several studies in terms of how effective specific assets are in positively impacting water quantity and quality. Wadzuk et al. (2017) suggest that back-to-back rainfall events should not be a primary concern in the Mid-Atlantic region specifically and thus GI might be effective in meeting volume control goals. However, the authors mention that it ultimately depends on local dynamics and patterns, which in light of climate change and evolving built environments are quite uncertain. Webber et al. (2020) indicate that a significant and large-scale application of GI could substantially reduce flood depth and velocity in the catchment, but that residual risk remains, particularly during extreme events. It is likely that most current GI installations have been designed and installed for smaller, more common rainfall events (e.g. 1- to 10-year events) (McPhillips et al., 2020), however in order for GI and Low Impact Design to meaningfully contribute to resilience and urban stormwater management, designs have to be scaled appropriately and likely in conjunction with gray assets. A hybridized, Green-Gray approach would provide the latitude to mitigate flooding. Gray assets are able to increase stormwater management capability when GI is limited by issues of volume capacities, saturation points, maintenance and damage issues, as well as stormwater runoff that is more intense, faster, and lasting for longer periods; while inclusion of GI increases stormwater management capacity for those urban areas in which runoff volumes can exceed those for which existing infrastructure was designed to convey.

For the modern city, it seems that an isolated approach that is purely green or gray is either unsustainable, infeasible, or insufficient. Considering water issues are increasingly pervasive, both in terms of quantity and quality, as well as climate change introducing storm events with characteristics that are unprecedented, a hybrid approach seems to be the most resilient way forward. A hybrid approach may offer increased or optimal resilience by comprehensively addressing issues of water quality and flood control, the reduction of greenhouse gas emissions and natural land cover losses, and ability to efficiently (e.g. maximizing production while minimizing wasted effort) and effectively (e.g. in a manner to achieve the desired result) manage stormwater across a wider range of characteristics of storm and rainfall events. There are also other ancillary benefits and tradeoffs of each individual approach; and thus tradeoffs for the hybrid approach. Nevertheless, with resilient systems in mind (e.g., those that are able to adapt across emergent scenarios) the tradeoffs do not trump the larger benefit. A diverse set of individual assets that make up a larger system is much like diversity in general, usually a positive thing. The same can be true for stormwater infrastructure. Gray and green systems can work together in complimentary fashion for more effective and efficient stormwater management. Gray assets are the systems that currently exists and may have been sufficient at the time of development in simply supporting rapid conveyance for more and faster runoff. However, future systems could benefit from a layer of green assets on top of gray systems as a retrofit to account for added imperviousness, address pollutant loading, slow runoff, and support climate change goals.

## 5 | CENTERING EQUITY AND RESTORATIVE JUSTICE TO ADVANCE HYBRIDIZED URBAN STORMWATER MANAGEMENT

While it is nearly universally accepted that GI can significantly contribute to local stormwater mitigation efforts, this ecosystem service is not always universally accessible to all residential stakeholders within municipalities. This is due in larger part to the fact that in many communities, GI has been historically distributed in an inequitable manner. For example, at the national scale, spatial differences in urban tree canopy have been attributed, in part, to variability in development history and the impact this has had on tree selection and distribution (Volin et al., 2020). Within municipalities, distribution of urban tree cover has been linked to spatial variability in various socioeconomic and demographic factors, including, but not limited to per capita income, median household income, and housing tenure. Canopy cover has often been found to be higher in neighborhoods in which home ownership, per capita income, and median household income are relatively high. However, in communities in which the converse is true, tree cover and the accessibility of its related ecosystem services are much more sparse (Landry & Chakraborty, 2009; Nyelele & Kroll, 2020). This inequitable distribution of canopy cover can create and exacerbate disparities in residential accessibility to the ecosystem services provided by urban trees, including stormwater mitigation (Nyelele & Kroll, 2020).

In addition to inequities in urban tree cover, other forms of green stormwater infrastructure have historically been dispersed disparately across cities, with patterns of lower investment and placement in communities characterized by lower household income and higher populations of people of color (Mandarano & Meenar, 2017). This therefore increases the likelihood that some marginalized populations may be more susceptible to the threats of localized flooding that adequate canopy cover and other green stormwater infrastructure help to mitigate. Likewise, decades of corroborated evidence within the environmental justice (Bullard & Johnson, 2000; Dunn & Derrington, 2009; Jennings et al., 2012; Sister et al., 2010) and social vulnerability (Adger & Kelly, 1999; Bergstrand et al., 2015; Highfield et al., 2014) literature suggests that lower income, particularly communities of color, are overburdened by locally unwanted land uses, sited with industry and consists of built infrastructures that are in disrepair. Recent scholarship provides additional context on these broader risks and built inequalities and conceptualizes gray and green stormwater system disparities, specifically arguing that these assets should be included in just flood risk assessments, plans for stormwater rehabilitation, and climate resilience (Hendricks & Van Zandt, 2021).

Despite these trends, there is hope in considering how the benefits of a hybrid approach to stormwater management may be more equitably available to all communities, and especially those that have remained vulnerable throughout the varying phases of urban development. In the United States, there is now an unprecedented level of investment in the planning, installation, and management of sustainable stormwater

infrastructure in communities across the country. The Inflation Reduction Act, Bipartisan Infrastructure Law, and American Rescue plan are poised to provide substantial funding for the inclusion of hybridized approaches to stormwater management (in addition to other GI goals), with an emphasis on ensuring that environmental justice communities (e.g., communities that disproportionately face the burden of environmental hazards and other environmental injustices) are prioritized in these initiatives. The introduction of this legislation provides an important opportunity to promote the Green–Gray approach as a means by which all communities can benefit from the combined, scalable impacts of engineered and natural solutions for reducing runoff while also gaining additional environmental, economic, and social goods affiliated with GI. It also provides the opportunity for innovative approaches to achieve this goal, such as use of block grants that may incentivize local-level action in the form of community development through urban greening.

## 6 | CONCLUSION

Future policies for water resource management and flood control should embrace and intentionally implement a hybrid approach for resilient stormwater management. As both gray and green infrastructure have respective unique capacities in mitigating urban stormwater; utilization of both in a hybrid manner is required for equitable and comprehensive runoff reduction across cities. The use of GI should be prioritized in those neighborhoods in which runoff volumes and flood frequencies are relatively high, and opportunity to modify gray stormwater infrastructure is relatively low. By incorporating GI such as increased urban tree cover into these neighborhoods, community resilience to issues stemming from stormwater excess will be mitigated (relative to scenarios in which no intervention is introduced), while members of these communities will be able to benefit from those ecosystem services provided by GI that improve quality of life for residential stakeholders (e.g., localized cooling and air quality improvement). It is of equal importance to maintain, retrofit, and in some instances enhance gray stormwater infrastructure, as these systems are vital for the management of runoff produced by storms of relatively high intensity and magnitude.

Cities are the epicenter of both the problem and solution for resilient stormwater management and can significantly impact our stormwater trajectory. Policies that streamline land use, hazard mitigation, growth management, and capital improvement planning should be the framework that cities operate within. At the state and federal levels, community development block grants (traditional and disaster recovery) should incentivize and promote hybridized approaches through comprehensive planning to redevelop or rehabilitate damaged or destroyed systems. Last, but certainly not least, policies that create opportunities for equity and civic participation, along a workforce development trajectory, doing condition inspection, planning and provision, maintenance, and beyond will provide the necessary reinforcement for the success of this hybrid approach for stormwater infrastructure resilience.

## AUTHOR CONTRIBUTIONS

**Marccus D. Hendricks:** Conceptualization; writing – original draft; writing – review and editing. **Asia L. Downtin:** Conceptualization; writing – original draft; writing – review and editing.

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## CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

## DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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