# Green Infrastructure on Vacant Land: Mitigating Aquatic Stressors of Urban Ecosystems through Green Stormwater Infrastructure

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NEIGHBORHOOD, ENVIRONMENT, AND WATER RESEARCH
COLLABORATIONS FOR GREEN INFRASTRUCTURE
NEW-GI WHITE PAPER NO. 2, AUGUST, 2018

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## ABOUT NEW-GI

NEW-GI *(Neighborhood, Environment, and Water research collaborations for Green Infrastructure)* contributes to knowledge about green infrastructure in legacy cities by integrating research about water quality, community well-being, governance and ecological design. Involving community, government and academic collaborators, it produces evidence-based guidance for sustainably managing stormwater in ways that enhance landscapes and the lives of residents in Detroit and other legacy cities.

NEW-GI ecological designs link Detroit's vacant property demolition process with new forms of green stormwater infrastructure (GSI) that aim to manage stormwater as well as increase nearby residents' well-being. This research uses a transdisciplinary design-in-science approach, in which researchers, practitioners and community members work together to contribute knowledge addressing social and ecological objectives. NEW-GI researchers assess the performance of different GSI designs and governance approaches. This assessment provides evidence for making decisions about how GSI can better achieve objectives.

## ACKNOWLEDGEMENTS:

Our work was funded with a grant to the University of Michigan Water Center from the Erb Family Foundation.

With research assistance from Michelle Hudson.

Graphic design by Marty Somberg / Somberg Design

Cite as:
Burton, G. A., Jr., McElmurry, S. P., & Riseng, C. (2018). *Mitigating Aquatic Stressors of Urban Ecosystems through Green Stormwater Infrastructure* (NEW-GI White Paper No. 2). Ann Arbor, MI: University of Michigan Water Center.

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# Executive Summary

Executive Summary

**GREEN STORMWATER INFRASTRUCTURE (GSI)** is becoming a widespread stormwater management practice. By managing stormwater where it falls, GSI aims to reduce flooding and combined sewer overflows (CSOs) and improve water quality. A growing body of research also indicates that GSI has the potential to enhance neighborhood attractiveness, increase property values, and improve the health and well-being of area residents; this research was synthesized in NEW-GI White Paper No.1 (Lichten et al., 2017).

GSI is a particularly promising strategy for addressing some of the social and environmental effects of population loss and infrastructure decay in legacy cities such as Detroit, where vacant land may present an opportunity for GSI to be designed to manage stormwater and serve as attractive green spaces for neighborhoods. Research about the potential management and governance strategies for GSI in legacy cities was also synthesized in NEW-GI White Paper No.1 (Lichten et al., 2017).

Functionally, GSI is implemented to improve water quality and mitigate deleterious effects of enhanced urban flows (i.e., water quantity). As GSI evolves, its purpose is increasingly recognized to be broader than simply altering the quality and quantity of stormwater flows; rather it is viewed as a cost-effective means of enhancing the resiliency of rigid urban systems and maximizing ecosystem services (Vogel et al., 2015. As a basis for understanding GSI and to support decision-making, this white paper synthesizes relevant peer-reviewed scholarly literature. In summary, this synthesis concludes that:

• While existing knowledge does not allow for the reliable prediction of water quality or the impact to aquatic ecosystems downstream from a given GSI practice, design and maintenance choices do suggest how and why certain approaches may be effective;

• Varied site and regional characteristics as well as varied design and construction choices influence GSI effectiveness in reducing stormwater quantities in downstream rivers or lakes;

• Performance of GSI changes over time with maintenance being a dominant factor;

• Focusing solely on the retention of the 'first flush' to treat urban stormwater often is not sufficient for achieving water quality or ecological objectives;

• Using suspended solids as an indicator of GSI performance has limitations that can lead to erroneous conclusions about downstream impact; and

• Overall performance of GSI is ideally assessed by monitoring the health of the receiving waters where GSI has been comprehensively employed upstream.

# Introduction: Urban runoff and GSI

**URBANIZATION ALTERS LANDSCAPES** so that rainfall runs rapidly across surfaces and through pipes rather than soaking slowly through the soil, arriving in waterways in bursts rather than the more gradual flows typical of non-developed watersheds. As stormwater flows across urban landscapes, interactions with the watershed surface entrain pollutants. As a result, stormwater often contains a complex mixture of chemical and microbial pollutants. These changes in the volume and quality of stormwater flows can contribute to flooding and degradation of the water and habitat quality of receiving waterways (National Academy of Sciences, 2008). Urban stormwater is the primary source of water quality impairments for at least 13% of all rivers, 18% of all lakes, and 32% of all estuaries in the United States, despite urban land use constituting only 3% of the nation's land cover (National Research Council, 2009). As urban centers continue to grow, this issue will also grow in importance for planners and managers. Traditional wastewater treatment approaches to mitigate these impacts are expensive and inflexible. The desire to reduce operation and maintenance costs has prompted new practices to be deployed, such as constructed wetlands and other types of GSI. For example, constructed wetlands require approximately 1/10th the energy of typical wastewater treatment and are orders of magnitude less expensive to construct and maintain (Brix, 1999). When GSI is compared against traditional end-of-pipe treatment approaches over the long-term, municipalities report a shift in cost from physical infrastructure expenses to maintenance-associated expenses (Houle et al., 2013), with an overall reduction in cost (Roseen et al., 2015).

GSI reduces the stormwater runoff impacts of urbanization by retaining and adsorbing rainwater where it falls. The National Academy of Sciences (2008) identified GSI as a critical strategy for managing both stormwater volume and pollutant loading, but argued more research is needed to understand how it can work across climates and soil conditions. GSI designs have historically focused on managing stormwater volumes, and there are many studies examining the hydraulics and hydrology of GSI (e.g., He and Davis, 2011; James and Dymond, 2011; Paus et al., 2014). In one example, Avellaneda et al. (2017) found decentralized GSI that occupied less than 1% of the catchment area achieved a 9% volume reduction by increasing evaporation and infiltration and decreasing surface runoff. These results, as well as others, suggest GSI may be particularly effective at reducing runoff for more frequent events, such as those that tend to occur, on average, about once every two years (i.e., 2-year storms) Generally, it is considered optimal to place GSI where high amounts of stormwater flow are generated (e.g., next to parking lots), although the spatial configuration of treatment properties within residential sewersheds "will not make a difference in overland flow mitigation" (Lim and Welty, 2017).

**Relatively little is known about how context and design may shape GSI's ability to manage chemicals and microbes in stormwater.**

Although GSI practices are increasingly being designed to manage chemicals and microbes in stormwater, relatively little is known about how context and design may shape GSI's ability to manage these pollutants. Furthermore, few studies attempt to assess how GSI's impacts on stormwater flows and pollutant loads across a watershed may affect the physical and biological quality of downstream ecosystems (Fletcher et al., 2014; Dovel et al., 2015).

GSI is a fundamental component of Detroit's stormwater management plan. As Detroit and other communities move forward in applying GSI, decision makers and stakeholders widely acknowledge the need for greater knowledge about how GSI will perform as part of an integrated socio-ecological system. Existing GSI knowledge in landscape design and planning and environmental engineering needs to be employed in decisions in Detroit. There also is a need for new GSI knowledge that is tuned to the opportunities and challenges that characterize Detroit's environmental, governance, and social characteristics. The NEW-GI project was developed to address these needs. Part of the project's effort is to synthesize relevant design and engineering, governance, social science, and water quality knowledge so that decision makers can consider its implications for Detroit. In this white paper we summarize and examine existing studies of GSI for stormwater management, including landscape conditions that contribute to water quality issues, and specificwater quality and quantity stressors that harm aquatic ecosystems. We further provide an overview of GSI techniques and identify challenges faced in evaluating their performance. We conclude with an evaluation of the strengths and weaknesses of the current state-of-the-art in GSI applications.

# Stormwater quality



**A MULTITUDE OF PUBLICATIONS** have been written over the past 40 years addressing the broad scale, pervasive and multiple harmful impacts of urban and agricultural stormwater runoff on receiving water ecosystems (primarily streams, rivers, and coastal systems) (e.g., Benke et al., 1981; Burton et al., 2000; Burton and Pitt, 2002; Klein, 1979; Masterson and Bannerman, 1994; Maltby et al., 1995). However, water quality improvements in the US essentially ended in the mid-1990s after point source (end-of-pipe) discharges, regulated under the federal Clean Water Act (1972), had been widely remediated. Water quality is no longer improving nationwide because at least half of water quality problems are caused by non-point source (diffuse) runoff from urban, rural and unsewered areas, and have not been regulated. Enhanced regulation and enforcement would likely have a significant impact.

Much of the scientific and engineering focus on stormwater has centered on the load of pollutants initially generated during a runoff event. The so-called "first flush" phenomenon is conceptually defined as the runoff generated during the first part of a storm, which is assumed to carry more pollutants than runoff produced later in the storm (Sansalone and Cristina, 2004). It is important to differentiate the scale at which this phenomenon occurs: the first flush behavior of combined sewage entering wastewater treatment plants and other end-points of combined sewer systems is well documented (e.g., Gupta and Saul, 1996; Barco et al., 2008). This same phenomenon has also been described at the micro-watershed scale (e.g., sheet flow generated by an individual parking lot) for some pollutants (Sansalone and Buchberger, 1997).

As a result of the scientific and engineering focus on first flush, stormwater treatment systems, including many GSI design standards, place a priority on capturing initial stormwater flows (Barco et al., 2008). However, many pollutants do not always exhibit first flush behavior, nor is it possible to predict when and to what extent pollutants will exhibit first flush behavior (Sansalone and Cristina, 2004) – this complicates an understanding of GSI performance. Therefore, it is not possible to base the design of GSI solely on assumed first flush behavior (Bertrand-Krajewski et al., 1998).

What is common across decades of runoff studies is their uniform identification of a number of "stressors" in human-dominated watersheds that adversely affect water quality if unmanaged. These include stressors that contribute to degraded water quality and habitat, including runoff with increased power and magnitude (i.e., highly "flashy" (Baker et al., 2004)), elevated temperatures and solar radiation, increased erosion and subsequent siltation, and increased exposure to pathogens, solids, nutrients, metals, and synthetic organic chemicals (discussed below). Harm to receiving water quality is similar across ecosystems around the world in a wide variety of human-influenced landscapes. All that varies among geographies and ecosystems is the relative magnitude of the adverse impacts of various stressors. This overwhelming, global "truth" that human-dominated runoff degrades waterways should prompt regulators and policy-makers to ensure adequate runoff management in the interest of protecting local ecosystems for habitat, public safety, public health, and enjoyment. There are many examples of stormwater management to address both flows and quality (Davis et al., 2009), resulting in the recovery and restoration of degraded agricultural and urban streams – allowing for a return of beneficial uses and ecosystem services.

**Conceptually, the way GSI is being approached and assessed is shifting from an individual unit process approach to an ecosystem services approach, which emphasizes the multifunctional benefits of green infrastructure.**

Conceptually, the way GSI is being approached and assessed is shifting from an individual unit process approach to an ecosystem services approach, which emphasizes the multifunctional benefits of green infrastructure. The US lags the European Union in adopting this approach. The EU Water Framework Directive 2000/60/EC is an example, calling for EU member states to improve the ecological status of surface water by 2015 using techniques that include GSI. However, legal barriers exist that inhibit full adoption of an ecosystem service approach (Kistenkas and Bouwma, 2018). Nonetheless, multiple authors recognize the need to move beyond focusing on water quality and quantity, and toward a broader ecosystem services approach (Lundy and Wade, 2011; Vogel et al., 2015).

### RUNOFF "STRESSORS" DEGRADE WATER QUALITY

As noted above, several water runoff-related problems exist in human-dominated watersheds and are the primary cause of water/ecosystem quality degradation. These can be referred to as stressors and include altered flows (flashy, with higher power and magnitude), degraded habitat (due to combined physical and chemical stressors), elevated temperatures and sunlight (solar radiation), and increased exposure to high levels of potentially toxic chemicals in water, sediments, and food sources (e.g., benthic invertebrates, periphyton/biofilms, and aquatic macrophytes) (Burton and Pitt, 2002). Repeated exposure to this array of stressors results in a more pollution-tolerant biota in urban receiving waters. This effect is so common it is referred to as the "urban stream syndrome" (Walsh et al., 2005), where urban (and agricultural) streams are dominated by pollution-tolerant species such as oligochaetes, midges, periphyton, and herbivorous and omnivorous fish such as carp and catfish. These species are tolerant of degraded habitats, with lower dissolved oxygen levels, higher temperature maximums, and higher concentrations of many chemicals.

One of the "truths" evident from decades of scientific studies is that differing land uses (e.g., croplands, pastures, concentrated animal feedlot operations, industrial, residential, commercial) in various geographic settings (arid vs. wet, northern vs. southern, developed vs. undeveloped countries) affect water quality and runoff differently. For example, croplands in the Midwest are dominated by corn and soybean crops, where the primary herbicide is atrazine (US Environmental Protection Agency, 2012). This controversial herbicide has been banned in Europe and Canada and is the subject of multiple US Environmental Protection Agency (EPA) reviews. It has been shown to be an ecological risk for small agricultural streams due to higher exposures from runoff (Solomon et al., 1996). However, large streams and rivers in the same watersheds are not classified as having an atrazine ecological risk. The old premise that the answer to "pollution is dilution" is sadly true for many of our systems and chemicals. Yet, for every large stream and river, smaller tributaries upstream in the upper part of the watershed could be at risk for higher concentration of chemical contaminants. These feeder streams are key to the biological health of nearby wildlife and organisms residing in the downstream aquatic ecosystems and riparian zones (Wipfli et al., 2007).

## WHICH WATER QUALITY STRESSORS ARE IMPORTANT?

One stressor that is perhaps the most pervasive and often does not dilute downstream is excess solids, defined as the sum of organic and inorganic particles. Solids enter human-dominated watersheds from a myriad of activities that cause erosion, such as farming, livestock operations, road and bridge installations, residential-commercial-industrial construction, and stream bank erosion resulting from increased stream power due to altered hydrology associated with impervious surfaces (e.g., parking lots, roof tops, and roads (Sansalone and Kim, 2008)). As a single stressor, excess solids cause a host of problems related to physical, chemical, and biological stressors.

**Differing land uses in various geographic settings affect water quality and runoff in different ways.**

Solids cause physical stress through increased turbidity; suspended solids block sunlight (thus photosynthesis), clog gills, and impair feeding ability. When clay and silt solids settle downstream, the siltation can smother fish eggs and benthic organisms, and reduce available habitat when fine particles embed between larger sand, gravel, and cobble (Wood and Armitage, 1997). Once these interstitial spaces are clogged, the benthic macroinvertebrate community changes from pollution-sensitive species (e.g., mayflies and stoneflies), to pollution-tolerant species (e.g., worms and midges). This has led to the loss of many game fish species (Burton et al., 2000).

Excess solids in runoff cause both chemical and biological stress. Organic and inorganic solid particles serve as a kind of magnet for nutrients, metals, pesticides, synthetic organics, and pathogens. Many of these other stressors attach to particles in the soil, atmosphere, and in products of combustion and tire wear and are carried in stormwater runoff (Brown and Peake, 2006; Thorpe and Harrison, 2008; MacKenzie and Hunter, 1979).

This solids-related problem actually presents excellent management opportunities to reduce ecosystem impairments by reducing erosion from high flows or by trapping excess solids before the particles enter aquatic systems. These management options are discussed below and support the use of GSI approaches.

**Excess solids in runoff cause both chemical and biological stress as they adsorb nutrients, metals, pesticides, synthetic organics, and pathogens.**

Interestingly, urban and suburban areas have many of the same stressors found in agricultural lands. The primary stressors from agricultural runoff are habitat and flow alteration (channelization, altered flows, removal of riparian zones), increased sunlight and temperature (loss of streamside trees), nitrogen and phosphorus (fertilizers, livestock manure, and biosolids), pathogens (manure and biosolids), solids (erosion), metals (components of fertilizers and some herbicides), and organic pesticides (weed and insect control). In addition to these, urban areas have stressors largely related to impervious area (e.g., roads, sidewalks, parking lots, and roof-tops). Impervious areas, where dry materials deposited by atmospheric pollution build up, typically deliver stormwater rapidly to streams and rivers. These dry materials include nitrogen and sulfur, which quickly convert to nitric and sulfuric acid when wet (Ashley and Crabtree, 1992; Wicke et al., 2012). Urban impervious surfaces may also have pollutant build-up from polycyclic aromatic hydrocarbons (PAHs) originating from combustion, asphalt and driveway/parking lot sealers, and oils dripping from cars and trucks. PAHs are common to urban waterways and can be toxic to aquatic invertebrates in very low concentrations when exposed to sunlight. In addition, billions of tons of tire particles erode off cars and trucks annually and contain myriad toxic metal and organic compounds (Wik and Dave, 2009). Zinc and copper also enter urban waterways in high levels from vehicles, brake pads, galvanized structures, and gutters (Burton and Pitt, 2002).

Adding to the degradation of urban water quality is the reality that urban centers are often located downstream while agricultural land uses are upstream. For example, when considering any large US river (e.g., Mississippi, Missouri, Ohio, Arkansas), particularly in the Midwest and South, cities and farmland are interspersed along the whole river from headwaters to mouth. Human activities in the upper Midwest are largely responsible for the massive nutrient loading of the Gulf of Mexico, causing annual "dead zones" due to hypoxia. Great Lakes tributaries are typically dominated by agriculture. This means both urban and rural land uses must be considered in management decisions aimed at improving stream and lake water quality. Given that the goal of the Clean Water Act is to restore and protect the physical, chemical, and biological integrity of our nation's waters, simply focusing on the small creeks and streams in urban areas is inadequate.

**Reducing the discharge of solids and erosional stream power into waterways would prevent many stressors from entering streams and lakes, resulting in improved water quality and biological life.**

US EPA reviews of biannual National Water Quality Inventory Reports to Congress show that altered habitat and flow, sediments, nutrients and low dissolved oxygen, pathogens, and metals consistently impair water quality and beneficial uses. As noted above, reducing the discharge of solids and erosional stream power into waterways would prevent many stressors from entering streams and lakes, resulting in improved water quality and biological life (Burton and Pitt, 2001).

# GSI: A stormwater treatment approach

GSI: A stormwater treatment approach

**A WIDE ARRAY OF GSI PRACTICES** are being deployed at increasing rates. Pollutants associated with solid particles, which have a high sorption coefficient, include metals and hydrophobic organic chemicals (e.g., PAHs). These pollutants tend to be removed readily by most GSI practices (Davis et al., 2009). A review of urban GSI found urban dust to be highly polluting, with over 75% of sorbed metal pollutants retained by the GSI (Kabir et al., 2014). Since one of the primary mechanisms for pollutant reduction is particulate retention, there is concern that GSI could serve as a reservoir for pollutants with possible health implications (Davis et al., 2006; Sun and Davis, 2007). Accumulation of pollutants in GSI over time could affect terrestrial ecosystems and have implications for human exposure on GSI sites. However, studies have yet to prove that the concentrations of pollutants in GSI accumulate at rates exceeding other urban reservoirs. For example, retention of metals in GSI has not been found to exceed that of adjacent non-GSI soil (Kondo et al., 2016).

Some more soluble pollutants, like nutrients, behave more unpredictably (Davis et al., 2006). Removal efficiencies of soluble pollutants vary considerably depending on the type of GSI (e.g., bioswale, bioretention basin, constructed wetland) (LeFevre et al., 2014).

In this white paper, we focus on GSI removal of the nutrient phosphorus – a pollutant receiving increased attention because its behavior can serve as an example for other chemicals that can adsorb (i.e., stick to) to particles, such as toxic metals and many synthetic organic compounds. This means that when GSI removes phosphorus, it often also removes metals (such as copper, lead, nickel, and zinc (Davis et al., 2003) and organics (such as PAHs, oils, and greases (DiBlas et al., 2008)). Removal efficiencies for phosphorus by bioswales have been reported to vary widely from 0% to 85% (Claytor et al., 1996; Yousef et al., 1985; Yu et al., 1993; Yu and Kaighn, 1995; Yu et al., 1994; City of Austin, 1995; Khan et al., 1992). Some studies report negative removal efficiences – these apparent anomalies may occur when fertilizer is applied to land, affecting runoff (Leisenring et al., 2010) or other biogeochemical processes (Clark and Pitt, 2009). Overall, bioswales are estimated to reduce phosphorous loads by approximately 50% when based on event-mean concentrations, but the range in empirical evidence is so wide that an event-mean may not be useful (Zhang et al., 2009). A similarly wide range of removal, 20-90%, is observed for total phosphorus concentrations in bioretention basins (Young et al., 1996; City of Austin, 1990; Yu et al., 1993; Yu et al., 1994; City of Austin, 1995; Gain, 1996; Harper and Herr, 1993; Martin and Smoot, 1986; Yu and Benelmouffok, 1988; Gibb et al., 1999; Watson et al., 2016). The amount of removal depends on the design of the bioretention basin (Hogan and Walbridge, 2007), with the presence of a wetpond or wetland having a significant impact on performance (Maxted et al., 1999). Constructed wetlands are also variable (25-70%) in phosphorus removal efficiencies (Zhang et al., 2009; US Environmental Protection Agency, 1993). Evidence suggests that bio geochemical cycling within these systems transforms particulate-bound phosphorus to dissolved forms of phosphorus, which implies that nutrients may be released downstream, contributing to pollution (Schueler, 1999; McElmurry et al., 2013).

The wide range of performance can be attributed to an array of site-specific characteristics and design factors that influence the functioning of GSI practices (Schueler, 1999; Shaver and Maxted, 1994), as well as challenges associated with measuring performance. Ammendments of fly ash (Penn et al., 2011; Zhang et al., 2008), biochar (Beck et al., 2011), iron filings (Erickson et al., 2012), and other calcium-rich materials (Vohla et al., 2011) can further enhance phosphorus retention in some systems. Some studys report little to no retention, however, suggesting further study is necessary (e.g., Iqbal et al., 2015). Watson et al. (2016) provide additional discussion through a review of available research, concluding that overall, the variability observed in phosphorous removal highlights the importance of additional research to better define the conditions that affect GSI performance.

### CHALLENGE OF EVALUATING GSI PERFORMANCE

Comparing the performance of GSI has proven difficult since it is affected by a variety of site conditions and has been assessed using a plethora of outcome metrics (Lenhart and Hunt, 2011). It is also challenging to evaluate stormwater treatment systems due to the massive spatial and temporal variation in rainfall events (Lenhart and Hunt, 2011). Further, the performance of treatment systems changes over time with maintenance being a dominant factor (Brown and Hunt, 2012; Houle et al., 2013). A commitment to maintenance is critical to ensuring the long-term viability of GSI and is a major potential barrier to implementation (Houle et al., 2013). Repeated, long-term experimental testing is needed to optimize GSI designs for effective and reliable pollutant removal (Roy-Poirier et al., 2010), yet this has not occurred.

**The performance of treatment systems changes over time, with maintenance being a dominant factor.**

**"Percent removal" is a problematic metric for GSI success because it depends on influent concentration and does not account for hydraulic processes or site-specific differences.**

GSI performance is most commonly described in terms of percent removal: the percentage change in concentration of a pollutant in water exiting a system as compared to water entering a system. Percent removal is a particularly problematic metric because it depends on influent concentration (e.g., Zhang et al., 2010), does not account for hydraulic processes (e.g., groundwater influx), and does not account for site-specific water quality and eco-regional differences. For example, runoff from a new residential development in Seattle will have much different water quality than runoff from an aging industrial park in Gary, Indiana, and so percent removal will vary vastly even with similar treatment methods. Percent removal also assumes that the concentration of a pollutant exiting a treatment system reflects the entrance concentration during the same storm event, which may not be true (McNett et al., 2011).

Although challenges make it difficult to evaluate performance and optimize the design of GSI, further research is essential. Just as phosphorus was used to demonstrate the behavior of other chemicals, suspended solids are often used as an indicator of performance. Using either percent removal or suspended solids as performance indicators has limitations that can lead to erroneous conclusions about the impact of GSI on downstream ecosystems (Williams et al., 2013).

**Conventional stormwater detention basins and wetlands remove larger particles and allow smaller, contaminant-laden particles to pass through.**

GSI approaches vary in their ability to remove dissolved pollutants, such as nutrients (LeFevre et al., 2014) including nitrogen (Li and Davis, 2014; Lucke and Nichols, 2015) and phosphorus (Li and Davis, 2016; Leisenring et al., 2010). Dissolved pollutants bind to smaller particles in stormwater at disproportionally greater rates because as particles decrease in size, their surface area increases relative to their mass. This has proven to be a challenge for the effectiveness of conventional stormwater detention basins and wetlands because these systems preferentially remove larger particles – allowing smaller, contaminant-laden particles such as clays to pass through (SWAMP Program, 2005; Johnson et al., 2003). Soil and compost type, loading rates, and retention times used in bioretention systems influence GSI performance, and treatment media (e.g., compost) may release previously retained pollutants (Mullane et al., 2015). Other factors influencing GSI performance include the configuration of filter media, the layout of the catchment basin, and the types of plants used (Hsieh and Davis, 2005; Hsieh et al., 2007; Paus et al., 2014; Rycewicz-Borecki et al., 2016; Brown and Hunt, 2010; Chen et al., 2013; Hunt et al., 2012; Lucas and Greenway, 2015 and 2011; LeFevre et al., 2014). Additional research on GSI design is necessary to further advance performance.

It is important that future research use rigorous sampling protocols to assess GSI effectiveness under a range of pollutant loads and in many land use scenarios and ecoregions (e.g., Hoppin, 2008). It is also critically important to evaluate replicate systems. Replication ensures that factors outside of the experimental design do not confound analysis or mask indicators of performance. Additionally, future studies should collect measurements in ways that can be compared across sites. Many past studies have relied on concentration-based assessments of GSI performance without comparing across sites. As an alternative to a concentration-based percent removal, researchers can compare the load (or total mass) of a pollutant in water flowing into and out of a GSI system, or compare the quality of water leaving the system to that of the water body into which it flows (Lenhart and Hunt, 2011).

Because pollutant loads vary throughout a storm, GSI systems must be sampled using flow-weighted event mean concentrations, which average the concentration of a pollutant across a storm. If GSI systems are large or contain vegetation (e.g., constructed wetlands), sampling will likely need to accommodate daily, weather-based, and seasonal variations (Burton and Pitt, 2001; Burton et al., 2000). Sampling must include multiple events and seasons to properly evaluate performance.

Extensive quality assurance and quality control guidance has been developed by the State of Washington with its Technology Assessment Protocol - Ecology (TAPE) (Washington Stormwater Center, 2018), which is used to evaluate whether new on-site stormwater treatment technologies are adequate. The TAPE program describes statistically-valid stormwater sampling approaches to determine the removal efficiencies of proposed technologies for phosphorus, total suspended solids, and copper, with oil and grease and other pollutants often considered. Similarly, the former Virginia Technology Assessment Protocol (VTAP) was developed to evaluate the use of manufactured treatment devices for the removal of phosphorus (Sample et al., 2012). Because phosphorus can serve as an example of many types of pollutants, the VTAP would likely be useful for evaluating performance for a range of chemicals. These protocols provide a template for evaluating the effectiveness of GSI technologies.

**Protocols like the State of Washington's TAPE program provide a template for evaluating the effectiveness of GSI technologies.**

**As virtually all urban runoff has been shown to be toxic, runoff toxicity is an important performance benchmark for GSI.**

To date, most GSI performance benchmarks have focused on hydrology and water chemistry rather than directly addressing the Clean Water Act's motivating goal: maintaining and restoring the biological integrity of the receiving waters. This goal points to runoff toxicity as a needed GSI performance benchmark. As discussed above, virtually all urban runoff has been shown to be toxic (Burton and Pitt, 2001; Burton et al., 2001). For example, a comprehensive study found all first flush stormwater runoff from highways to be both acutely and chronically toxic to zooplankton and salmon (McIntyre et al., 2015). McIntyre et al. (2015) demonstrated how using soil media as a bioretention treatment helps to reduce runoff toxicity for juvenile salmon and their prey. As GSI's removal of pollutants is variable, associated reductions in toxicity will also vary.

For example, green roofs have been proposed as tools for mitigating stormwater and air pollutants (e.g., Rowe, 2011). While results for the impact of green roofs on stormwater are mixed, several studies show an increased removal of nutrients, total and dissolved solids, and major ions by green roofs (Berndtsson, 2010). Initially, these systems may increase nutrients and organic matter in runoff, but these decrease with time (e.g., Beecham and Razaghmanesh, 2015; Harper et al., 2015). However, other ecosystem services provided by green roofs, like reduced energy demand for heating and cooling (Castleton et al., 2010), may relax requirements for stringent treatment efficiency and universal adoption, increasing the viability of this treatment approach.

The level of treatment efficiency and adoption affects the utility of GSI practices. For example, a Chicago study found 30% of homeowners were willing to mitigate stormwater on their property by using either rain barrels or rain gardens, while installations amounted to only 10-12% of homes in a watershed with 13-20% impervious area (Roy et al., 2014). Minor effects in volume and water quality were observed but failed to improve biotic health. These disappointing results were likely due to the low participation rate and the need to treat widespread impervious surfaces like roads and parking lots.

Further, GSI adoption may not be directly related to residents' risks of being affected by stormwater management. For example, residents at increased risk of flooding are not more likely to purchase rain barrels (Ando and Freitis, 2011). Research is needed to define minimum effect thresholds for retrofitting catchments and improving stream ecosystems (Roy et al., 2014). Relatively low participation in household-level forms of GSI is a reality that must be considered. This points towards the need for integrated GSI management practices that address hydrological, ecological, economic, and social functions in urban neighborhoods (Hoang and Fenner, 2016).

**Low participation in household-level forms of GSI suggests a need for integrated GSI management systems that address hydrological, ecological, economic, and social functions.**

The effects of GSI on water quality remain poorly quantified, impeding the development of accurate stormwater quality models that incorporate GSI (Hoang and Fenner, 2016). Some trends are apparent, but more research is needed to determine the long-term cost-effectiveness of alternative GSI practices. The NEW-GI project is generating some of this critical research, which be reported in future publications.

### OTHER CHALLENGES

In examining GSI effectiveness for water quality improvements, climate change should be considered. Bioretention basins have been found to reduce nutrients and be cost-effective in some studies. Specifically, Wang et al. (2013) considered future climate challenges and found that these practices are expected to yield good performance with lower climate and economic costs (green house gases as measured in kg CO2, and US dollars) than grey systems. The installation of GSI prior to *municipal separate storm sewer systems,* commonly referred to as MS4s, has been found to be more cost-effective than traditional grey infrastructure approaches (Wang et al., 2013). However, given that GSI effectiveness depends on many different variables, and the difficulty in measuring effects in a way that allows comparison, more research is needed to guide decisionmaking and investment for effective climate change mitigation.

**Costs associated with treating stormwater, including GSI costs, will increase if climate change requires larger reductions in runoff volumes or pollutant loads.**

Moving forward, integrated management approaches are needed that can adapt to a changing climate. System management should be flexible to account for variations in precipitation intensity and impervious cover. Optimal GSI scenarios are likely to change with land use and climate (Liu et al., 2016) and, as expected, GSI costs will increase (as would any treatment system) if climate change requires larger reductions in runoff volume and pollutant loads. More research is needed to understand the impact of increased storm intensity and frequency, particularly regarding the impacts of increased storm intensity on water quality (Vogel et al., 2015).

# Conclusion

**THE USE OF GSI** in urban environments was initially intended to improve hydrology (reduce peak flow, etc.), but is increasingly being applied to improve water quality as well (Vogel et al., 2015). While many GSI systems improve some physical-chemical parameters of water quality (e.g., removal of suspended solids), the ability of these systems to remove pollutants, such as phosphorus, is little studied and not consistent. Performance variations among different GSI practices and designs have been difficult to evaluate. To optimize performance, GSI should be designed to address specific conditions of its site and context. A mechanistic understanding of how pollutants are retained and released is required to accurately predict GSI performance, as well as to enhance the design and maintenance of these systems. Evaluating GSI performance must also be conducted over the long-term, as system function is known to vary with time. Ultimately, the behavior of individual pollutants does not address a fundamental question: *Does GSI performance improve overall water quality?* The quality of surface waters impacted by complex mixtures is best assessed by evaluating the impact to aquatic organisms and integrating conditions across the ecosystem. The NEW-GI project is currently working to address these gaps in knowledge by evaluating the effectiveness of replicate bioretention practices installed in Detroit.

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## APPENDIX A: USEFUL WEB LINKS

Center for Watershed Protection
*https://www.cwp.org*

Center for Urban Waters – University of Washington, Tacoma
*https://www.tacoma.uw.edu/center-urban-waters/center-urban-waters*

Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers
Allen Burton & Robert Pitt, CRC Press 2001.
*http://rpitt.eng.ua.edu/Publications/BooksandReports/Stormwater%20Effects%20 Handbook%20by%20%20 Burton%20and%20Pitt%20book/MainEDFS_Book.html*

Technology Assessment Protocol - Ecology (TAPE) – State of Washington Department of Ecology
*https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Emerging-stormwater-treatment-technologies*

University of New Hampshire Stormwater Center
*https://www.unh.edu/unhsc/*

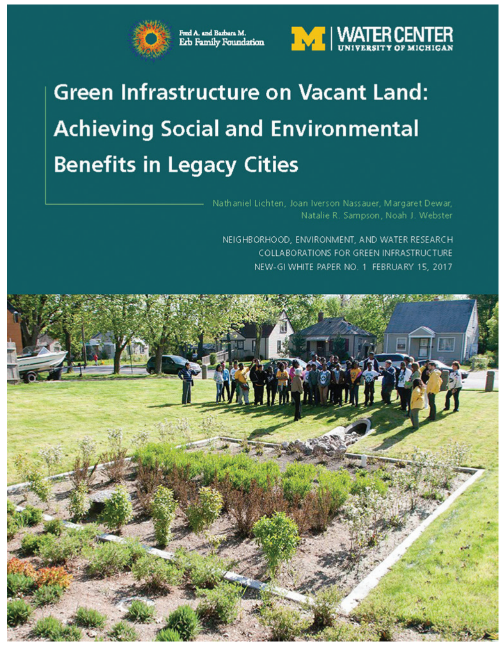
Washington Stormwater Center
*http://www.wastormwatercenter.org/*

This report concludes that:
To optimize performance, GSI should be designed to address specific conditions of its site and context. A mechanistic understanding of how pollutants are retained and released is required to accurately predict GSI performance, as well as to enhance the design and maintenance of these systems.

We address issues of context in this NEW-GI publication:


Nassauer, J.I., & Feng, Y. (2018). *Different Contexts, Different Designs for Green Stormwater Infrastructure* (NEW-GI Technical Report No. 1) Ann Arbor, MI: University of Michigan Water Center.

We address design and maintenance of GSI in this NEW-GI publication:




Lichten, N., Nassauer, J. I., Dewar, M., Sampson, N., & Webster, N. J. (2017). *Green Infrastructure on Vacant Land: Achieving social and environmental benefits in legacy cities* (NEW-GI White Paper No. 1) Ann Arbor, MI: University of Michigan Water Center.

Forthcoming NEW-GI publications address exemplary governance and maintenance approaches from U.S. legacy cities, results of our social survey of households in the Upper Rouge Tributary area of Detroit, and results of our water quality assessment of NEW-GI pilot sites in Detroit. To request copies of any of NEW-GI publications, email newgi-contact@umich.edu.

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