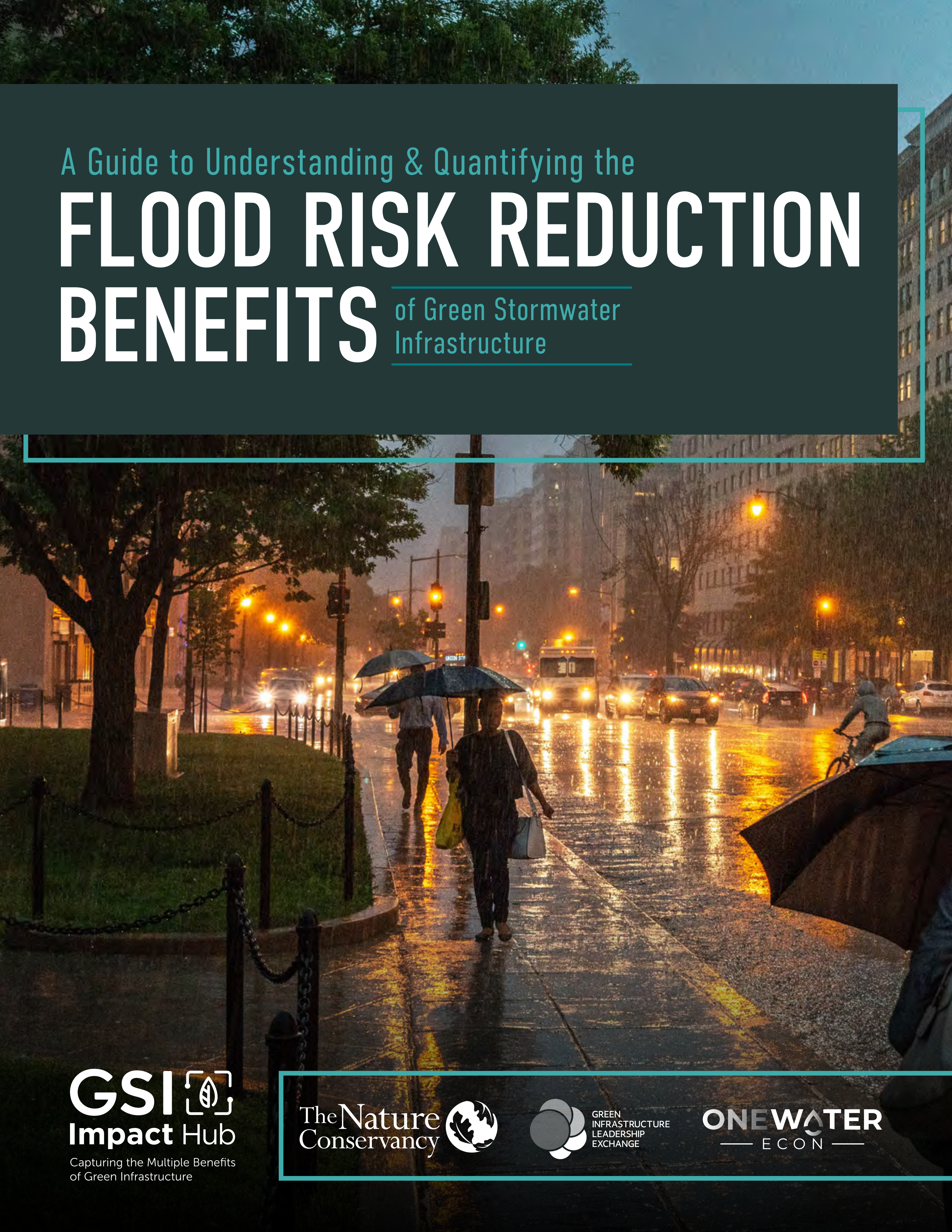

# A Guide to Understanding & Quantifying the FLOOD RISK REDUCTION BENEFITS of Green Stormwater Infrastructure

GSI Impact Hub

Capturing the Multiple Benefits of Green Infrastructure

The Nature Conservancy

GREEN INFRASTRUCTURE LEADERSHIP EXCHANGE

ONEWATER ECON

**Credit:** Michael B. Maine

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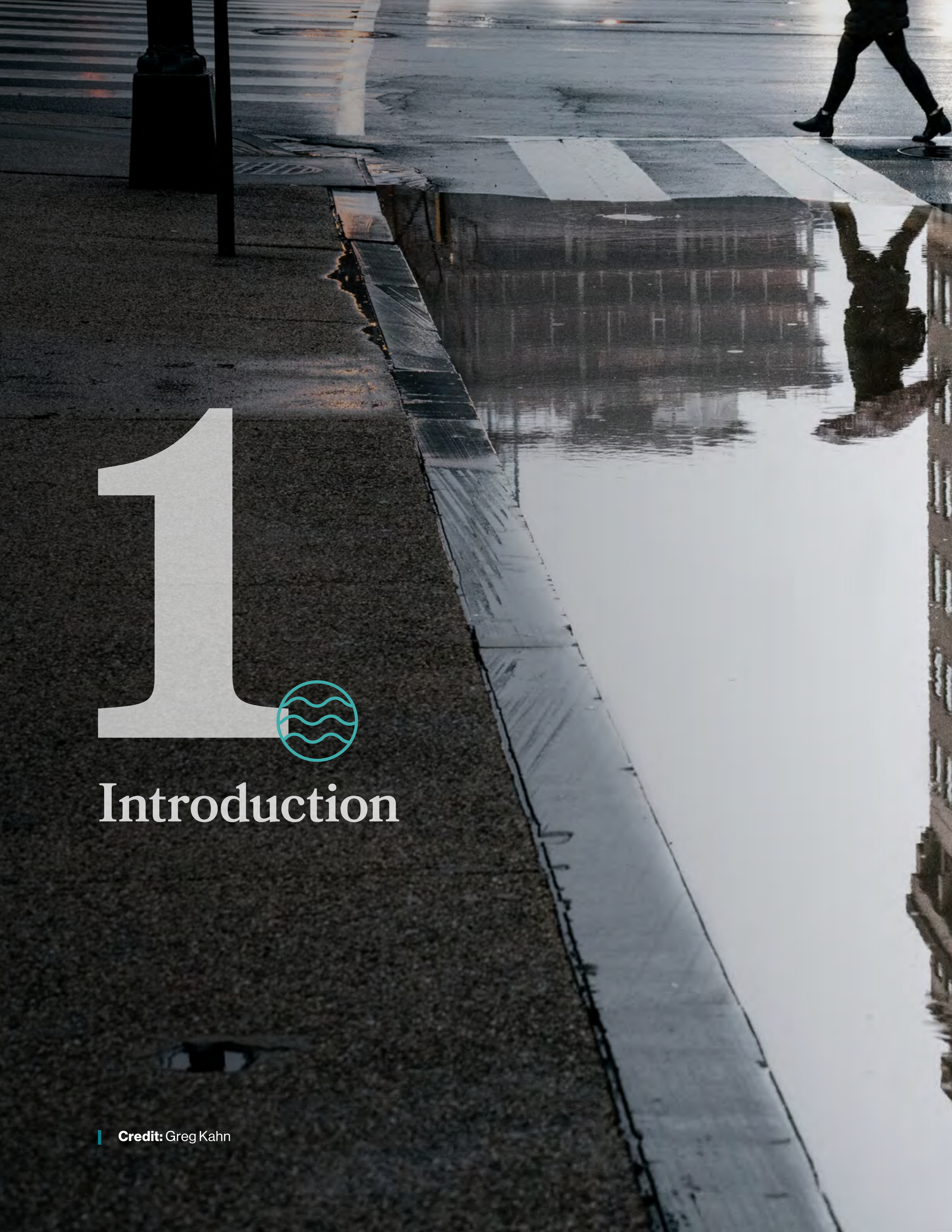


# 1

# Introduction

**Credit:** Greg Kahn

# INTRODUCTION

Green stormwater infrastructure (GSI) is increasingly being recognized as an important strategy for building flood resilience in urban and suburban areas. This guide summarizes the most recent findings on the effectiveness of GSI in reducing the risk associated with localized and riverine flooding and assists practitioners in planning GSI projects to achieve these benefits.

Municipalities experience several different types of flooding. Prolonged or intense rain events that generate large volumes of stormwater cause waterways to overflow their banks, resulting in riverine flooding. These floods can be influenced by conditions far upstream, and the degree and timing of flood flows are often beyond the direct control of municipalities. Coastal flooding can result from rain events combined with wind-driven storm surge, resulting in additional flood risk. Localized flooding occurs when rain overwhelms drainage systems and waterways in direct proximity to a precipitation event. Localized flooding can be separate from, or in addition to, riverine or coastal influences. Many severe urban floods are caused by coincident flooding, where an area is exposed to multiple flood risks at the same time.

In many areas, the effects of climate change will result in more frequent and intense rain events. Municipalities and utilities across the United States must adapt to manage the increase in stormwater runoff and mitigate the associated risk of flooding in urban locales. To address this challenge, cities across the globe are rethinking and adapting their approach to flood risk management, transitioning from traditional engineered “flood defense” strategies to incorporate the concept of flood resilience, “where urban spaces are designed to make space for water and adapt to the increasing threat of urban flooding while providing wider improvements to the environment and society.”[1]

Green stormwater infrastructure (GSI) is increasingly being recognized as an important strategy for building flood resilience in urban and suburban areas. However, questions remain on the effectiveness of GSI for managing different storm events (i.e., of varying rainfall depths and intensity), as well as the scale of application necessary to reduce flood related impacts. Increased understanding of the effectiveness of GSI

## GSI Impact Hub

This guide is a component of the GSI Impact Hub, a larger project that provides resources and support related to specific GSI co-benefits. Please visit the GSI Impact Hub website to explore additional resources including:

- Compendium of GSI Co-benefits Valuation Resources
- GSI Impact Calculator, a block-level tool for quantifying and monetizing co-benefits
- Benefit guides related to flood risk reduction, habitat and biodiversity, heat risk reduction, and transportation.

The GSI Impact Hub is a collaboration between The Nature Conservancy, Green Infrastructure Leadership Exchange, One Water Econ, government agencies and technical partners.

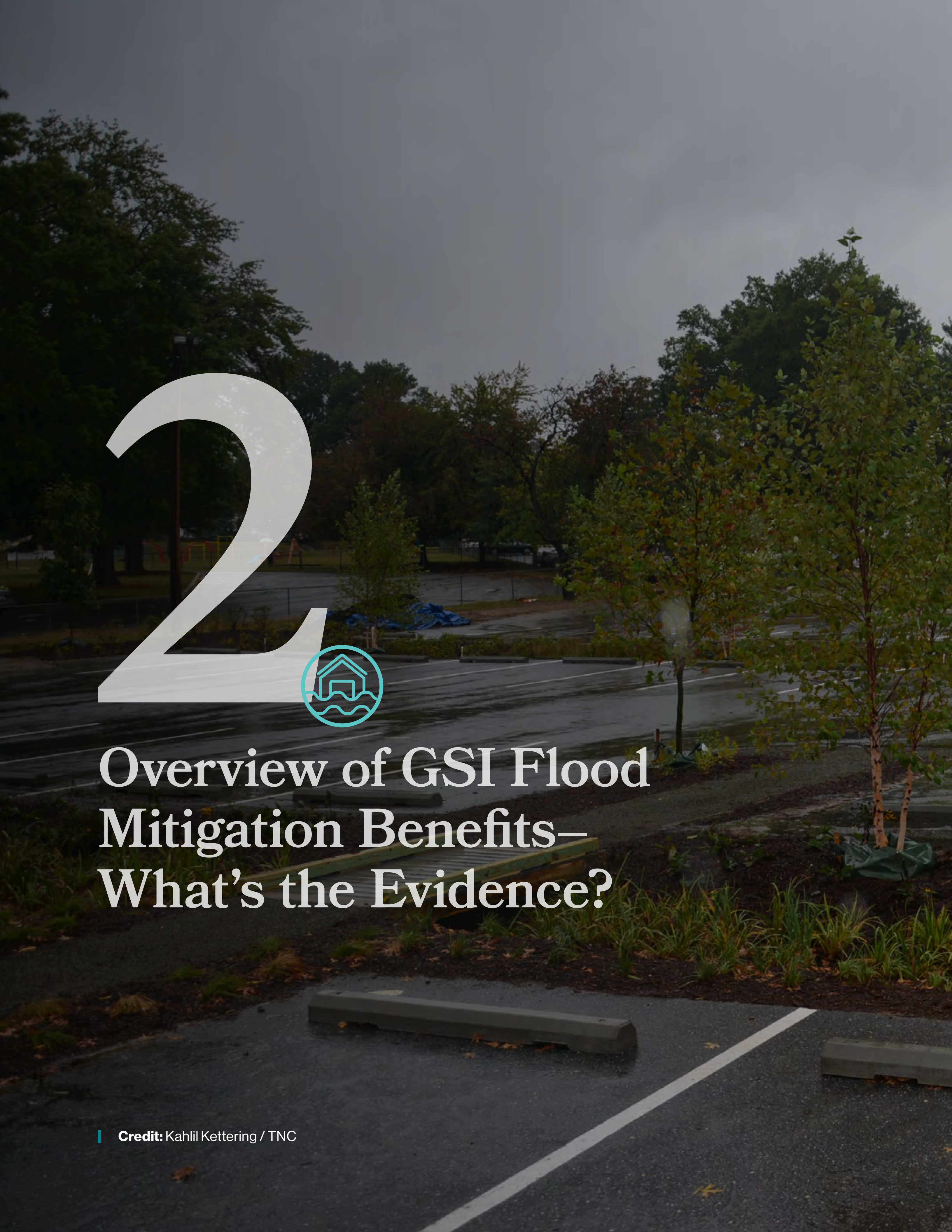
to enhance urban flood resilience is necessary to support widespread and holistic adoption of GSI for this purpose. This guide aims to summarize the most recent findings on the effectiveness of GSI in managing localized and riverine flooding[2] and assist practitioners in understanding the flood risk reduction benefits of GSI installations in their jurisdictions. It is organized as follows:

- **Section 2** provides an overview of findings from key studies on the effectiveness of GSI in reducing localized and riverine flooding, highlighting general conclusions and lessons learned across geographies and scales of implementation.
- **Section 3** covers siting, design, and implementation considerations for localized and riverine flooding including case studies, equity considerations, and cost-effectiveness of hybrid green/grey solutions.
- **Section 4** describes methods for quantifying the flood risk reduction benefits of GSI.
- **Section 5** highlights funding, financing, and partnership opportunities for using GSI to manage flood risk.
- **Section 6** summarizes key takeaways and outlines uncertainties and research gaps.

## Key Questions Addressed in This Guide

- What is distributed green stormwater infrastructure?
- What GSI practices can reduce localized and riverine flooding in my area?
- What siting, design, and implementation considerations should I consider when planning and implementing GSI for flood reduction?
- How can I quantify and monetize the flood reduction benefits of GSI? Is there a way to do this early in the planning process?
- How have other communities leveraged GSI to reduce flooding?
- What are available funding sources and partnership opportunities for GSI projects with flood reduction potential?
- What gaps in research exist with respect to this co-benefit?


**Credit:** Kahlil Kettering / TNC



# 2

# Overview of GSI Flood Mitigation Benefits–What’s the Evidence?

**Credit:** Kahlil Kettering / TNC

# OVERVIEW OF GSI FLOOD MITIGATION BENEFITS–WHAT'S THE EVIDENCE?

Managing stormwater runoff through GSI, or natural processes that retain and slow flood waters, can help to mitigate urban flooding. This section provides a summary of recent studies that evaluate the effectiveness of GSI for flood mitigation.

Strategies for managing flooding in urban areas have traditionally focused on hard-engineering approaches that contain and convey water through urban systems as quickly as possible. Increases in storm frequency and intensity, coupled with increased urban development and inadequate drainage systems, means that in many areas, reliance solely on these "gray infrastructure" solutions is becoming costly, ineffective, and impractical. Managing stormwater runoff through GSI, or natural processes that retain and slow flood waters, can help to mitigate urban flooding in the following ways:

- At the site, block, or sub-catchment level, targeted GSI can reduce localized flooding. This in turn reduces related impacts such as basement backups and so called "nuisance flooding" that occurs when stormwater inundates backyards, streets, and other public areas.
- More widely distributed GSI practices dispersed throughout a watershed or catchment can reduce total runoff and peak flows, helping to mitigate downstream riverine flooding and associated damages.
- GSI-based solutions can provide a more flexible and adaptive approach to reducing flood risk in the face of uncertainties surrounding future climate, rainfall patterns, and level of urbanization. Targeted GSI installations can also help extend the lifetime of aging gray infrastructure assets by expanding the capacity of existing drainage networks.

A review of real-world projects indicates that at the site or block-level, GSI strategies can effectively target flood prone areas and reduce localized flooding associated with small to moderate storm events. Examples in this guide highlight significant site- and neighborhood-scale projects that use GSI-based approaches to manage localized flooding up to at least the 10-year storm event, including New York City's Department of Environmental Protection's cloudburst management approach and the City of Detroit's block-level application of GSI to reduce basement backups in a highly impacted neighborhood (refer to case studies on subsequent pages). These examples point to the importance of larger-scale storage opportunities for infiltration – such as routing stormwater flows to open spaces (e.g., parks, playing fields, and medians) to manage larger storm events.

**Credit:** Courtney Baxter / TNC

> GSI strategies can effectively target flood prone areas and reduce localized flooding associated with small to moderate storm events.

While limited, empirical studies confirm that site- and block-level interventions can enhance flood resilience while providing other important stormwater management benefits.[3] A study reporting results from 20-years of monitoring the effectiveness of stormwater management controls in Montgomery County, MD compared runoff volume and peak flows under a range of storm events for a street with disconnected downspouts and vegetated swales (green street) and a street with traditional curb and gutter drainage (gray street).[4] Up to the 0.8-inch rainfall event, the green street produced less runoff than the gray street; beyond that depth, runoff yields converged. However, peak runoff from the green street was less than the gray street for all but the most infrequent, extreme events, indicating that street-side swales provided enhanced flow attenuation compared with curb and gutter.[5]

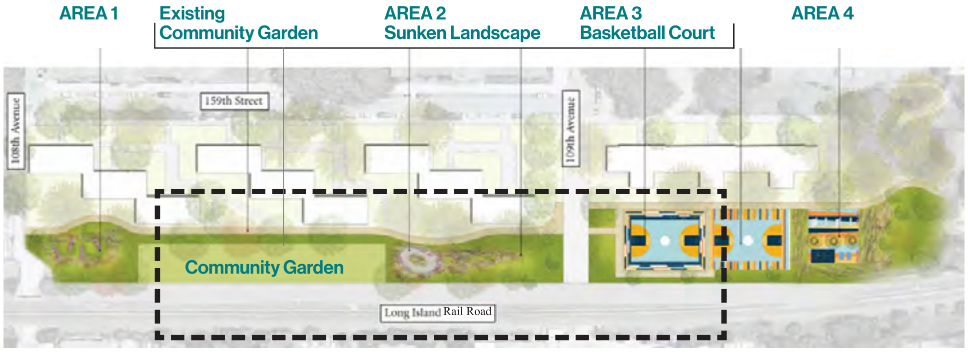
Modeling studies also suggest significant potential for GSI to increase flood resilience through block level interventions.[6,7,8] The city of LaCrosse, WI examined the potential for three green street designs to mitigate localized flooding in a 770-acre catchment, where intense storms resulted in drainage system backups and street flooding. Based on available land area, one green street design added bioretention to 30% of local roads, while two added permeable pavements (with varying storage capacities) along 80% of major roads and 90% of local roads. Results indicated that all three systems would eliminate flooding from the 3-month, 24-hour event (0.83-inch rainfall depth). However, permeable pavement was the most effective in reducing the extent and duration of flooding associated with the 10-year, 2-hour storm (2.86-inch precipitation depth). The model predicted that full implementation of permeable pavement (four feet of storage depth) would reduce flooding by 87% with fewer than 10% of manholes overflowing (this compared to 63% of manholes flooding without GSI). While this study evaluated basin-wide implementation, results suggested that prioritizing problem areas would result in less costly solutions.[9]

At the watershed scale findings are mixed, particularly because GSI is not typically designed for larger-scale events and flood risk reduction benefits vary based on overall impervious area and other watershed characteristics.[10] For example, a study of flood risk reduction in the 213 square mile Lamprey River watershed near Newmarket, NH found that distributed GSI implementation across the watershed did not significantly alter downstream hydrology for the 100-year, 24-hour event (8.5-inch depth) relative to a conventional build-out scenario. The authors concluded that this was because total overall impervious cover in the watershed was low (less than 7.5% of the watershed area). However, further analysis indicated that the impact of GSI was substantial in three of the area's highly developed sub watersheds. These smaller urbanized areas demonstrated significant runoff reductions compared to a conventional build out approach.[11] In one watershed, the GSI-based redevelopment scenario reduced runoff from current conditions.

Several studies report that flood risk reduction benefits are higher in watersheds with distributed and GSI-based practices than in watersheds with direct conveyance or detention-based control measures.[12,13,14] The Montgomery County, MD study referenced above highlighted findings related to the effect of watershed scale distributed practices, including recharge chambers, infiltration trenches, tree planting, and underground detention, on downstream hydrology. Comparing three treatment watersheds to a reference (forested) watershed, and an urban control watershed with centralized facilities, researchers found that distributed stormwater management can mitigate changes to streamflow and, in some cases, replicate reference conditions. Runoff yields in

**Credit:** Green Infrastructure Leadership Exchange

Rendering of South Jamaica project site final recommended design options



## Cloudburst Management in New York City – Designing Neighborhood Solutions to Manage Urban Flood Risk

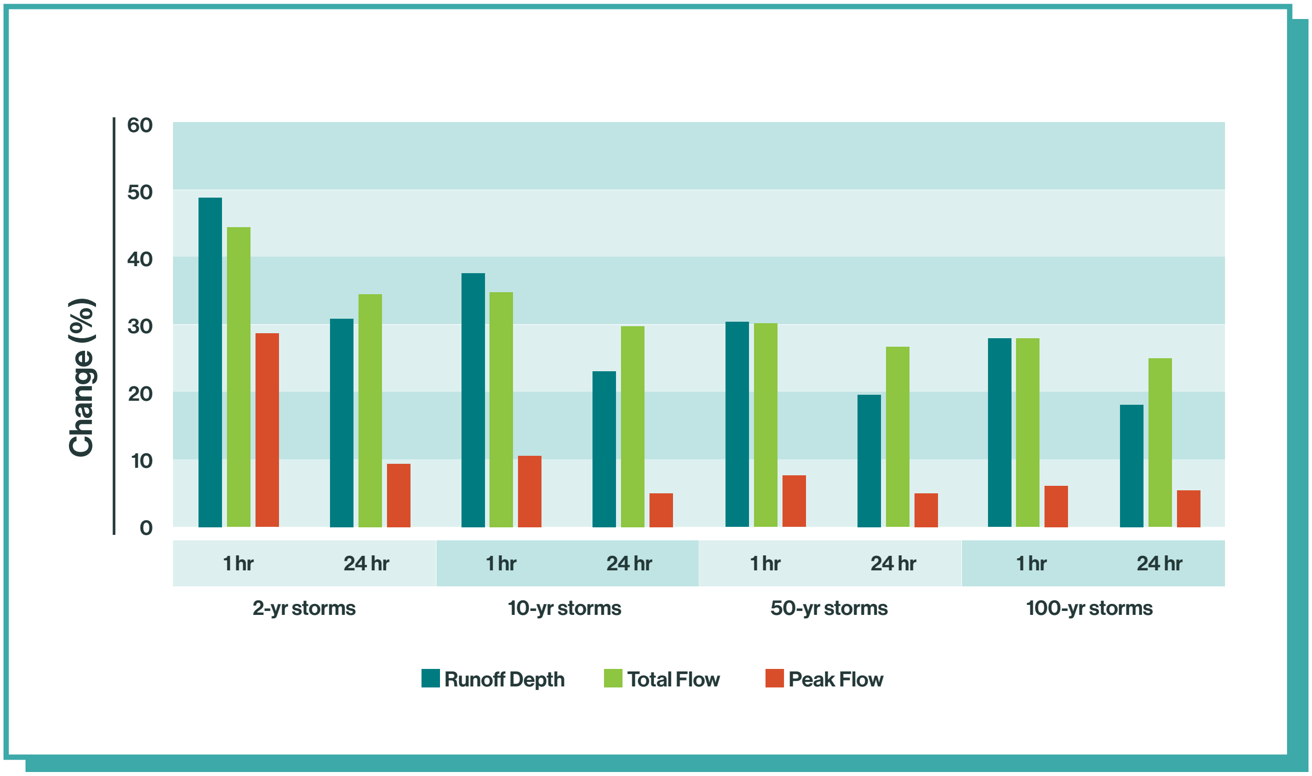
New York City Department of Environmental Protection (DEP) defines a cloudburst as a sudden, heavy downpour where large volumes of rain fall in a short amount of time, causing flooding, property damage, critical infrastructure disruption and pollution in local waterways. DEP typically uses a combination of blue, green, and gray infrastructure to manage the increasing occurrences of localized flooding due to cloudburst storms and to reduce the strain on the sewer system. To test the implementation of cloudburst management, DEP partnered with the NYC Housing Authority's South Jamaica Houses in 2018 to develop a master plan to manage cloudburst stormwater runoff in the South Jamaica neighborhood in Queens.

The goal of the plan was to identify strategies for managing flooding associated with rain events ranging from everyday rainfall up to the 10-year storm. The drivers behind the plan include ongoing and increasingly frequent flooding in the neighborhood. DEP and the Housing Authority worked diligently to gather as much public commentary as possible, holding public design charette and two different workshops in a variety of locations, times and formats. Residents favored designs that managed the most stormwater above grade, creating green spaces that could be occupied when not actively flooded.

As shown in the figure below, the final design identified four potential options that would create open spaces and enhance existing recreational amenities (e.g., a basketball court and community garden), infiltrating stormwater and creating large storage spaces. Initial cost estimates indicated that the blue-green infrastructure plan cost less than half of the capital construction costs of installing more gray storm sewer infrastructure, and although the annual maintenance costs 30% more than a traditional piped system, the plan offers the co-benefits of improved public space and a healthier environment. Final implementation will likely focus on one or two identified project areas.

Source: NYCHA (2018).

**Figure 1.** Flood risk reduction performance of distributed GSI (reducing effective impervious cover from 30% to 10%) and other BMPs in 185-acre Berry Brook watershed, Dover, NH



Source: Hastings (2021)

the treatment watersheds were lower than in the urban control watershed up to about 0.8 inches of precipitation.[15] However, for all but the most extreme events, peak runoff magnitudes in the treatment watersheds fell between the peaks from the forested and urban control watersheds.

In another study, researchers evaluated flood management strategies in three watersheds in suburban Baltimore, MD. Two of the watersheds drained to stormwater detention facilities, and the third had virtually no stormwater management in place; all varied in the amount of impervious cover. The authors examined watershed responses to short periods of intense rainfall (between 3.5 and 16.1 inches, with peak rates between 0.47 and 3.5 inches per hour). Designed for the 2.7-inch storm, the stormwater detention basins did not significantly reduce peak runoff rates. The primary difference in hydrographic response between the basins suggested instead that reduction in impervious cover has a larger impact on runoff volume than detention alone. One conclusion is that the impervious area reduction techniques that are common with GSI-based approaches may be more instrumental in reducing flood risk than the construction of large-scale detention facilities.[16]

Others have confirmed that reducing effective impervious cover can contribute to meaningful downstream flood management benefits. A recent PhD dissertation examined the effectiveness of GSI and other BMPs to control urban flooding for extreme precipitation events in the 185-acre Berry Brook watershed in Dover, NH. Improvements to the watershed included building additional headwater wetland area, daylighting and restoring 1,100 feet of stream, and redirecting stormwater to GSI, thereby reducing effective impervious cover from 30% to 10%. Consistent with other studies, findings indicated that GSI can reduce flooding caused by smaller precipitation events (less than 1.3 inches) but does not eliminate it for extreme events. Figure 1 shows the decrease in peak flows

(5 to 29%), runoff depth (19% to 49%), and total flow volumes (25 to 45%) across the range of storm events analyzed.[17]

The authors note that the decrease in annual peak flow caused by BMP implementation ranged from 5% to 38%, with a median decrease of 8% (rainfall depth of 2.05 inches). This means that the BMPs decrease flooding in Berry Brook by 8% for the typical large storm. In other words, watershed hydrology improved even in storms twice the size of the 1-inch storm event for which most GSI is designed.

> GSI-based practices can reduce localized flooding and contribute to improved hydrologic performance downstream, helping to mitigate the impacts of riverine flooding in many cases.

The scale of application is an important consideration when assessing the effectiveness of GSI for flood risk reduction benefits. In general, increased GSI increases flood resilience benefits, although marginal benefits begin to decrease after a certain point. In addition, GSI is more effective when implemented as part of a holistic management approach – i.e., individual projects have negligible effects at the catchment or watershed scale. In a study of green roofs and permeable pavement in Genoa, Italy, modeling indicated a linear relationship between effective impervious area reduction and downstream hydrologic performance for a small catchment.[18] Simulation results revealed that an 11% reduction in effective impervious area would be required to reduce peak flows and run-off volumes by 10% and 5%, respectively. Further, an effective impervious area reduction of 5% would be required to obtain noticeable hydrologic benefits.

Another study examining scale of application simulated conditions within a combined sewer area of Chicago with limited drainage capacity. Modeling showed that at 10% GSI coverage, more water would be directed to GSI than to sewers in 5-year storms. Surface flooding and runoff to downstream areas would also be eliminated. At 20% GSI coverage, sewer intake began to level off and the marginal benefit of adding GSI decreased. The study found that at least 10% to 15% GSI coverage would be needed to outpace the sewers and significantly reduce block flooding. At 30% coverage, GSI would alleviate the sewer system from operating at full capacity and eliminate downstream outflow.[19] In a recent study of 372 watersheds across the U.S., researchers examined the relationship between urban greening and downstream hydrologic conditions, finding that on average, a 10% increase in “greenness” resulted in corresponding reductions in total flow (–3.8%), peak flows (–4.7%), and high flows (–7.6%), and a corresponding increase in baseflow (4.3%).[20]

Table 1 provides a summary of studies that have evaluated the effectiveness of different GSI practices to reduce localized and riverine flooding, including those discussed above. While studies are difficult to compare due to location- and study-specific characteristics, general findings indicate that GSI-based practices can reduce localized flooding and contribute to improved hydrologic performance downstream, helping to mitigate the impacts of riverine flooding in many cases. Targeted GSI projects can significantly reduce flooding associated with small to moderate events (e.g., 10-year storms); and, when distributed throughout a catchment, can reduce overflows and backups associated with localized flooding. At the watershed scale, the ability of GSI to reduce runoff volumes and peak flows varies by the magnitude of the flood, size of the watershed, and other site-specific characteristics (e.g., upstream contributing area, soil infiltration properties, slopes). Several studies have found that GSI is most effective when projects are planned as part of a connected network[21] or integrated into a holistic green-gray infrastructure approach.[22,23]

**Table 1.** Summary of recent studies on the effectiveness of GSI for flood risk reduction

| GSI Practice | Location | Description | Storm Size |
|---|---|---|---|
| Rain gardens | Philadelphia, PA | Simulated rain garden performance with large amount of precipitation at a sustained high intensity. Results were combined with monitoring of actual performance in average rainfall years. | 1.65″-5″ |
| Green street-downspout disconnects and vegetated swales | Montgomery County, MD | Compared runoff volume and peak flows under a range of storm events for green street and to traditional curb and gutter drainage. | Monitored across a range of storm events |
| Permeable pavement and bioretention | LaCrosse, WI | Modeled the effectiveness of three green street designs. One added bioretention along 30% of local roads, while two added permeable pavements (with varying storage capacities) along 80% of major roads and 90% of local roads. | 3-month, 24-hr (0.83″)<br>10-yr, 2-hr (2.86″) |
| Blue-green infrastructure - Detention ponds, green roofs, infiltration basins, bioswales | Malmö, Sweden | Examined insurance claims over a 20-year period and for a single extreme event in neighborhoods with and without blue-green infrastructure | 50 to 200-yr event (2.36″-4.72″) |
| Bioretention, rain gardens, rainwater harvesting systems | Dallas, TX | Used hydrological modeling and spatial analysis to identify how GSI can reduce flooding in areas where existing drainage network is undersized, considering capacity, cost, and future climate change scenarios. | models run for 2-, 10-, and 100-year, 24-hour storms. |
| Rain gardens, rain barrels | Cincinnati, OH | Monitored stream discharge and precipitation data for 3 years before and after implementation of stormwater control measures at a sub catchment scale. The GSI for flood control included 85 rain gardens and 175 rain barrels installed on private properties. | Monitored across range of storm events |
| Green roofs and permeable pavement | Genoa, Italy | Analyzed effect of GSI in restoring natural flow regimes at urban catchment scale under different land use conversion scenarios. | 2-, 5-, and 10-yr event |
| Infiltration, permeable pavement, bioretention, undisturbed cover | New Market, NH | Examined downstream hydrologic performance in extreme events under GSI and conventional buildout scenarios. Land use conditions were modeled for historic, current, and future climate change scenarios. | 100-year, 24 hr (8.5″) |

|  | Scale | Results |  |
|---|---|---|---|
|  | Site-scale | Rain gardens designed to manage a 1.65" storm were capable of treating the volume from a 5" event. | Albright (2021)[24] |
|  | Site- scale/ localized flooding | Up to ~ 0.8-inch rainfall event, the green street produced less runoff than the gray street. Peak runoff from green street was less than the gray street for all events except the most infrequent, extreme events. | Woznicki et al. (2018)[25] |
|  | Small catchment/ localized flooding | All three systems would eliminate flooding from 3-month, 24-hour event. Permeable pavement was the most effective in reducing flooding from 10-year, 2-hour storm. Full implementation, permeable pavement (four feet of storage depth) would reduce flooding by 87% compared to baseline. | U.S. EPA (2014)[26] |
|  | Neighborhood/ localized flooding | Flood magnitude was less than 1/10th in area with blue-green infrastructure compared to surrounding neighborhoods with conventional sewer system. Blue-green infrastructure effectively reduces flood risk but greening surfaces have a limited effect during extreme events. | Sörensen & Emilsson (2019)[27] |
|  | Catchment scale/localized flooding | If GSI were deployed in all identified opportunity areas, inlet overflows would be reduced by 31%, 25%, and 17% under 2, 10, and 100- yr storms. For 100-yr storm, GSI was 77% less costly than gray alternative. A combined green/gray alternative managed more stormwater under 100-yr conditions and at a lower per gallon cost than for gray alone. | TNC (2022)[28] |
|  | Urban sub catchment | Results showed small but significant correlation between precipitation and discharge compared to control catchments, indicating that parcel-level green infrastructure added detention capacity to treatment basins, decreasing otherwise uncontrolled runoff. Additional retrofits could accrue proportionally greater reduction in stormwater runoff volume. | Shuster and Rhea (2012)[29] |
|  | Urban catchment | Modeling results confirmed effectiveness of GSI for 10-yr. event. Effective Impervious Area reduction (EIA) of 5%, is required to obtain noticeable hydrologic benefits. Hydrologic performance linearly increases with increasing the EIA reduction percentages. At 36% EIA reduction (corresponding to the whole conversion of rooftops and parking lot areas), peak and volume reductions rise until 0.45 and 0.23. | Palla and Gnecco (2015)[30] |
|  | Watershed/ subwatershed | In highly developed subwatersheds, GSI had substantial impact and in one instance reduced runoff beyond current conditions. Conventional build-out had increases in runoff ranging from 29-36% relative to baseline. GSI build-out had increases from -2-7%. | Scholz (2011)[31] |

**Table 1. (continued)** Summary of recent studies on the effectiveness of GSI for flood risk reduction

| GSI Practice | Location | Description | Storm Size |
|---|---|---|---|
| Recharge chambers, infiltration trenches, trees | Montgomery County, MD | Compared two treatment watersheds to a reference (forested) watershed and an urban control watershed with centralized detention facilities. Comparing three treatment watersheds to a reference (forested) watershed and an urban control watershed with centralized detention facilities | Monitored across a range of storm events |
| Detention facilities and impervious area reduction | Baltimore, MD | Compared watershed responses to short periods of intense rainfall in three suburban watersheds with various amounts of impervious cover. Two watersheds drained to stormwater detention facilities, third had no stormwater controls. | 3.5" - 16.1" storms, with peak rates between 0.47 and 3.5 in/hr |
| GSI at new and redevelopment sites | 20 HUC 8 watersheds across U.S. | Modeled GSI practices in 20 sample HUC8 watersheds across the country to estimate avoided costs from GSI practices between 2020 to 2040. Practices designed to capture 85th – 90th percentile storms. | Models run for 2-, 5-, 10-, 25-, 50-, and 100-year events |
| Reduced impervious cover, wetland, daylighting 1,100 feet of stream | Dover, NH (Berry Brook watershed) | Examined effectiveness of GSI and other BMPs to control urban flooding for extreme precipitation events in 185-acre watershed. GSI BMPs reduced effective impervious area in watershed from 30% to 10%. | Modeled a range of storm depths and duration |
| Rainwater capture, green roofs, permeable paving, and enhanced storage in the upper catchment | Melbourne, Australia | Evaluated effectiveness of 12 GSI-based scenarios for reducing flooding during intense rainfall events in highly urbanized catchment. Assessed changes in peak flood depths across three watershed zones – with Zone 1 being located the furthest downstream point of the catchment, with the largest contributing area. | 5% and 1% Annual Exceedance Probability (AEP) event |
| Feasible GSI retrofits, identified through community input and land use assessments. | Silver Creek in Toledo, OH and Chester Creek in Duluth, MN | Used HEC-RAS and FEMA's Hazus-MH to model flooding and property damage under current and projected future precipitation levels under climate change. Incorporating GSI retrofits identified through community input and land use assessments. | 100-year event |

|  | Scale | Results |  |
|---|---|---|---|
|  | Watershed | Runoff yields in treatment watersheds were lower than in urban control watershed up to ~0.8". Except for the most extreme events, peak runoff magnitudes in the treatment watersheds fell between the peaks from the forested and urban control watersheds. Distributed stormwater management can replicate reference conditions in small events. | Hopkins et al. (2021)[32] |
|  | Watershed | Designed for the 2.7-inch storm, the stormwater detention basins did not significantly reduce peak runoff rates. Reduction in impervious cover has a larger impact on runoff volume than detention alone. | Miller et al. (2021)[33] |
|  | Watershed | GSI implementation can reduce floodplain area by 3%-8% in storms with a smaller than 20-year return interval.<br>GSI can be effective at reducing larger-scale flood events; this effectiveness tapers off as storm size increases. | U.S. EPA (2015)[34] |
|  | Watershed | GSI can reduce flooding caused by smaller precipitation events (less than 1.3 inches) but does not eliminate it for extreme events. Decrease in peak flows (5 to 29%), runoff depth (19% to 49%), and total flow volumes (25 to 45%) across storm events analyzed. | Hastings (2018)[35] |
|  | Watershed | For 5% AEP, GSI strategies reduced peak depths in Zone 1 by 25% to 50%. Flooding was eliminated in many Zone 2 and 3 areas. The most effective interventions were those applied across large areas of the catchment. For 1% AEP event, rainfall exceeded capture capacities; interventions led to a delay, rather than reduction, in peak runoff volume. | Webber et al. (2020)[36] |
|  | Watershed | Implementing these practices to reduce peak discharge by 10% in a 100-year storm would reduce economic damages in Silver Creek watershed by 39% under current precipitation levels and 46% under expected future precipitation. In the less developed Chester Creek watershed, GSI implementation to reduce peak discharge by 20% would reduce economic losses from a 100-year storm by 27% under current conditions and 16% under the increased rainfall levels associated with climate change. | Eastern (2014)[37] |

# 3

# Planning and Designing GSI for Flood Risk Reduction Benefits

**Credit:** Jen Guyton


VIETNAMESE KITCHEN
VIETBOWL
vietname

# PLANNING AND DESIGNING GSI FOR FLOOD RISK REDUCTION BENEFITS

GSI can be an important component of a broader, holistic approach to urban flood management if it is correctly designed and implemented. This section covers siting, design, and implementation factors that help maximize the effectiveness of GSI for flood risk reduction benefits. It also highlights equity considerations specific to flood risk reduction planning.

## 3.1 Siting considerations

Achieving flood reductions through GSI practices requires a strategic approach to project siting and design that marries information about critical vulnerabilities with information about the effectiveness of individual GSI practices. Local stormwater managers can take advantage of spatial data to identify priority locations where GSI interventions can have meaningful flood reduction and community benefits.

Flood risk reduction benefits can be maximized through a tailored review of spatial data to identify high priority areas for localized or riverine flood management. Information on sewer capacity limitations, topography, and other data in a Geographic Information System (GIS) can reveal interesting intersections between hydrology, flooding, and other assets or vulnerabilities, including identifying potentially vulnerable populations within a community (see section 3.3). Other forms of information can also be useful in identifying locations where storm-related flooding causes property damage and other impacts. For example, data and reports detailing flood damage claims, basement backups, road closures or complaints about street flooding compiled from residents and local government agencies can illuminate problem areas. CoreLogic and the Pima Association of Governments offer examples of how to use mapping information to identify GSI project opportunities (see text box on the following page.)

GIS analysis can also be used to identify spatial opportunities and constraints for GSI implementation. At the catchment or watershed scale, studies show that distributed GSI projects can be more effective in reducing downstream flood risk compared to clustered or centralized projects.[38] However, there must be enough land area to support the level of implementation necessary to improve hydrologic performance downstream.[39] The case study on the following page highlights a study led by The Nature Conservancy (TNC) that used spatial data to identify catchments where limited storm sewer system capacity causes localized flooding and to identify areas within the catchment that could accommodate different types of GSI. The researchers used US EPA's Stormwater Management Model (SWMM) to examine how different practices would reduce localized flooding across a range of storm events.

As in the TNC Dallas example, a mapping analysis to identify opportunities for GSI deployment should not be constrained to public property. Private property can be an essential part of the solution to achieve the necessary scale of GSI implementation and/or provide connectivity across flood management infrastructure. In many cases, private property interventions can also be more cost-effective than projects in the public right-of-way.[40] Several municipalities have successfully incentivized private property owners to implement GSI or have directly installed projects on private land. The District of Columbia Department of Energy and Environment's (DOEE) RiverSmart Program is just one example of a successful GSI incentive program. In the past, DOEE has targeted groups of property owners to participate in the program who are located upstream of stream restoration or larger-scale stormwater capture projects to protect the downstream investment.[41] Stormwater agencies may also be able to collaborate with local transportation or other government agencies to implement GSI retrofits on public parcels or into planned roadway improvements.

Finally, when developing a watershed or catchment scale flood reduction strategy, care should be given to examine the potential for interconnection between GSI practices and complementary local "gray" infrastructure, as well as to what many refer to as "blue" infrastructure - the watercourses, ponds, wetlands, and detention basins that exist within drainage networks.[42] Research indicates that when many relatively small GSI installations are interconnected (e.g., through green corridors or with gray infrastructure buried underground) and designed to operate synergistically as a stormwater treatment train, they can be more effective than a single centralized asset.[43] Some even report that uncoordinated placement of GSI systems can cause hydrographs to compile, actually contributing to larger downstream flows.

### Practice Spotlight – Tools for Mapping Flood Vulnerabilities

CoreLogic, a data analytic provider, modeled flood impacts using local hydrology, meteorology, and flood-related environmental conditions to Chicago neighborhoods to determine a Flash Flood Risk Score at a parcel scale, indicating a range of potential risk to flood damage. This type of analysis can highlight neighborhoods, or parcel clusters, at high risk from storm-associated flooding.

In Arizona, the Pima Association of Governments and the Pima County Regional Flood Control District hosts an interactive mapping tool that helps local residents, developers, and planners evaluate the connections between community vulnerabilities, resources, and stormwater GSI opportunities. Notably, the tool incorporates stormwater flowlines that can inform decisions about placing GSI and other stormwater management techniques.

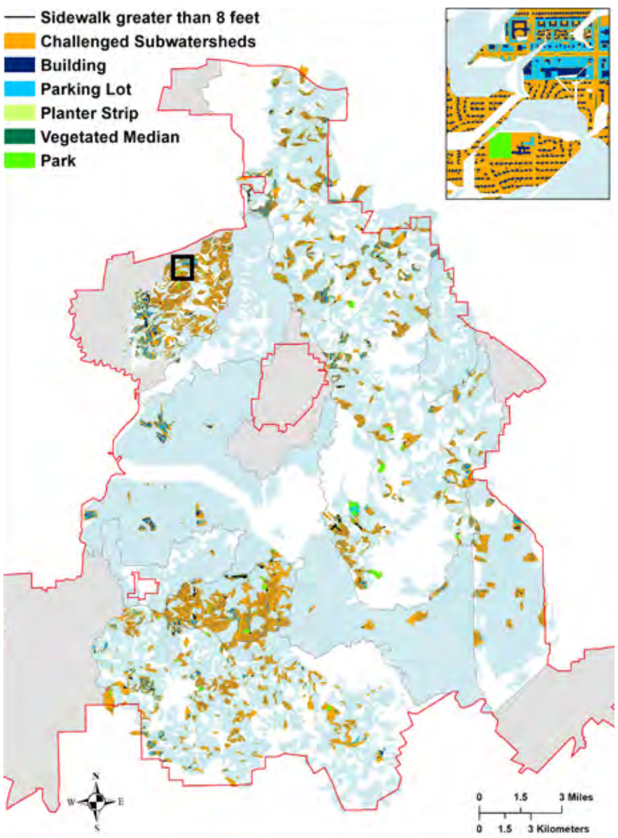
Spatial data on infrastructure, environment, and social characteristics can be used to guide city-or watershed-scale multisystem flood management for actively managing connections between infrastructure systems to convey, divert, and store flood water.[44,45]

## 3.2 Additional design and implementation considerations

The spatial analyses and considerations suggested in the previous section reflect a strategic level of GSI flood intervention planning. Additional design and implementation considerations can optimize flood risk reduction benefits at the site or network scale. This level can overlap with a more detailed consideration of optimal GSI practices for a given setting.

Challenged watersheds (all levels of severity) and GSI opportunities (based on land use and other spatial constraints), Dallas, TX.

## Using Spatial Analysis and Modeling to Identify Sewer System Hotspots and Opportunities for GSI in Dallas, TX



This study used hydrological modeling and spatial analysis to identify where and to what extent GSI can enhance urban flood management within the city of Dallas, Texas, considering existing sewer capacity, cost, and future impacts of climate change. The focus was on enhancing flood management where the existing drainage network is limited – so called "hotspots" where the drainage network is undersized and contributes to inlet overflows and areal flooding under a variety of precipitation events. Models were run for the 2-, 10-, and 100-year 24-hour storms, for current conditions and forecasted climate change scenarios for 2045.

The challenged watersheds contributing to system hotspots were spatially evaluated for opportunities to deploy bioretention, cisterns, and rain gardens. Costs were estimated for the maximum implementation scenario of these practices, for each of the selected current conditions storms. These figures were compared between gray and green infrastructure for the 100-year design storm.

Models indicate that larger amounts of precipitation will lead to more, and more severe, system hotspots and contributing subwatersheds. Substantial cost-effective opportunity was identified to deploy GSI for improved stormwater management within the study area. If GSI were deployed in all identified opportunity areas approximately 31%, 25%, and 17% of overflows resulting from the 2, 10, and 100- year storms, respectively, could be managed at an average cost of approximately $2.40/gallon. When compared to the capacity and costs for upgrading gray infrastructure for the 100-year design storm, GSI was approximately 77% less costly. However, a combined green/gray alternative managed more stormwater leading to a 45.1% reduction in modeled overflows for the 100-year design storm, and at a lower per gallon cost than for gray alone.

Note: White areas have limited sewer network data available. Gray areas have substantial land outside city.

Source: Jack (2022).

As shown in Table 2, at the watershed or catchment scale, the effectiveness of different practices can depend on the hydrological zone in which they are located. Capturing and retaining stormwater in the upper contributing zone of a watershed – the area farthest from the point of collection – can help to prevent flooding lower in the watershed by reducing runoff volumes closer to their sources. The collection zone is in the middle of the watershed. In this zone, flooding problems are generally greater as groundwater saturation may occur and rainfall begins to pool as stormwater is collected and infiltrated. This area is generally a good location for small-scale stormwater management installations for both water quality and water quantity purposes. In a watershed's lower conveyance zone, reducing water volume using GSI can be more difficult because of the rapid runoff flowrate and likelihood that the water table is closer to the surface.[46]

Placement also matters at the block-level or within a small catchment. An analysis of GSI in an area of Chicago draining to a combined system found that clustering GSI upstream or downstream reduces its effectiveness in routing runoff away from the sewer system for both small and large storms, while spreading it out in the landscape increases exposure, storage, and infiltration. Further, GSI located adjacent to roads (curb cuts) showed an advantage over other dispersed patterns by greatly reducing neighborhood flooding (again, for both small and large storms). This is true particularly when there are few locations available to install GSI. As opportunities for adding GSI increase—and as storm severity increases—a hybrid approach that incorporates dispersed GSI installations upstream and a layout of curb cuts can be more effective.[47]

The scale of GSI implementation is also a key consideration. As evidenced throughout this guide, GSI alone cannot address all scales of urban flood risk management but should be considered as part of a wider system that integrates across spatial scales. At catchment or watershed scale, increased GSI coverage generally increases flood risk reduction benefits. However, at some level, the marginal benefits of GSI will begin to diminish. Understanding the cost-effective "tipping point" of GSI can help determine the appropriate balance of GSI for managing different storm sizes.

**Table 2.** Guidelines for GSI system selection based on location within the watershed or sub-watershed

| | Location in the Watershed | | |
|---|---|---|---|
| GSI Practice | Contributing Zone (Upper) | Collecting Zone (Middle) | Conveyance Zone (Lower) |
| Retention basins | ** | ** | - |
| Rainwater harvesting | ** | ** | - |
| Constructed wetlands | * | * | * |
| Detention basins | ** | ** | - |
| Bioswales | - | ** | * |
| Rain gardens | - | ** | ** |
| Green roofs | - | ** | * |
| Permeable pavement | ** | ** | ** |

**Key:** ** Very appropriate * Moderately appropriate - Mildly or not appropriate

Source: McFarland 2019

Project rendering cross section (left) and GSI on Oakman Blvd. during 2021 flood (right)

**Credit:** Detroit Water and Sewerage Department
Oakman Boulevard Project Overview (2020)

## Managing Localized Flooding at the Block-Level, Oakman Boulevard, Detroit, Michigan

In 2014, 4 inches of rain fell in 9 hours, flooding 56% of the basements in the Aviation subdivision in Detroit, Michigan. Responding to this event, the Detroit Water and Sewerage Department (DWSD) implemented the Oakman Boulevard GSI Program. The $6.8 million project aimed to provide stormwater volume reduction for small storms, detention for large storms, and rerouting of stormwater away from small pipes to protect basements during flooding events. Implemented at the neighborhood scale, the project included bioretention on 10 surface medians over 0.8 miles. Flow reroutes to subsurface infiltration galleries were included in 8 of those medians, with a total storage capacity of 1.75 million gallons. The project was designed for a 10-year, 24-hour storm, or approximately 3.31 inches of rainfall, with a peak flow of 1.67 inches per hour. The project was completed in November 2020, redirecting 63 acres of stormwater runoff, reducing surcharging associated with limited sewer capacity, which is the most common cause of basement backups in this area.

Less than a year later, Detroit experienced two significant rainfall events within a month. In June 2021, the Aviation neighborhood received 8.24 inches of rain over a 3-hour period with a peak intensity of 3.5 inches per hour. The following month, the neighborhood experienced another significant event with 3.8 inches of rain over a 7-hour period and a peak flow of 1.98 inches per hour. During the first large storm event, basement backups were extensive. During the following smaller storm event, street flooding occurred during peak flows, but basement backups were much less frequent than previously experienced.

Because basements still flooded after the project, many residents felt that the project had failed. However, the storms Detroit experienced in 2021 were significantly larger than what the project was designed for. Also, the project engineers speculate that part of the flooding was due to backups in the CSO system downstream. While it is impossible to know what would have happened had the GSI project not been installed, DWSD feels strongly that the flooding would have been significantly worse if the GSI installation was not in place.

Thinking about lessons learned, DWSD representatives shared that it is important to “clean and inspect all sewer assets in the project area during the planning and design phase.” They also emphasized the importance of resident education, communicating the benefits conveyed by a project without over-promising results, and helping residents understand what they need to do on their own properties to help reduce flooding.

Sources: Mobley, et al. (2021); Water Environment Federation (2022).

Several municipalities have used established stormwater models (e.g., U.S. EPA SWMM) to examine the cost effectiveness of green, gray, and hybrid solutions.

At the site level, projects that take advantage of large storage areas can effectively manage larger storm events (see case study on Detroit's Oakman Boulevard project). NYC DEP's cloudburst management approach also uses natural and designed landscape elements (e.g., open green spaces, playing fields, basketball courts), that are designed to turn "blue" during rainfall events to fulfill their flood risk management function.[48]

The appropriate scale of GSI implementation for enhancing flood resilience may also consider the principle of "designing for exceedance,"[49] or accepting that an area should have an acceptable level of flood protection but should be designed to safely fail when this capacity is surpassed. GSI failures are often less catastrophic when compared with gray infrastructure failures, and some levels of protection are still offered even when the design level of flood protection is exceeded, which is often not the case for gray infrastructure as it is seldom designed to be "safe-to-fail."[50]

Finally, GSI implementation for flood risk reduction should be integrated into an adaptive management framework. GSI can provide incremental benefits in the face of uncertainty surrounding future climate, extreme events, and level of urbanization. Continuous evaluation will highlight where incremental investment in infrastructure can effectively meet performance requirements and remain cost-effective. Careful monitoring of GSI practices also provides useful insights. For example, a researcher in Philadelphia learned that some retention practices deliver performance that greatly exceed design specifications. Their study of rain garden performance revealed that rain gardens designed to manage a 1.65" storm were, in fact, capable of treating the volume from a 5" event." While these results are likely not universal, they do suggest that careful monitoring of actual performance can provide important insights on the implementation of GSI for flood risk reduction benefits.

## 3.3 **Equity considerations for flood risk reduction**

Across the U.S., localized and riverine flooding disproportionately affect communities of color and low-income residents.[51] Underserved communities experience more frequent flood events, leading to disproportionate disruptions and economic impacts, particularly for vulnerable communities where residents may not have the level of resources necessary to manage these effects.[52] Understanding the distribution of flooding impacts through mapping can guide investment in GSI strategies that redress this imbalance. Going a step further with this information, local planning efforts can incorporate equity goals to make long-term commitments to GSI and other strategies that reduce disparities in flood and water quality impacts.

Socioeconomic data from the U.S. Census American Community Survey (available at the Census tract level) can be used to identify potentially vulnerable populations, based on variables such as income and poverty rates, age, race and ethnicity, and home ownership, among others. U.S. EPA (EPA)'s EJScreen or similar tools

### Practice Spotlight – Mapping Flood Equity in Chicago

The Center for Neighborhood Technology (CNT) in Chicago examined ten years of insurance payments for flood damage and documented neighborhood-scale impacts associated with localized flooding. Notably, this analysis revealed that neighborhoods with higher levels of poverty and lower income face disproportionate frequency and severity of localized flooding. An interactive map created by CNT is an example of the usefulness of mapping in understanding the human and economic impacts of stormwater-related floods.

Sources: CNT (2014)

**Credit:** Fauna Creative

also provide socioeconomic indicators that allow for the evaluation of impacts across communities. As noted by the EPA, "EJScreen uses maps and reports to present three kinds of information: Environmental indicators, socioeconomic indicators and EJ/supplemental indexes. The EJ and supplemental indexes summarize how an environmental indicator and socioeconomic factors come together in the same location."[53]

Socioeconomic data and information on vulnerable populations should be incorporated into project prioritization criteria. Seattle Public Utilities (SPU) serves as a model for ensuring equity objectives. The agency has developed a multi-objective decision analysis (MODA) framework for reviewing alternative stormwater/infrastructure projects. The purpose of MODA is to evaluate and rank how individual projects contribute to key SPU performance categories. The MODA includes values associated with providing benefits to historically underserved neighborhoods and protecting against potential displacement impacts in these neighborhoods. The case study on the following page provides another example of prioritizing projects that provide benefits to the most vulnerable communities, rather than selecting areas with the highest volumes of flooding or the highest volume of resident complaints. For this project, researchers worked with the City of Tucson, AZ to evaluate the effect of flooding on multi-modal transportation systems in low-income and minority neighborhoods. This project advances national research methods for assessing flood vulnerability and prioritizing transportation improvement investments to ensure that no community is left stranded when the next flood occurs.[54]

## Equity Guide for GSI Practitioners

For more information on incorporating equity considerations into GSI planning, see the Green Infrastructure Leadership Exchange's Equity Guide for Green Stormwater Infrastructure Practitioners.

# Using GSI to Advance Transportation Equity in Tucson, Arizona

Researchers at the University of Arizona, in partnership with the National Institute for Transportation and Communities, Pima County Flood Control and Tucson Water conducted a vulnerability assessment to identify areas within Tucson where GSI strategies could help to reduce flooding across city's multi-modal transportation system in low-income and minority neighborhoods. Researchers intentionally focused on low-income neighborhoods, since too often people living in those areas are hardest hit by the impacts of natural disasters. This research consisted of the following components:

1. **Estimate flood conditions in low-income neighborhoods:** Researchers used modeling to estimate flood conditions for a 5-year, 1-hour storm event.
2. **Identify multimodal transportation priorities:** The team analyzed transportation system performance in flood conditions across three modes (driving, bicycling and transit). For each mode, flood data was cross referenced with 10 years of vehicular counts, bicycle counts, and bus stop ridership to identify ten priority locations for flood mitigation.
3. **Analyze GSI scenarios:** Researchers modeled GSI scenarios at the top ten sites for each transportation mode to evaluate the change in transportation network accessibility under the same flood conditions.
4. **Identify priority locations:** Finally, the team identified priority areas for mitigating transportation system flooding and are now working with city and regional agencies to implement findings.

A key finding of this study is that building comprehensive neighborhood-scale GSI in the right-of-way is effective in moderate flooding conditions. Rather than selecting areas with the highest volumes of flooding or the highest volume of resident complaints, funds for GSI should be invested in low-income neighborhoods subject to moderate flooding to achieve the most improvement of multimodal access.

# 4

# Quantifying and Monetizing Flood Risk Reduction Benefits

**Credit:** Julia Rendleman


ROANOKE MARSHES
BREWERY

# QUANTIFYING AND MONETIZING FLOOD RISK REDUCTION BENEFITS

Estimating the value of flood risk reduction benefits associated with GSI can help make the case for specific interventions or a watershed-scale plan, leverage additional funding sources, and/or track performance post-construction.

Traditional approaches for quantifying flood reduction benefits involve estimating avoided damages to buildings and infrastructure resulting from flood risk reduction projects. In some cases, these methods also capture avoided socioeconomic impacts and related expenses such as cleanup costs, lost workdays, and avoided deaths associated with large flood events. These approaches are typically applied to larger-scale riverine flooding and are not necessarily appropriate for the type of localized flooding that GSI often targets. This section provides an overview of several different methodologies for quantifying and monetizing the flood risk reduction benefits associated with GSI, from the watershed scale to the site level.

## 4.1 Avoided flood damage estimates

Federal agencies and others have developed well-established methods and tools for assessing avoided flood damages to capital assets. These approaches are generally applied to riverine flooding and involve estimating the amount of flood losses that will be avoided over the life of a flood risk reduction project or suite of investments. Depending on the extent and severity of the flooding event, avoided damages may include structural damages to buildings, loss of building contents, damages to infrastructure or critical facilities, loss of wages and profits to businesses, emergency response costs, displacement, injury or loss of life, and post-flood cleanup costs (Figure 2). To calculate avoided damages, practitioners must estimate flood damages with and without project implementation. Key steps include:

**Define and inventory the area over which flooding will be mitigated.** A floodplain inventory is needed to determine zero-damage elevations (the depth of flooding at which no damages occur), as well as the types of buildings and other assets at risk. Key data requirements include size, population, property type, property values, and structure characteristics within the management area. This does not have to involve an extensive study - the US Army Corps of Engineers (USACE) developed and maintains the National Structure Inventory (NSI), a repository of structure point data containing building-level attributes in a GIS base layer that can be used for this purpose.

**Figure 2.** Metrics used to value the avoided costs of flood risk mitigation projects.

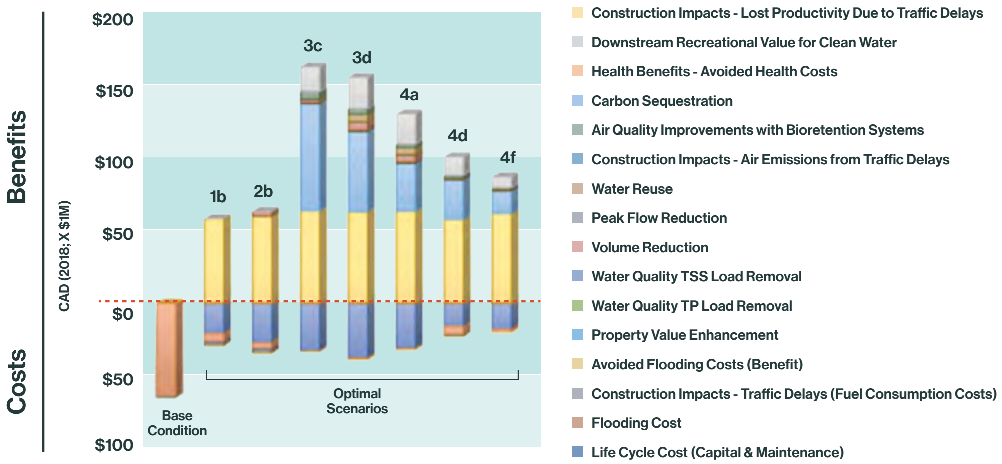
| Benefit Category | Quantification Unit |
|---|---|
| Avoided damages to property | Cost of replacement or property value per square foot |
| Avoided loss of function of critical facilities | Impacts to hospitals, schools, and emergency centers |
| Avoided loss of utilities | Cost of providing generators, potable water, heat, etc. to residence for the duration of the outage |
| Avoided displacement | Lodging and meals for residents displaced |
| Avoided agricultural crop loss | Value of agricultural crops per acre |
| Avoided debris clean up | Cost of debris removal per ton |
| Avoided loss of life | U.S. EPA value of statistical life estimate |
| Avoided emergency management | Costs of volunteers, costs to city officials |

**Conduct hydrologic and hydraulic modeling:** The next step is to understand how flood depths will change spatially with and without the proposed flood risk mitigation measures. This requires a rainfall-runoff (hydrologic) model to route rainfall over the landscape. A hydraulic model is also needed to understand the performance of the stormwater and wastewater system during rain events. This combined hydrologic-hydraulic (H&H) modeling result in flood depths across a flood zone for different flood events (ideally under current and future climate change scenarios). H&H modeling will also guide where to locate GSI (see Section 3), and given different design elements of the BMPs, modeling will dictate the reduction in flooding under different infrastructure scenarios.

**Estimating damages with and without project:** Depth-to-damage functions (DDFs) are then used to translate the depth of flooding into physical damages, given the existing stock of buildings and their general classification (e.g., residential, commercial, industrial classification codes), as well as nonphysical damages (e.g., emergency response, displacement, flood cleanup costs). The range of storm event return periods and their expected damage amounts can then be used to calculate an equal annual expected amount of damage across all storm event types. This process accounts for the probability of occurrence of different flood events. Damages will need to be estimated for the H&H modeling both pre- and post-project implementation. Damage estimates can be conducted using tools developed by USACE or FEMA that provide standardized relationships for estimating flood damages and other costs of flooding based on actual losses from flood events that have occurred across the U.S.[55] Examples include FEMA's HAZUS, FAST, and BCA tools, as well as the HEC-FIA tool, which was developed by USACE.

As exemplified by the range of studies included in this guide, GSI distributed across a watershed or catchment can improve downstream hydrologic conditions, particularly by reducing peak flows, thereby reducing associated flood damages. In 2015, U.S. EPA conducted a national study using 20 watersheds in the United States to examine the effect of GSI on avoiding flood damages as applied to new development or redevelopment.[56] Examining avoided flood damages from 2020 to 2040, the study estimated flood depths with and without GSI and determined the value of avoided flood damages using the building inventory approach. The study modeled three retention scenarios – the 85th, 90th and 95th percentile storm, but concentrated on the 'medium' scenario of retaining the 90th percentile storm. The analysis was applied at the HUC8 watershed level in each location, and GSI was applied to the urban development areas in that HUC8.

Triple bottom line cost-benefit comparison of gray, green and hybrid flood management scenarios



## Analyzing Avoided Damage Costs Across Alternatives to Reduce Localized Flooding and Basement Backups in Calgary, Alberta

In 2018, Calgary conducted a pilot study in the Renfrew neighborhood, a residential neighborhood experiencing redevelopment that is projected to have 60% impervious area by 2076. Renfrew already experiences significant localized flooding and basement backups, and as impervious area increases, these challenges are expected to increase. Additionally, the stormwater flowing into the neighboring Nose Creek shows increasing discharges of suspended sediments and phosphorus. Renfrew underwent an integrated stormwater management planning process to attempt to target these issues while continuing to grow sustainably.

The planning process included modeling of future infrastructure under increasing storm sizes to identify the most cost-effective solution to reducing flooding. Infrastructure was modeled to manage a 50-year 4-hour storm, and results were optimized for the most cost-effective improvements. The stormwater management infrastructure considered included: rainwater harvesting, right of way bioretention, community stormwater capture and irrigation, as well as gray infrastructure (upsized pipes, inlet control devices, community underground detention). Decision makers looked at financial, social, and environmental, or triple bottom line, benefits of 14 different scenarios, each involving a different mix of grey and/or green practices. Generally, scenarios in group 1 and 2 contained more gray practices, group 3 were primarily GSI, and group 4 represent a mix of gray and green. The costs and benefits were compared with the baseline conditions, which represent the flood damage costs. The optimal scenarios are shown in the image below, with each block above the dotted line representing a benefit and the blocks below the line representing costs. Under all modeled scenarios, flood damages are significantly reduced. The cost-benefit ratio was highest in scenario 3c, but if budgets are constrained, option 4f provided similar flood risk reduction benefits for less cost with additional co-benefits.

Source: S. Struck (2019).

**Credit:** Green Infrastructure Leadership Exchange

## Equity Considerations for Avoided Flood Damage Estimates

Traditionally, projects with higher benefit cost ratios have generally been deemed to be more economically efficient. When property values are higher, or properties have seen greater investment by owners, the benefit of avoiding damages in areas with these high-value properties is greater. Consequentially, if practitioners are comparing the benefits of a flood mitigation project in two locations, the resulting BCA would show lower benefits in low-income communities. Without considerations for equity, this could lead to increased mitigation in wealthier areas and undervalue the risks associated with damages in disadvantaged communities.

Researchers have sought to address this dilemma by estimating equity-weighted utility functions for avoided damages that demonstrate increased benefits of restoration interventions in low-income areas. Local authorities have addressed equity in policies surrounding flood management, as well. Mecklenburg County in North Carolina developed a prioritization framework for a floodplain buyout program that weights equity considerations in purchasing homes and buildings located in flood risk areas. On a larger scale, advocates for equitable funding argue that BCA criteria should be revised and broadened beyond property values to accommodate social and environmental benefits.

Across the modeled locations, the estimated reduction in floodplain area was up to 8% for the 2-year event, whereas the maximum floodplain reduction was 2.5% for the 100-year event. The study developed regression models to extrapolate the study's findings to other watersheds that were not modeled. Results of this analysis indicated that the national annual avoided flood damage in the year 2040 from installation of GSI at new and redevelopment sites would amount to $328 million under the 5-year zero damage threshold (2011 dollars). This total only reflects benefits for cities in the country that did not already have retention standards in place at the time of the study.

For this guide, and the block-level tool that accompanies it, the project team used the FEMA Hazus model (with data from 2020) and adapted EPA's regression models to estimate flood damage benefits associated with distributed GSI implementation (retrofits) in HUC 8 watersheds for several cities in different regions across the U.S.

## 4.2 Alternative approaches to valuing flood risk reduction

Generating an estimate of the flood loss avoidance benefits associated with projects that mitigate localized flooding is difficult because data does not exist on damages from small, frequent storm events. The types of flooding targeted by GSI also does not always result in the types of damages captured in the models mentioned above (i.e., impacts associated with nuisance flooding). Economists have developed alternative approaches for valuing flood risk reduction benefits, including:

- **Willingness to Pay:** Researchers have used contingent valuation surveys to estimate the willingness-to-pay (WTP) of households to avoid street flooding, basement flooding, or basement backups. As demonstrated in Table 3, household WTP to avoid or reduce flooding ranges from $50 - $88 per year. While individual household WTP might seem low, aggregating over time and across households can reveal substantial value.

- **Hedonic Pricing:** Hedonic pricing methods can be used to investigate the effect that location within the floodplain has on housing prices. Most of these studies estimate the impact on residential home prices of locations inside or outside of the 100-year floodplain. These studies have found that the value of homes within the 100-year floodplain are 2% to 8% lower than equivalent homes outside the floodplain.[57] This approach has been used to examine the benefits of flood risk mitigation projects across a range of flood event types.
- **Avoided gray infrastructure costs:** An additional method for valuing flood mitigation benefits is to estimate the avoided costs of upgrading existing gray infrastructure and/or providing equivalent flood risk reduction services using conventional approaches. Several municipalities have found much more cost-effective solutions to flood risk reduction using GSI or hybrid green-gray approaches compared to gray infrastructure alone. In addition, GSI can capture incremental stormwater (e.g., such as associated with increased rainfall depths associated with climate change), reducing the burden on outdated stormwater systems with limited capacity.[58] This can avoid costly sewer system upgrades.

**Table 3.** Summary of findings from flood risk reduction valuation studies

| Evaluation Method | Location | Findings (2022 USD) | Source |
|---|---|---|---|
| Willingness to Pay | Champaign-Urbana, Illinois | Residents willing to pay $50/year to reduce basement flooding by 50% | Cadavid and Ando (2013)[59] |
| Hedonic Pricing | Meta-analysis of studies across U.S. cities | On-site retention to mitigate flooding increases property values by 2-5% for all properties in the flood plain | Braden and Johnston (2004)[60] |
| Hedonic Pricing | Analysis of studies across U.S. cities | Home prices within a 100-year flood plain are discounted 2-8% compared with those outside the flood plain | CNT (2010)[61] |
| Hedonic Pricing | New York City, NY | Properties within flood zone caused by Hurricane Sandy sell for up to 8% less than homes outside flood damages | Ortega and Taspinar (2018)[62] |
| Avoided costs of gray infrastructure at new and redevelopment sites | National | Average capital cost for stormwater management of $3 per square foot of impervious area managed. Represents the stormwater management allowance cost from RS Means for a typical gray infrastructure scenario, "absent further information" or specific cost detail. | R.S. Means estimate, (WRF 2021) |
| Avoided costs of gray infrastructure upgrades | Dallas, TX | GSI was found to be 77% less costly than upgrading gray infrastructure alone to meet modeled overflows | TNC (2022)[63] |
| Avoided costs of flood insurance payouts | Cook County, IL | Average payout per urban flood insurance claim for basement backups was $5,281 | CNT (2014)[64] |

# 5

# Funding, Financing, and Partnership Opportunities

**Credit:** Matthew McDaniel

# FUNDING, FINANCING, AND PARTNERSHIP OPPORTUNITIES

Designing GSI projects with flood mitigation benefits in mind can open additional funding and partnership opportunities. This section provides a snapshot of some options available at the federal, state, and local levels, as well as some private financing and potential partnerships to explore.

## 5.1 Accessing public grant opportunities

Federal and state agencies sponsor a range of grant programs which fund floodplain restoration and flood risk reduction projects. These sources of support are likely to be very familiar to regional flood control districts and other flood management agencies. Overlapping interests between municipal stormwater managers and flood management agencies may open opportunities for collaboration to identify available grants, plan relevant GSI projects, and navigate the grant proposal process. This type of collaboration may result in 'whole watershed' scale interventions which compete well in the crowded pool of grant applications.

Table 4 identifies some federal grant programs that may be supportive of GSI projects. The American Flood Coalition hosts a web-based discovery tool that provides information about federal funding programs.

## 5.2 Community Rating System with National Flood Insurance Program (NFIP)

While not a direct funding program, FEMA also administers the Community Rating System incentive program which rewards voluntary flood risk mitigation activities with reductions in NFIP premium levels. Through the program, flood insurance premium rates can be discounted from 5% to 45% based upon the implementation of local government programs or projects that:

1. Reduce and avoid flood damage to insurable property
2. Strengthen and support the insurance aspects of the National Flood Insurance Program
3. Foster comprehensive floodplain management

The FEMA published guide CRS Credit for Stormwater Management provides details for local governments, indicating the stormwater management measures that can qualify as activities that increase a community's Rating score. Among the eligible activities is the adoption of local stormwater management standards that require GSI (or, in the terminology of the guide, Low Impact Development / LID).

**Table 4.** Federal Grant Programs that may support funding for GSI projects

| Funding Agency | Grant Program | Eligibility | Notes |
|---|---|---|---|
| Federal Emergency Management Agency (FEMA) | Flood Mitigation Assistance Funds (FMA) | Projects that reduce or eliminate the risk of repetitive flood damage to buildings insured by the National Flood Insurance Program. Eligible activities include: Project Scoping, Technical Assistance, Community Flood, Mitigation Projects, Individual Structure/ Property-Level Flood Mitigation Projects, Management Costs | Projects must be located in NFIP communities; 25% non-federal match required for most projects. Program is typically passed through to states which then administer applications and awards. |
| FEMA | Hazard Mitigation Assistance Grant Program (HMA) | Provides funding to state, local, tribal and territorial governments so they can develop hazard mitigation plans and rebuild in a way that reduces, or mitigates, future disaster losses in their communities. | Can be used to develop or adopt hazard mitigation plans; acquisition of hazard prone homes and businesses; drainage improvement projects to reduce flooding (flood risk reduction projects), and more. |
| FEMA | Pre-Disaster Mitigation Program (PDM) | Funding to plan for and implement sustainable cost-effective measures designed to reduce the risk to individuals and property from future natural hazards | Administered by State Hazard Mitigation Offices. |
| FEMA | Building Resilient Infrastucture and Communities Program | Projects designed to increase resilience and public safety, reduce injuries and loss of life, and reduce damage to property, critical services, facilities, and infrastructure from flooding. | Provides funding for public infrastructure projects and mitigation efforts that bolster a community's flood resilience before a disaster strikes. Non-federal match required |
| Department of Agriculture | Watershed and Flood Prevention Program | Financial and technical assistance for erosion and sediment control; watershed protection; flood prevention; water quality improvements; water management; fish and wildlife habitat enhancement; hydropower sources; and efforts related to rural, municipal and industrial water supplies | Federal-state-local cooperative efforts to mitigate erosion, floodwater, and sediment damage, as well as to further watershed conservation |
| National Fish and Wildlife Foundation | National Coastal Resilience Fund | Planning, design, or implementation of projects that reduce regional threats due to changes in sea and Great Lakes levels; storm surge, ocean surge, and tsunamis; or increased flooding due to storms, subsidence, and erosion | Eligible entities include: local and municipal communities, nonprofit 501c3 organizations, educational institutions, state and territorial government agencies and Tribal governments. 50% non-federal match required |
| U.S. Army Corps of Engineers Floodplain Management Services | Interagency Nonstructural Flood Risk Management | Funds USACE technical engineering or planning services to local, county, state, tribal, or other partners | |
| Department of Housing and Urban Development | Community Development Block Grant - Disaster Recovery | Flood-related activities include open space acquisition; construction, repair, replacement, or relocation of public facilities; and improvements, such as dams or levees | Funded through HUD and administered by state agencies. |

## 5.3 Innovative approaches to funding natural flood mitigation infrastructure

While public agency grants are a well-trodden path for many stormwater and flood control agencies, they have significant constraints and limitations. Other approaches that can leverage grants and local revenue sources may provide attractive options for project funding and implementation. For example, the City of Evanston, Illinois requires that developers seeking TIF funding either obtain a LEED Silver rating or implement a prescribed number of "Sustainable Building Measures" including advanced stormwater reduction, retention, and treatment measures. A second pathway is for the local municipal government to use TIF revenues to directly install GSI and other flood mitigation measures. The City of Milwaukee, for example, used TIF revenues and grant funding to construct the 45-acre Menomonee Valley Stormwater Park. The entire development is a single, unified stormwater system that utilizes permeable surfaces, constructed wetland areas, and natural vegetation to reduce stormwater pollutants and volumes. These stormwater management features are integrated into active and passive recreational opportunities (ball fields and river access) including two miles of trails and connections to broader trail networks, parks and neighborhoods.

### Practice Spotlight

Floodplains by Design, an innovative, multi-partner collaboration in Washington State, is pioneering this emerging approach to floodplain management.

**Credit:** Marlin Greene/One Earth Images

### 5.3.1 Public-Private Partnerships (P3s)

For municipalities or local governments that have a steady source of repayment revenue, such as a stormwater fee or flood assessment, public-private partnerships can offer a cost-effective, risk-limited approach to installing and implementing GSI and other flood risk reduction practices. Prince George's County, Maryland has entered into an innovative "community-based public private partnership" that has successfully blended the design, implementation, and maintenance of GSI and stream restoration projects with obligatory community investments. Enacted as the Clean Water Partnership, by 2022 this project had managed runoff from over 5,300 impervious acres at a cost of approximately $239 million while exceeding local job training, creation, and business involvement goals.

### 5.3.2 Tax Increment Financing

Many municipalities around the country utilize some form of tax increment financing (TIF) to support public and private redevelopment projects and associated infrastructure improvements. Because property tax payers are the ultimate source of revenue for TIF programs, there can be considerable social and political support for using TIF to deploy multi-benefit infrastructure, including GSI. While the statutes that authorize TIF programs differ from state to state, generally two approaches to utilizing TIF to support GSI are possible. First, eligibility and/or scoring criteria for applicants seeking TIF funding support for projects should prioritize the inclusion of GSI and other community resilience measures. Second, TIF funding can be used directly by the TIF agency to construct GSI projects that comport with TIF's purposes.

### 5.3.3 Community and private foundations

Private and corporate philanthropic foundations are poorly understood and utilized by many public agencies. This is regrettable, as many foundations have long and deep track records of investing in community resilience projects, usually through local non-profit organizations. One pathway to accessing foundation support is through partnering with community-based and watershed organizations to develop and implement GSI and waterway restoration projects. The collaboration with these entities can have its own rewards, including in-kind or financial match for projects and community engagement.

### 5.3.4 Environmental Impact Bonds

Environmental Impact Bonds are an approach to financing infrastructure investments that borrows from the well-established, well-understood model of municipal debt finance and leverages both environmentally-oriented investor interest and repayments linked to environmental outcomes.[65] The City of Hampton Roads, Virginia is facing increasing flood frequency and severity linked to sea level rise, increased land use conversion and imperviousness, and land subsidence. To redress these impacts and mitigate the severity of future flooding, the city worked with Quantified Ventures to develop and issue a $12 million bond that will finance the construction of three nature-based projects that will help slow, store, filter, and redirect stormwater in low- to moderate-income neighborhoods within the city. These projects will reduce flood volumes by nearly 9 million gallons per year in a heavily urbanized watershed. This level of environmental performance proved highly attractive to bond buyers; competition to purchase the bond drove interests and other costs down.[66]

### 5.3.5 Nature-based insurance/ community resilience insurance

Working with re-insurance provider MunichRe, The Nature Conservancy has promoted a form of flood insurance which both protects property owners against loss and provides funding for flood risk mitigation projects. Referred to as "Community Flood Resilience Insurance," this strategy capitalizes on the monetary value of reduced flood risk to create revenue for project implementation out of the reduced premiums charged to property owners. Using this strategy, a local agency (or coalition of agencies, etc.) would first calculate the long term (e.g. 30 year) insurance premium savings to property owners that would result from risk reduction projects, such as GSI, floodplain enhancement, etc. Participating property owners would agree to continue paying the full premium amount for a shorter period of time (e.g. 10 years); this revenue would support repayment of a 10 year bond issuance by the local agency. Bond proceeds would be invested in the risk reducing projects.[67] Also known as parametric insurance, this model is relatively well understood within the insurance sector, and has been applied to boost local level resilience in a number of countries.[68]

## 5.4 Intra-municipal partnerships

Given the overlapping responsibilities between stormwater management departments and agencies tasked with flood control, cross-departmental collaboration can effectively leverage public staff, budgets, and project maintenance capabilities. In many areas, local or regional flood control agencies have recognized GSI's ability to reduce flood volumes in urban stream and river channels. In central Michigan, the Ingham County Drain Commissioner has a history of deploying GSI solutions to address flooding and stormwater pollution. A large-scale GSI project to upgrade undersized and failing drainage infrastructure within the Montgomery Drain will restore aquatic and terrestrial habitat, reduce surface flooding, and improve water quality. Across the country, in the desert landscape of metropolitan Tucson, AZ, the Pima County Regional Flood Control District has incorporated GSI into several of its projects through both regional scale, multi-benefit installations and smaller, neighborhood-scale infiltration practices. The District pioneered the use of a triple-bottom line cost benefit analysis to evaluate the flood reduction, environmental and economic benefits of GSI alternatives within heavily urbanized floodplains/watercourses.[69] To ensure consistency between County and City of Tucson stormwater standards, Flood Control District and City departments collaborated on a joint Green Stormwater Infrastructure and Low Impact Development Standard Details and Site Guidance. This cross-jurisdictional partnership will prioritize GSI approaches to reduce flooding in the seasonal creeks ("washes") that criss-cross the Tucson metro area.

# 6

# Conclusion

**Credit:** Jason Whalen/
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# CONCLUSION

## Available studies and practical experience indicate that GSI practices can be instrumental in reducing localized flooding associated with the most frequently experienced levels of rainfall.

GSI practices, such as retention basins, rain gardens, and pervious pavements, have reduced street flooding caused by drainage constraints, eliminated basement flooding linked to sewage system overloads, and limited damage to properties and public infrastructure. In addition to its effectiveness at reducing localized flooding, GSI can effectively contribute to strategies that reduce larger scale riverine flooding. Integrated, catchment-scale flood management using upstream GSI practices can help reduce the impacts of damaging riverine flooding events. Reducing runoff volumes can positively impact flood-stage levels in mainstem rivers or in lakes as the tributary flows combine. Where land availability and hydrology permit, larger scale approaches such as floodplain restoration, retention park lands, and stream channel restoration can be effective in reducing "riverine" flooding.

**Credit:** Kari Marciniak / TNC

# ENDNOTES

1. Green, D., E. O'Donnell, M. Johnson, L. Slater, C. Thorne, S. Zheng, R. Stirling, F. Chang, L. Li, and R. Boothroyd. 2021. Green Infrastructure: The future of urban flood risk management? WIREs Water. DOI: 10.1002/wat2.1560.
2. This guide does not cover coastal flooding although employing GSI in coastal areas can reduce coastal flooding impacts.
3. Albright, C. 2018. Resilience Strategies for Climate, Hydrology and Urban Green Infrastructure. Dissertation, College of Engineering, Villanova University.
4. Woznicki, S.A., K.L. Hondula, and S.T. Jarnagin. 2018. Effectiveness of landscape-based green infrastructure for stormwater management in suburban catchments. Hydrological Processes 32(15): 2293-2451.
5. Ibid.
6. Shuster, W. and L. Rhea. 2013. Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA). Journal of Hydrology 485:177-187.
7. Jack, K., F. Jaber, B. Heidari, and V. Prideaux. 2022. Green Stormwater Infrastructure for Urban Flood Resilience: Opportunity Analysis for Dallas, Texas. The Nature Conservancy and Texas A&M AgriLife Extension. Available: https://www.nature.org/content/dam/tnc/nature/en/documents/GSIanalysisREVFINAL.pdf?vu=dallasgsi.
8. U.S. EPA. 2014. Using Green Infrastructure to Mitigate Flooding in La Crosse, WI. EPA 832-R-15-002.
9. Ibid.
10. Hastings, R. 2021. An Assessment of the Use of Green Stormwater Infrastructure for Flood Mitigation at Berry Brook. Thesis. Master of Science in Civil Engineering, University of New Hampshire.
11. Scholz, A. 2011. Climate and Land Use Consequences to 100-year Flooding. Thesis for Master of Science in Civil Engineering. University of New Hampshire. Available: https://lamprey100flood.sr.unh.edu/resources/pdf/2011_Scholz_MScThesis.pdf.
12. Jefferson, A.J., A.S. Bhaskar, K.G. Hopkins, R. Fanelli, P.M. Avellaneda, and S.K. McMillan. 2017. Stormwater management network effectiveness and implications for urban watershed function: A critical review. Hydrological Processes 1-25. DOI: 10.1002/hyp.11347.
13. Hood, M.J., J.C. Clausen, and G.S. Warner. 2007. Comparison of stormwater lag times for low impact and traditional residential development. Journal of the American Water Resources. DOI: 10.1111/j.1752-1688.2007.00085.x
14. Loperfido, J.V., G.B. Noe, S.T. Jarnagin, and D.M. Hogan. 2014. Effects of distributed and centralized stormwater best management practices and land cover on the urban stream hydrology at the catchment scale. Journal of Hydrology 519(C):2584-2595. DOI: 10.1016/j.jhydrol.2014.07.007.
15. Hopkins, K.G., S.A. Woznicki, B. Williams, C. Stillwell, E. Naibert, M.J. Metes, D.K. Jones, D.M. Hogan, N.C. Hall, R.M. Fanelli, and A.S. Bhaskar. 2022. Lessons learned from 20 years of monitoring suburban development with distributed stormwater management in Clarksburg, Maryland, USA. Freshwater Science 41(3). DOI: 10.1086/719360.
16. Miller, A. J., C. Welty, J.M. Duncan, M.L. Baeck, and J.A. Smith. 2021. Assessing urban rainfall-runoff response to stormwater management extent. Hydrological Processes 35. DOI: 10.1002/hyp.14287.
17. Hastings, R. 2021
18. Palla, A. and I. Gnecco. 2015. Hydraulic modeling of Low Impact Development systems at the urban catchment scale. Journal of Hydrology 528:361-368. DOI: 10.1016/j.jhydrol.2015.06.050.
19. Zellner, M., D. Massey, E. Minor, and M. Gonzalez-Meler. 2016. Exploring the effects of green infrastructure placement on neighborhood-level flooding via spatially explicit simulations. Computers, Environment and Urban Systems 59: 116-128.
20. Conley, G., R. McDonald, T. Nodine, T. Chapman, C. Holland, C. Hawkins, N. Beck. 2022. Assessing the influence of urban greenness and green stormwater infrastructure on hydrology from satellite remote sensing. The Science of Total Environment 817:152723. DOI: 10.1016/j.scitotenv.2021.152723.
21. Dawson, D.A., K. Vercruysse and N. Wright. 2020. A spatial framework to explore needs and opportunities for interoperable urban flood management. Philosophical Transactions. Royal Society Publishing A 378:20190205. DOI: 10.1098/rsta.2019.0205.
22. Green, D. et al 2021

23. Opperman, J.J. 2014. A Flood of Benefits: Using Green Infrastructure to Reduce Flood Risks. The Nature Conservancy. Arlington, Virginia.
24. Albright, C. 2018
25. Woznicki, S.A. et al 2018
26. U.S. EPA 2014
27. Sörensen, J. and T. Emilsson. 2018. Evaluating Flood Risk Reduction by Urban Blue-Green Infrastructure Using Insurance Data. Journal of Water Resources Planning and Management. DOI: 10.1061/(ASCE)WR.1943-5452.0001037.
28. Conley, G. et al 2022
29. Shuster, W. and L. Rhea 2013
30. Palla, A. and I. Gnecco 2015
31. Scholz, A. 2011
32. Hopkins, K.G. et al 2022
33. Miller, A.J. et al 2021
34. U.S. EPA. 2015. Flood Loss Avoidance Benefits of Green Infrastructure for Stormwater Management. Prepared by Atkins. December 2015.
35. Hastings, R. 2021
36. Webber, J.L., T.D. Fletcher, L. Cunningham, G. Fu, D. Butler, and M.J. Burns. 2020. Is green infrastructure a viable strategy for managing urban surface water flooding? Urban Water Journal 17(7): 598-608. DOI: 10.1080/1573062X.2019.1700286.
37. Eastern Research Services. 2014. Economic Assessment of Green Infrastructure Strategies for Climate Change Adaptation: Pilot Studies in The Great Lakes Region. U.S. National Oceanic and Atmospheric Administration (U.S. NOAA). Available: https://coast.noaa.gov/data/digitalcoast/pdf/climate-change-adaptation-pilot.pdf. Accessed 3/2023.
38. Webber, J.L. et al 2020
39. Webber, J.L., M.J. Gibson, A.S. Chen, D. Savic, G. Fu, and D. Butler. 2018. Rapid assessment of surface-water flood-management options in urban catchments. Urban Water Journal 15(3):210-217. DOI: 10.1080/1573062X.2018.1424212.
40. Clements, J., J. Henderson, R. Raucher, R. Sands, and S. Sommer. 2018. Incentives for Green Infrastructure Implementation on Private Property: Lessons Learned. The Water Research Foundation. ISBN: 978-1-60573-382-1.
41. Ibid.
42. See Holland, C. and J. Israel, "'Smart' Stormwater Infrastructure Monitors, Produces Big Benefits for Nature," The Nature Conservancy. Sept. 28, 2021. Available https://www.washingtonnature.org/fieldnotes/smart-stormwater-infrastructure.
43. Green, D. et al 2021
44. Dawson, D.A. et al 2020
45. McFarland, A., L. Larsen, K. Yeshitela, A.N. Engida, and N.G. Love. 2019. Guide for using green infrastructure in urban environments for stormwater management. Environmental Science. Water Research and Technology 4. DOI: 10.1039/c8ew00498f.
46. Ibid.
47. Zellner, M. et al 2016
48. New York City Housing Authority. 2018. South Jamaica Houses Cloudburst Master Plan. Available: https://www.nyc.gov/assets/nycha/downloads/pdf/NYCHA-South-Jamaica-Clouburst-Plan-Report-2019.pdf. Accessed 2/2023.
49. Digman, C., R. Ashley, L. Dudley, P. Hargreaves, E. Gill, J. Hunter, K. Grose, S. Simmons, and P. Shaffer. 2014. Safe routes for urban flooding – encouraging the uptake of designing for exceedance: sharing the learning. UDG4.
50. Green, D. et al 2021
51. Keenan, M.B., P. Shankar, and P. Haas. 2019. Assessing disparities of urban flood risk for households of color in urban Chicago. Illinois Municipal Policy Journal 4(1):1-18.
52. Ibid.
53. U.S. EPA. 2023. EJScreen: Environmental Justice Screening and Mapping Tool. Available: https://www.epa.gov/ejscreen. Accessed 3/2023.
54. Crosson, C. 2020. The potential of green infrastructure in mitigating flood impacts on the mobility of low income and minority neighborhoods. Project Brief 1262. National Institute for Transportation and Communities. Available: https://ppms.trec.pdx.edu/media/project_files/1262_Project_Brief_-Flood_Vulnerability_in_Tucson.pdf. Accessed 3/2023.
55. U.S. FEMA. 2019. Introduction to Benefit-Cost Analysis, Unit 5: BCAs for Flood Mitigation Projects, Version 2.0. Student Manual (page 5-4). FEMA's BCA Toolkit. Available: https://www.fema.gov/sites/default/files/2020-04/fema_bca_student-manual_unit-5.pdf. Accessed 3/2023.
56. U.S. EPA 2015
57. Center for Neighborhood Technology (CNT) and American Rivers. 2010. The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental, and Social Benefits. Available: www.cnt.org/repository/gi-values-guide.pdf. Accessed 3/2023.
58. Jack, Jaber, Heidari, and Prideaux. 2022.
59. Cadavid, C. and Ando, A. 2013. Valuing preferences over stormwater management outcomes including improved hydrologic function. Water Resources Research. 49(41): 4114–4125, DOI:10.1002/wrcr.20317.

60. Braden, J. and D. Johnston. 2004. Downstream economic benefits from storm-water management. Journal of Water Resources Planning and Management 130:6. Available: https://doi.org/10.1061/(ASCE)0733-9496(2004)130:6(498).
61. CNT and American Rivers 2010
62. Ortega, F. and S. Taspinar. 2018. Rising sea levels and sinking property values: Hurricane Sandy and New York's housing market. Journal of Urban Economics 106(2018):81-100.
63. Jack, K. et al 2022
64. Center for Neighborhood Technology (CNT). 2014. The Prevalence and Cost of Urban Flooding: A Case Study of Cook County, IL. Available: https://www.cnt.org/sites/default/files/publications/CNT_PrevalenceAndCostOfUrbanFlooding2014.pdf. Accessed 3/2023.
65. See WaterNow *Alliance, Tap into Resilience Toolkit: Environmental Impact Bonds*. Available https://tapin.waternow.org/toolkit/?item=eib-bond
66. Lee, J. 2020. Novel financing for a historic city plagued by flooding: the Hampton Environmental Impact Bond. Available: https://www.quantifiedventures.com/blog/designing-the-hampton-environmental-impact-bond. Accessed 3/2023.
67. Jack, K. et al 2022
68. Kousky, C. and L. Shabman. 2015. A Proposed Design for Community Flood Insurance. Resources for the Future.
69. Watershed Management Group. 2015. Solving Flooding Challenges with Green Stormwater Infrastructure in the Airport Wash Area. Available: https://watershedmg.org/sites/default/files/documents/solving-flooding-challenges-with-green-stormwater-infrastructure-in-tucsons-airport-wash-2015.pdf.

# FIGURE CITATIONS

New York City Housing Authority (NYCHA). 2018. South Jamaica Houses Cloudburst Master Plan . Available https://www1.nyc.gov/assets/nycha/downloads/pdf/NYCHA-South-Jamaica-Clouburst-Plan-Report-2019.pdf

Hastings, R. 2021. An Assessment of the Use of Green Stormwater Infrastructure for Flood Mitigation at Berry Brook. Thesis. Master of Science in Civil Engineering, University of New Hampshire.

Jack, K., F. Jaber, B. Heidari, and V. Prideaux. 2022. Green Stormwater Infrastructure for Urban Flood Resilience: Opportunity Analysis for Dallas, Texas. The Nature Conservancy and Texas A&M AgriLife Extension. Available: https://www.nature.org/content/dam/tnc/nature/en/documents/GSIanalysisREVFINAL.pdf?vu=dallasgsi.

Center for Neighborhood Technology (CNT). 2014. The Prevalence and Cost of Urban Flooding: A Case Study of Cook County, IL. Available: https://www.cnt.org/sites/default/files/publications/CNT_PrevalenceAndCostOfUrbanFlooding2014.pdf.

Crosson. 2020. The Potential of Green Infrastructure in Mitigating Flood Impacts on the Mobility of Low Income and Minority Neighborhoods, NITC Project Brief 1262.

S. Struck. 2019. Optimization Modeling: Can we plan our infrastructure more efficiently? Minnesota Stormwater Seminar Series.

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