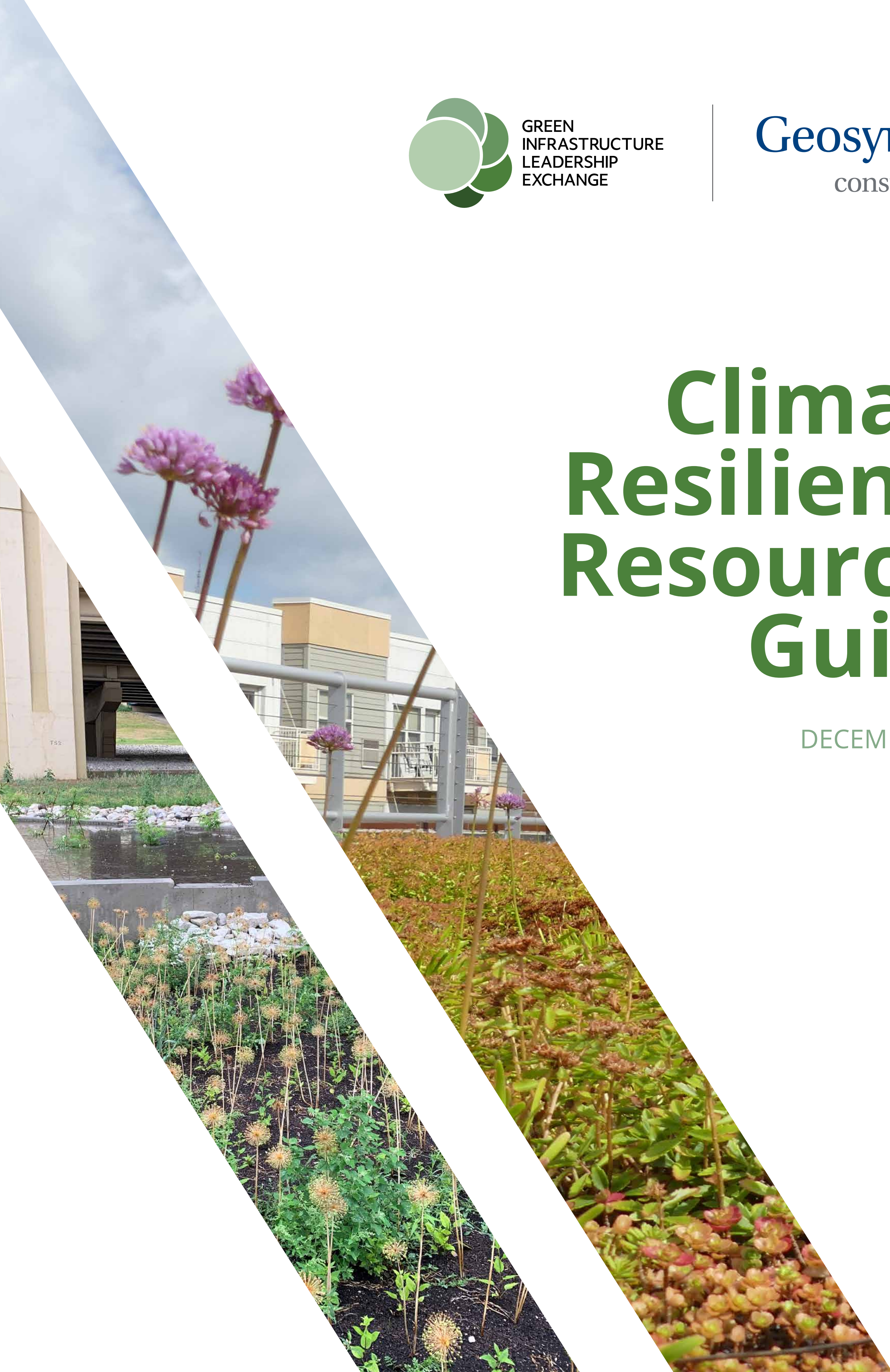

GREEN INFRASTRUCTURE LEADERSHIP EXCHANGE

Geosyntec consultants

Climate Resilience Resources Guide

DECEMBER 2023

Acknowledgments

THE GREEN INFRASTRUCTURE LEADERSHIP EXCHANGE | PROJECT MANAGER

Green Infrastructure Leadership Exchange ("the Exchange") strives to accelerate the affordable and equitable implementation of green stormwater infrastructure (GSI) throughout North America by supporting peer learning, innovation and collaboration among cities, counties, and utilities. We're a highly connected peer learning network that offers a platform for practitioners to share experiences, circulate ideas, and solve problems together toward finding more sustainable water infrastructure solutions. The Exchange is a project of the Global Philanthropy Partnership. For more, visit giexchange.org.

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Statements and views expressed in this Guide are solely those of the authors and do not imply endorsement by the Global Philanthropy Partnership.

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ACRONYMS

BMP: Best Management Practice

CBOs: community-based organizations

CID: climatic impact driver

CSOs: combined sewer overflows

CSS: combined sewer systems

CWA: Clean Water Act

GSI: green stormwater infrastructure

CRRG, or the Guide: Climate Resilience Resources Guide

IDF: intensity, duration, and frequency

IPCC: Intergovernmental Panel on Climate Change

MS4: municipal separate storm sewer

NOAA: National Oceanic Atmospheric Administration

NPDES: National Pollutant Discharge Elimination System

O&M: operations and maintenance

POTWs: publicly operated treatment works

GILE, or the Exchange: Green Infrastructure Leadership Exchange

GLOSSARY

Asset management: Ongoing and long-term management of water and stormwater systems to ensure that there is sufficient investment for maintenance, repair, replacement, and upgrades of the physical components (such as pipes, valves, pump stations), or "assets", to maintain the system's service life and minimize potential for damage or failures.

Bioretention: The practice of capturing runoff within a matrix of soil and plant roots. Following capture, the runoff is evapotranspirated or infiltrated to surrounding and underlying soils. During frequent or intense runoff events, the soil-and-plant-root matrix may become saturated, in which case excess runoff may be discharged to an underdrain (biotreatment).

Biotreatment: The practice of filtering runoff through a matrix of soil and plant roots prior to discharge to a receiving water or municipal storm drain.

Clean Water Act (CWA): The principle law governing pollution control and water quality of waterways of the United States. The object of the CWA is to restore and maintain the chemical, physical, and biological integrity of U.S. waters (33 U.S.C. 1251). The basis of the CWA was enacted in 1948 but was significantly reorganized and expanded in 1972. It also establishes the National Pollutant Discharge Elimination System of permits to regulate surface water discharges from municipal storm drains, publicly owned treatment works, industrial discharges, and construction sites.

Climate change: Long-term shifts in average weather patterns at local, regional, or global scales. Climate change effects can result in warming, droughts and water scarcity, fires, rising sea levels, flooding, catastrophic storms, and declining biodiversity.

Climate change vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

Climatic impact drivers (CID): Physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems.

Cloudburst: Events in which an extreme amount of precipitation falls in a short period of time, which can create flood conditions.

Coastal flood: Covering or accumulation of water over normally dry coastal land as a result of high or rising tides or storm surges.

Community-based organizations (CBOs): Public or private nonprofit organizations aimed at making desired improvements to a community's social health, well-being, and overall functioning.

Constructed wetlands: Treatment systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality.

Combined Sewer Systems (CSSs): Refers to a system used to collect rainwater runoff, domestic sewage, and industrial wastewater and transport the combined flows to a treatment plant.

Combined Sewer Overflows (CSOs): When the amount of runoff in a CSS exceeds the treatment capacity, resulting in the discharge of untreated stormwater and wastewater flows into nearby waterbodies. CSOs are subject to the NPDES permitting program.

Underserved Populations/Communities: Groups that have limited or no access to resources or that are otherwise disenfranchised. These areas often suffer more from a variety of economic, health, and environmental burdens which may be related, such as poverty, unemployment, air and water pollution, presence of hazardous wastes, poor infrastructure, and short-term or chronic health issues.

Drawdown: A process wherein a stormwater treatment facility drains and returns to the dry-weather condition.

Erosion: The wearing away and transport of the land surface by natural forces such as wind or water.

Evapotranspiration: The sum of processes by which water moves from the land surface to the atmosphere via evaporation and transpiration.

Extreme heat: Rising long-term average temperatures and increased heat waves, which are periods of excessive heat, often combined with excessive humidity.

Filtration: Process in which suspended solids are removed from water, such as stormwater runoff, by using one or more filter media.

Fire weather: Weather conditions conducive to triggering and sustaining wildfires, usually based on a set of indicators and combinations of indicators including temperature, soil moisture, humidity, and wind.

Green stormwater infrastructure (GSI): Stormwater treatment measures that are engineered to passively capture and treat stormwater using natural processes. GSI measures are decentralized or distributed. They capture, slow, and infiltrate rain where it falls, thus reducing local stormwater runoff and improving the health of surrounding waterways.

Green streets: A holistic stormwater management approach that incorporates vegetation, soil, and engineered systems (e.g., permeable pavements) to slow, filter, and cleanse stormwater runoff across entire, or segments of, streets.

Grey infrastructure: Conventional stormwater infrastructure in the built environment which utilizes concrete or other impervious structures for stormwater management such as gutters, channels, and pipes.

Groundwater recharge: Natural or artificial replenishment of groundwater supplies through infiltration or injection of water, typically captured stormwater.

Heavy precipitation with pluvial flood: Overflowing or accumulation of water over areas that are not normally submerged and often caused by unusually heavy rain. Pluvial floods are rain floods versus river (fluvial) floods.

Hydrologic benefits: Refers to GSI benefits related to stormwater volume and flow, such as reducing peak flow, minimizing local flooding, infiltration for groundwater recharge, and direct or indirect reuse.

Hydrological drought: A period with large runoff and water deficits in rivers, lakes, and reservoirs.

Imperviousness: Surfaces such as roads, sidewalks, rooftops, and parking lots, that prevent or significantly inhibit rainfall from infiltrating into native soils and groundwater.

Infiltration: Flow of water into and through subsurface soils, where it may reach underlying groundwater.

Living Shorelines: Protected, stabilized coastal edges that contain natural materials such as plants, sand, shells, or rock which can reduce erosion and property damage by reducing the velocity and intensity of waves.

Localized flooding: Smaller-scale ponding or flooding that occurs in low-lying areas after a rain event and caused by localized drainage problems within the watershed.

Mean precipitation: Average precipitation.

Municipal separate storm sewer (MS4s): A system of conveyances owned or operated by a public body, which are designed or used for collecting or conveying stormwater and discharging to surface waters. Flows in MS4s generally do not go through advanced treatment before they are discharged and must be regulated to prevent detrimental impacts on receiving waterbodies.

National Pollutant Discharge Elimination System (NPDES) permit: An authorization, license, or equivalent control document issued by EPA or a U.S. state agency to implement the requirements of the NPDES program, under the CWA. The NPDES program was established to regulate municipal sanitary sewer and industrial discharges and was expanded in 1987 to incorporate stormwater.

Nature-based solutions: Actions to protect, sustainably manage, or restore natural ecosystems, or mimic natural processes, that address societal challenges such as climate change, human health, food and water security, and disaster risk reduction effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Examples include large open natural spaces, riparian areas, wetlands, living shorelines, and greening of steep hillsides, all of which provide hydrology and water quality benefits.

Non-potable uses: Water used for non-drinking purposes, such as toilet flushing, clothes washing, and irrigation.

One Water: One Water is an approach that views and manages all water—whether from the tap, a stream, a storm, an aquifer, or a sewer—in a collaborative, integrated, inclusive, and holistic manner that centers around core principles of water equity, water affordability and water access. The One Water approach is important in managing finite water resources for long-term resilience and reliability to meet both community and ecosystem needs.

Operations and maintenance (O&M): Regular performance of activities required to inspect and implement preventative and corrective of facilities (i.e., GSI measures) in perpetuity.

Parcel-based facilities: Smaller-scale GSI measures that capture and manage runoff from a single parcel.

Permeable pavement: A porous urban surface composed of pavers, concrete, or asphalt with an underlying stone reservoir which catches precipitation and surface runoff and allows it to infiltrate into the soil below or discharge via a drain tile.

Planter boxes: Bioretention treatment control measures that are completely contained within an impermeable structure filled with planting soil media, vegetation, and gravel. As stormwater (typically roof runoff) passes through, pollutants are filtered, adsorbed, and biodegraded by the soil and plants, and treated runoff leaves through a drain pipe.

Regional facilities: Larger-scale GSI measures that capture and manage runoff from a large drainage area upstream of the project, typically by diverting flows from a storm drain or channel.

Resilience: The capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption.

Retention: The capture and long-term storage of stormwater, where it will either eventually infiltrate to subsurface soils and groundwater, or evaporate.

River flood: Overflowing or accumulation of water over areas that are not normally submerged and often caused by unusually heavy rain. Fluvial floods are river floods versus rain (pluvial) floods.

Snow, glacier, and ice sheet: Glacier is a perennial mass of ice and snow, and ice sheets are land masses of continental size.

Stormwater capture and use: Refers to systems designed to capture, retain, and treat stormwater for direct beneficial use at the point of capture, such as irrigation.

Stormwater regulations: Federal, state, and local regulations established to help protect the natural environment from anthropogenic sources of pollution, including spill control measures, water quality standards for discharges, best management practices, and pollution prevention plans.

Treatment media: Different types of media, such as sand or carbon, that are used to treat stormwater runoff by filtering out pollutants.

Tropical cyclone: General term for strong, cyclonic-scale disturbance that originates over tropical oceans.

Urban heat island: Urbanized areas that experience higher temperatures than surrounding and outlying areas due to the greater retention and reflection of heat by structures and impervious surfaces, as compared to areas with more vegetation and soil.

Vegetated filter strips: Linear strips of vegetated surfaces that are designed to treat sheet runoff flow from adjacent surfaces.

Vegetated swales: Open, shallow channels with vegetation covering side slopes and bottom that collect and slowly convey runoff flow to downstream discharge points.

Watershed: An area of land that drains rainfall and runoff into a specific waterbody, which can vary greatly in size. Some watersheds encompass many smaller subwatersheds.

1. Introduction

Bay View Montessori School, Milwaukee, WI.
Photo Credit: Reflo Sustainable Water Solutions

This Climate Resilience Resources Guide (CRRG, or the Guide) was developed by the Green Infrastructure Leadership Exchange. The Guide explores the intersection of green stormwater infrastructure (GSI) and urban impacts from climate change. GSI is a decentralized approach to stormwater management that mimics natural hydrology by slowing and/or retaining runoff generated from rainfall. Resilience-focused policy, planning, and implementation of GSI could make communities more resilient to climate change while providing human health benefits. However, existing regulatory, planning, design, and maintenance standards for GSI might leave this infrastructure at risk of not performing per current stormwater quality requirements or being damaged because of the impacts of a changing climate. Given the current lack of alignment of water quality and resilience goals, local agencies struggle to integrate GSI and climate initiatives, despite the potential corresponding benefits.

The primary target audience for this Guide includes municipal staff, decision-makers, and regulatory entities. Recommendations in this Guide may also be helpful for community members and stakeholders to advocate, plan, implement, and maintain GSI.

The Guide references relevant resources throughout, including frameworks for considering equity in GSI planning. **A full matrix of GSI climate-related resources is provided in Appendix A.** This Guide examines and incorporates decision-making process tools for planning and implementing GSI based on climate resilience, public engagement, and equity considerations. The tools were developed in part based on input gained through an extensive outreach effort conducted specifically as part of the development of this Guide, which included a survey, roundtables, and interviews. The Guide is intended to be a living document that is updated at a pace aligned with evolving climate resilience science, policy, and funding opportunities.

This Guide explores potential changes to current GSI policy (Section 4), planning (Section 5), design (Section 6), operations and maintenance practices (Section 7) that could enhance the climate resilience benefits provided by GSI.

GSI FOR CLIMATE RESILIENCE
(Section 3)

GSI POLICY FOR CLIMATE RESILIENCE
(Section 4)

GSI PLANNING FOR CLIMATE RESILIENCE
(Section 5)

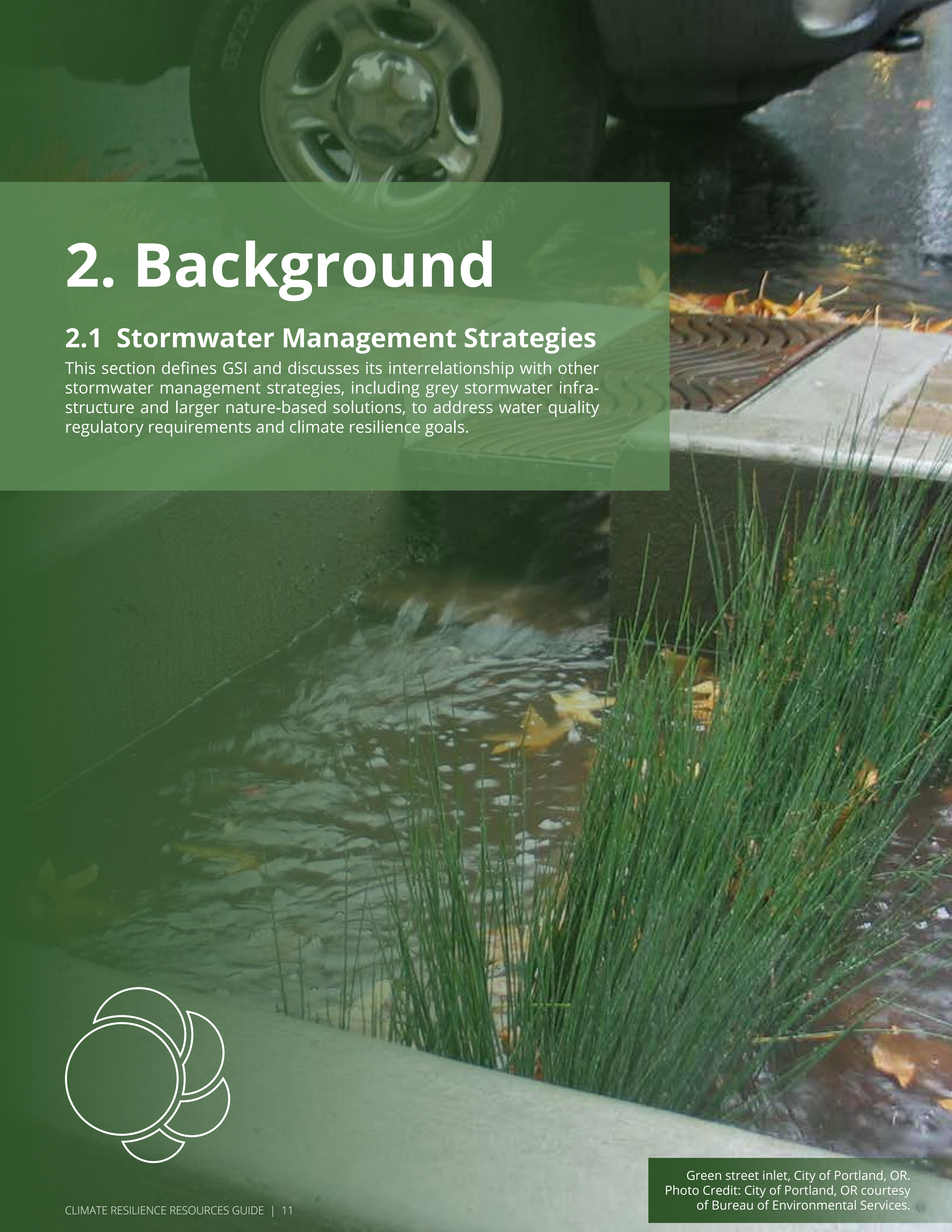
GSI DESIGN FOR CLIMATE RESILIENCE
(Section 6)

GSI OPERATIONS AND MAINTENANCE FOR CLIMATE RESILIENCE
(Section 7)

2. Background

2.1 Stormwater Management Strategies

This section defines GSI and discusses its interrelationship with other stormwater management strategies, including grey stormwater infrastructure and larger nature-based solutions, to address water quality regulatory requirements and climate resilience goals.



Green street inlet, City of Portland, OR.
Photo Credit: City of Portland, OR courtesy of Bureau of Environmental Services.

2.1.1 GREEN STORMWATER INFRASTRUCTURE (GSI)

Infrastructure is the basic equipment and structures essential for functional, healthy, and vibrant communities.[1] "Green" stormwater infrastructure includes a range of measures that are engineered to passively capture and treat stormwater using natural processes. Most GSI measures are decentralized or "distributed", that is, they capture, slow, and infiltrate rain where it falls, thus reducing local stormwater runoff and improving the health of surrounding waterways.[2] As referenced in this Guide, the primary treatment mechanisms that GSI employs include:

- Retention (i.e., preventing discharge) of stormwater runoff through infiltration to the subsurface, evapotranspiration, or capture and use;
- Filtration of stormwater runoff through vegetation and biologically active treatment media (i.e., biofiltration); and
- Treatment using passive biological processes (i.e., biotreatment) to treat stormwater runoff before discharge.

GSI measures are intentionally sized and designed to meet water quality regulatory requirements or provide other specific hydrologic benefits. GSI typically uses vegetation and engineered soil or treatment media; permeable pavement or other permeable surfaces or substrates; and/or storage for subsequent use.

Typical types of GSI, organized by treatment mechanism, include:

Infiltration measures, including infiltration basins, infiltration trenches, bioretention,[i] drywells, and permeable pavement[photo1]

Practices to promote evapotranspiration, including tree planting, green roofs, and impervious surface dispersion[photo2]

Capture and use or rainwater harvesting (i.e., cisterns or rain barrels)[photo3]

Biofiltration, including bioretention, planter boxes, vegetated swales, vegetated filter strips, and proprietary biotreatment devices[photo4]

Biotreatment basins, such as wet detention basins and constructed wetlands[photo5]

[i] While bioretention primarily uses biofiltration as a treatment mechanism, it can be designed to infiltrate captured stormwater or treat and discharge it. When designed to infiltrate, bioretention is sometimes called "bioinfiltration".

[photo1] Geosyntec Consultants

[photo2] South Waterfront neighborhood building ecoroof and stormwater facilities in Elizabeth Caruthers Park. Photo Credit: City of Portland, OR, courtesy of Bureau of Environmental Services.

[photo3] EcoCenter at Heron's Head Park, San Francisco, CA.

[photo4] Lake Merritt, Oakland, CA Photo Credit: City of Oakland.

[photo5] Large biofiltration system treating runoff from Interstate 5 and local roads. Photo Credit: City of Portland, OR, courtesy of Bureau of Environmental Services.

88.9 Radio Station, Milwaukee, WI
Photo Credit: Milwaukee Metropolitan Sewerage District, WI

This document uses “GSI” to refer to these measures or “GI” when a cited report uses this acronym instead. GSI measures are also implemented at different scales, including:

Street-scale facilities or “green streets”, such as curb extensions and bulb-outs designed to treat roadway runoff[photo6]

Parcel-based facilities, which are GSI measures sized to treat an entire parcel; and

Regional facilities, which are GSI measures that treat runoff generated from a larger area, such as a neighborhood[photo7]

The ability of GSI to deliver multiple ecological, economic, and social benefits or services has made GSI an increasingly popular strategy. In addition to reducing polluted stormwater runoff, GSI measures can decrease urban heat, provide buffer for multi-modal transportation, reduce energy consumption, improve air quality, provide carbon sequestration, increase property prices, encourage nearby recreation, and provide other elements of community health and vitality that have monetary or social value.[3] Moreover, GSI measures provide flexibility to communities facing the need to adapt infrastructure to a changing climate. For more details on the benefits of GSI for climate adaptation, see Section 3.

[photo6] City of Pittsburgh, PA
[photo7] City/County Association of Governments of San Mateo County, CA

Photo Credit: Geosyntec Consultants

2.1.2 GREY STORMWATER INFRASTRUCTURE

Traditional "grey" stormwater infrastructure includes the curbs, gutters, catch basins, inlets, storm drain and sewer piping, detention basins, treatment plants, and outfalls used to collect and convey urban stormwater away from the built environment. Grey infrastructure collects and conveys stormwater from impervious surfaces, such as roadways, parking lots, and rooftops, into a series of piping that ultimately discharges stormwater into a local water body. Combined sewer systems (CSS) convey stormwater and various wastewaters, typically to publicly operated treatment works (POTWs) designed to overflow. CSS and related POTW discharges of stormwater from overflows are regulated. Separate systems, which for public entities are known as municipal separate storm sewer systems (MS4s), only convey stormwater. Grey infrastructure is so-called because it is often constructed from concrete. It is designed to quickly convey stormwater and wastewater in and from urban environments and is often used to convey stormwater to and from GSI.

2.1.3 OTHER NATURE-BASED SOLUTIONS

Landscape or watershed scale nature-based solutions include large open natural spaces, riparian areas, wetlands, living shorelines, or greening of steep hillsides.[4] These broad-scale, "blue-green" solutions provide hydrology and water quality benefits (i.e., integrated stormwater management of flow and pollutants), and are also essential in the toolbox for climate change adaptation, providing ecological benefits and recreational opportunities. In addition, landscape features such as urban forest patches, parks, street trees, and living walls can provide similar benefits within the built environment. Another example, "Living Shorelines" are protected, stabilized coastal edges that contain natural materials such as plants, sand, shells, or rock[5] which can reduce erosion and property damage by reducing the velocity and intensity of waves.[6] While these larger features are often referred to as "green infrastructure", they are typically not engineered to meet specific stormwater regulatory requirements, as GSI is (as defined by this Guide). Other important examples of nature-based solutions intended to address precipitation related climate impacts include measures focused on mitigating the impacts of extreme, back-to-back rainfall or "cloudburst" events that have been studied by some major cities.[7] Examples include conveying water along the roadway's center (rather than the edges) or the use of a concave or sunken park for temporary flood storage.

While these larger-scale nature-based solutions are not the focus of this Guide, this Guide describes exampes of how these solutions are being deployed with GSI nationally.

[ii]Cloudburst management is the management of extreme back-to-back rainfall events through intentional flooding, conveying, and storing water where it is favorable in the landscape.

2.2 Climate Change Impacts

This section summarizes the overall regional impacts of climate change in the U.S. and Canada and climate-related vulnerabilities for society and ecosystems.

2.2.1 REGIONAL CLIMATE IMPACT DRIVERS (CIDS)

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. In the most recent Assessment Report (AR6[8]), the IPCC identifies 30 climatic impact drivers (CID) relevant to land and coastal regions. CIDs are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions.[9] The CIDs applicable to GSI policy, planning, and design include the following listed in Table 1.

Table 1. Climatic Impact Drivers Relevant to GSI Policy, Planning, Design, and Operations and Maintenance[10]

CLIMATIC IMPACT DRIVER	EXPLANATION (Adapted from IPCC)
Extreme heat	Rising long-term average temperatures and increased heat waves, which are periods of excessive heat, often combined with excessive humidity.
Mean precipitation	Average precipitation.
River flood	Overflowing or accumulation of water over areas that are not normally submerged and often caused by unusually heavy rain. Fluvial floods are river floods versus rain (pluvial) floods.
Heavy precipitation with pluvial flood	Overflowing or accumulation of water over areas that are not normally submerged and often caused by unusually heavy rain. Pluvial floods are rain floods versus river (fluvial) floods.
Hydrological drought	A period with large runoff and water deficits in rivers, lakes, and reservoirs.
Fire weather	Weather conditions conducive to triggering and sustaining wildfires, usually based on a set of indicators and combinations of indicators including temperature, soil moisture, humidity, and wind. Does not include the presence or absence of fuel load.
Tropical cyclone	General term for strong, cyclonic-scale disturbance that originates over tropical oceans.
Snow, glacier, and ice sheet	Glacier is a perennial mass of ice and snow, and ice sheets are land masses of continental size.
Coastal flood	Overflowing or accumulation of water over areas that are not normally submerged and often caused by unusually heavy rain.

Figure 1 shows the direction of projected change (increase or decrease) for the nine CIDs in Table 1 for six regions in North America in the mid-twenty first century. In general, the northern, central, and eastern regions of North America are expected to have hotter and wetter extremes and, in some regions, more overall precipitation. In western North America, future changes are generally expected to be hotter and drier, with wetter extremes (i.e., higher flood potential when it does rain).[11]

Region	Extreme Heat	Mean Precipitation	River Flood	Heavy Precipitation with Pluvial Flood	Hydrological Drought	Fire Weather	Snow, Glacier, Ice Sheet	Tropical Cyclone	Coastal Flood/ Erosion
North-Western North America (NWN)	↑	↑	↑	↑	↑	↑	↓		↑
North-Eastern North America (NEN)	↑	↑	↑	↑	↑	↑	↓		↑
Western North America (WNA)	↑		↑	↑	↑	↑	↓		↑
Central North America (CNA)	↑		↑	↑	↑	↑	↓	↑	↑
Eastern North America (ENA)	↑	↑	↑	↑	↑	↑	↓	↑	↑
Northern Central America (NCA)	↑	↓		↑	↑	↑	↓	↑	↑

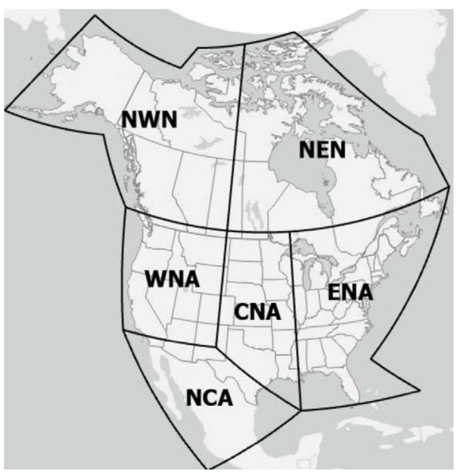


Figure 1. Projected change (increase or decrease) for selected climatic impact drivers in six regions in North America.[12]

Legend

- High confidence of increase/decrease
- Medium confidence of increase/decrease
- Low confidence in direction of change or not relevant

Assessed future changes: Changes refer to a 20 to 30-year period centered around 2050 and/or consistent with 2C global warming, compared to a similar period within 1960-2014, except for hydrological drought which is compared to 1850-1900.

Source: IPCC Working Group 1 Interactive Atlas: Regional synthesis

Iturbide, M., Fernández, J., Gutiérrez, J.M., Bedia, J., Cimadevilla, E., Díez-Sierra, J., Manzanas, R., Casanueva, A., Baño-Medina, J., Milovac, J., Herrera, S., Cofiño, A.S., San Martín, D., García-Díez, M., Hauser, M., Huard, D., Yelekci, Ö. (2021) Repository supporting the implementation of FAIR principles in the IPCC-WG1 Atlas. Zenodo, DOI: 10.5281/zenodo.3691645. Available from: https://github.com/IPCC-WG1/Atlas

Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I.V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L.Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K.Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press. Interactive Atlas available from Available from http://interactive-atlas.ipcc.ch/.

City Hall, Brisbane, CA. Photo Credit: City/County Association of Governments of San Mateo County

A list of example tools for assessing past and future climate changes regionally and locally is provided in Table 2. This is not intended to be a comprehensive list of all available resources, but a starting point for examining potential climate change.

Table 2. Tools for Assessing Past and Future Climate Changes

RESOURCE	REGION	DESCRIPTION
IPCC Working Group 1 Interactive Atlas	Global	A tool for global observed and projected regional climate change information as described in the IPCC Sixth Assessment Report, including regional synthesis for Climatic Impact-Drivers (CIDs).
Climate Data Extraction Tool (Canada)	Canada	A tool for viewing and downloading statistically downscaled climate scenarios for Canada.
Climate Data for a Resilient Canada	Canada	Provides high-resolution historic and future climate projection summaries for Canadian cities/towns.
The Climate Explorer	United States	A tool to explore how climate is projected to change in any county in the U.S., including Hawaii and the U.S. territories. Provides interactive graphs and maps showing past and projected climate conditions to support the U.S. Climate Resilience Toolkit.
Climate Information for Water Resource Managers	United States	Maps and graphics showing weather and climate outlooks across the U.S. Provides resources for short-term (<1 week) weather forecasts to medium-term (monthly) outlooks to future sea level rise and climate projections.
Cal-Adapt	California	Tool for viewing and downloading future climate change projection data at the local level for California.

2.2.2 CLIMATE-RELATED VULNERABILITIES

Considering climate vulnerability is important for increasing community resilience. Examples of climate-specific vulnerabilities relevant to GSI are described below.

Human Health and Vulnerable Populations

Climate affects all areas of human health. Increased heat waves, changes in precipitation, and sea-level rise affect health via multiple pathways. Some populations will be at higher risk from climate change impacts than others. Children, older adults, low-income communities, some communities of color, and communities that experience discrimination are disproportionately affected by extreme weather and climate events.[13] Additionally, communities with less access to information or support may be less able to avoid the health risks of climate change.[14]

Biodiversity

Biodiversity and species conservation are important for ecosystem balance and human populations (e.g., pollination of food crops). Current and future stressors are projected to reduce the capacity of ecosystems to recover from extreme events like floods and fires. Climate change is also projected to lead to losing iconic species from certain regions or becoming extinct altogether.[15]

Urban Heat Island

The urban heat island effect refers to the tendency for urban areas to absorb and release solar heat,[16] resulting in higher local surface temperatures. Reducing the urban heat island effect is important to maintaining human health and biodiversity. Larger temperature differences have been observed in cities with larger and denser populations.[17] The urban heat island effect is projected to become stronger as temperatures rise and urban areas densify and grow.

Water Scarcity/Water Stress

Water scarcity and water stress are affected by both human and natural systems. Climate change may result in reducing quantity and quality of water supplies, and cause water infrastructure impacts due to sea-level rise and the frequency of extreme events.[18]

3. GSI for Climate Resilience

"Resilience", as defined by the U.S. Climate Resilience Toolkit,[19] is "the capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption." GSI can be a valuable tool for communities to adapt to climate change and buffer against negative impacts. Many considerations can be incorporated into GSI planning and design to increase community resilience. Yet, at the same time, there are limitations to using GSI to solve all community climate-related challenges. GSI is a part of an extensive set of solutions to increase community resilience to climate change.

Photo Credit: City of Tucson, AZ

3.1 Potential Resilience Benefits of GSI

Maryland Ave, Pittsburgh, PA.
Photo Credit: City of Pittsburgh

Photo Credit: City of Tucson, AZ

3.1.1 MANAGING LOCALIZED URBAN FLOODING

The most apparent benefit for GSI to buffer against climate change impacts is the potential to reduce localized flooding associated with increased extreme precipitation (not including riverine or sea level rise related flooding). GSI can be designed to reduce runoff from larger precipitation events through infiltration and the incorporation of detention storage, reducing the potential of existing infrastructure becoming overwhelmed by storm events.[20] When GSI is implemented in coordination with other landscape features connecting urban hydrologic and vegetation systems, significant benefits can be achieved. For example, GSI constructed with larger-scale nature based or detention solutions can lessen impacts from cloudburst events.

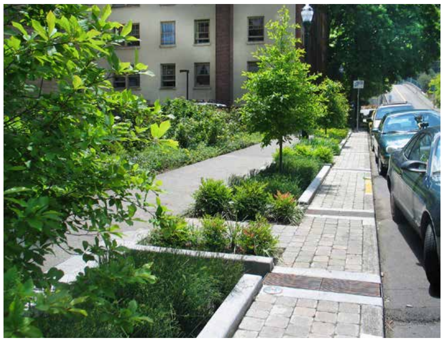
3.1.2 PREVENTING AND REDUCING EROSION

GSI implementation can provide benefits in mitigating creek and coastal erosion. Projected future increases in the frequency of intense precipitation could cause increased runoff volumes and flow rates, leading to creek erosion, bank incision, degradation, and related water quality issues in downstream receiving waters. GSI that detains and infiltrates stormwater runoff, especially at the regional scale, reconnects the natural water cycle and can reduce downstream hydrologic impacts.

Photo Credit: Geosyntec Consultants

3.1.3 REDUCING URBAN HEAT IMPACTS

Communities can reduce urban heat island impacts using vegetated GSI that provides natural heat-regulating services, such as shading, evapotranspiration, and thermal insulation of buildings.[21] Planting urban trees in urban hot spots can appreciably reduce urban heat impacts.[22] Strategies targeting buildings such as cool roofs or green roofs in some climates, can reduce heat absorption while reducing the energy needed to cool buildings and improve stormwater runoff.[23] Vertical green structures such as vegetated facades and walls have been found to provide similar heat mitigation benefits to green roofs but at a smaller magnitude.[24]



City of Portland Downtown Sidewalk Planters. Photo Credit: City of Portland, OR, courtesy of Bureau of Environmental Services

3.1.4 IMPROVING AIR QUALITY

Urban trees, green roofs, and other vegetated GSI solutions can improve urban air quality, although the ability to do so is highly context dependent. GSI can improve air quality impacts on human health by introducing linear vegetative barriers between traffic and pedestrians.[25] Some evidence suggests that increased leaf area associated with certain GSI solutions can improve air quality by air pollution preferentially depositing onto vegetation.[26] However, implementation must be extensive enough to make an appreciable impact on ground-level air quality. For this reason, large "green walls" provide the most significant benefit for air quality.[27]

Orange Memorial Stormwater Capture Project, South San Francisco, CA. Photo Credit: Lotus Water

3.1.5 WATER SUPPLY AUGMENTATION

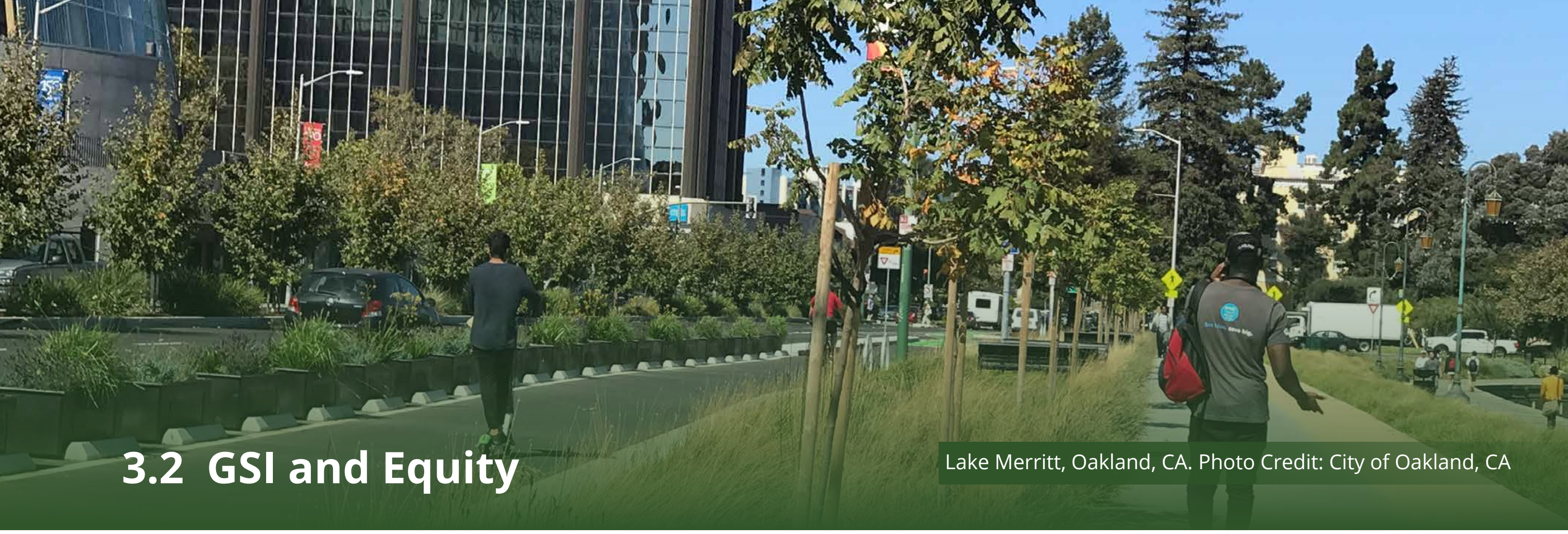
Stormwater (or rainwater) harvesting and groundwater recharge or replenishment from GSI can increase local water supplies, buffer against droughts, and reduce energy requirements and emissions associated with importing water from other locations.28 Stormwater can serve a range of non-potable uses such as irrigation, toilet flushing, and cooling. Through regional capture projects, stormwater may be used to recharge groundwater, improving local potable water supplies.[29] For example, the Orange Memorial Park Regional Stormwater Capture Project Park in South San Francisco diverts flow from a channel for water quality treatment, beneficial reuse (e.g., irrigation), and local flood reduction.[30] The project will offset an estimated 15 million gallons of potable water per year (resulting in $140,000 annually in water savings) and recharge 240 acre-ft to groundwater annually.

Photo Credit: City of Palo Alto, CA

3.1.6 HUMAN HEALTH BENEFITS

GSI has been shown to improve human health outcomes across various categories[31] and can be utilized to address health disparities that may be exacerbated by climate change. Through proximity, passive recreation, or active recreation, people derive many positive benefits from GSI. Schools might be a focus area for GSI in many communities and adding green spaces in schools has the potential to improve children's well-being, learning, and play while contributing to the ecological health and climate resilience of cities.[32]

Tree density and proximity to passive and active green spaces have been shown to provide physical, mental, and behavioral benefits.[33] Direct physical benefits of green space include improved cardiovascular health, reduced respiratory diseases, and reduced obesity.[34] Mental health benefits are associated with a reduced risk of depression, anxiety, and mood disorders.[35,36] Other benefits include a reduction in anti-social behaviors such as property and violent crime[37] and an improvement in helpful and generous behaviors.[38] Fewer studies are available on the human health benefits of specific types of GSI; however, similar benefits have been documented for green roofs, rain gardens, and bioswales.[39,40] Additional health-related GSI benefits include improved habitat, water quality, and carbon sequestration.[41]



Lake Merritt, Oakland, CA. Photo Credit: City of Oakland, CA

3.2 GSI and Equity

The effects of climate change disproportionately impact low-income and historically underserved communities, and GSI can play an important role in improving environmental and social equity outcomes. Low-income neighborhoods are more likely to be near or within industrial areas and have fewer parks, street trees, and other green spaces.[42,43] In a recent study, McDonald et al.[44] showed that, on average, low-income blocks have 15.2% less tree cover and are 1.5ºC (2.7ºF) hotter than high-income blocks. In addition, historically underserved neighborhoods are often at low elevations, vulnerable to sea-level rise and aging or failing stormwater infrastructure. These communities will disproportionally feel the impacts from rising temperatures, urban heat island effects, poor air quality, and flooding, further contributing to inequity in health and well-being.[45]

By providing green spaces and a means for improved stormwater management, implementation of GSI in low-income and historically underserved communities can help alleviate some of the negative impacts of climate change. Integrating GSI projects with necessary infrastructure such as active transportation (e.g., bike lanes) and street improvement projects is significant for communities that rely most on public and active means of transportation.[46] Providing access to green spaces also can improve mental and physical health overall and can indirectly improve equity outcomes through visible investments that communicate worth.[47]

Westlake Elementary School, Daly City, CA. Photo Credit: San Carlos, CA. Photo Credit: City/County Association of Governments of San Mateo County

Critically, any GSI project proposed, but especially in underserved communities, must be developed and designed with direct, frequent, respectful, and receptive communication with affected and nearby residents (see Section 3.3 for more details). As presented in the Equity Guide for GSI Practitioners,[48] well-designed green infrastructure programs can make direct contributions to equity in the following ways:

- Expand nature in communities,
- Increase resilience to climate hazards,
- Invest in economic stability,
- Create spaces that facilitate community cohesion,
- Increase community participation and power, and
- Build trust and acknowledge past harms.

It is critical to have equitable access to green spaces; however, the distribution of GSI in urban planning is often itself inequitable. A joint study initiated in 2018 by the Cary Institute of Ecosystem Studies and the Urban Systems Lab assessed equity in GI Plans from 20 cities across the U.S. The researchers found that the patterns of urban greening tended to follow existing patterns of uneven urban development rooted in historical inequities (www.giequity.org). Furthermore, GSI is often implemented by municipalities when technically feasible based on physical site characteristics or necessary to support grey infrastructure projects, such as managing stormwater to reduce combined sewer overflows (CSOs) or improve water quality in streams (i.e., separate sewer systems).

It is important to consider multiple factors beyond engineering feasibility at the planning stages to address inequities in GSI implementation. At a workshop organized by National Oceanic Atmospheric Administration (NOAA) and the Water Research Foundation in 2020, the organizers noted the importance of integrating physical science with social and infrastructure data to understand vulnerability, identify where improvements are most needed, and provide the most benefits.[49] Similarly, the U.S. Water Alliance suggests a cost-benefit approach and conducting triple- bottom-line analyses that include environmental, economic, and social impacts when selecting sites.[50]

The City/County Association of Governments of San Mateo County has created a countywide Sustainable Streets Master Plan to help equitably adapt the roadway network to climate change and clean stormwater runoff to meet municipal stormwater regulatory requirements.

Development of the Master Plan included an interwoven focus on equity, with prioritization criteria supporting projects in areas where:

1. **Vehicle ownership** is low and residents are more likely dependent upon active transportation or transit
2. **Runoff volume** is likely to increase the most due to climate change and lead to potential roadway flooding
3. **Heat impacts** are expected to worsen due to climate change,
4. **Multiple environmental** or social vulnerable or disadvantaged community indicators overlap
5. **There is lower tree canopy coverage** that could benefit from increased urban greening.

CRRG ROUNDTABLE DISCUSSION

Groundwork Milwaukee has a program called Ground Corps that engages residents directly through training in GSI installation and maintenance.

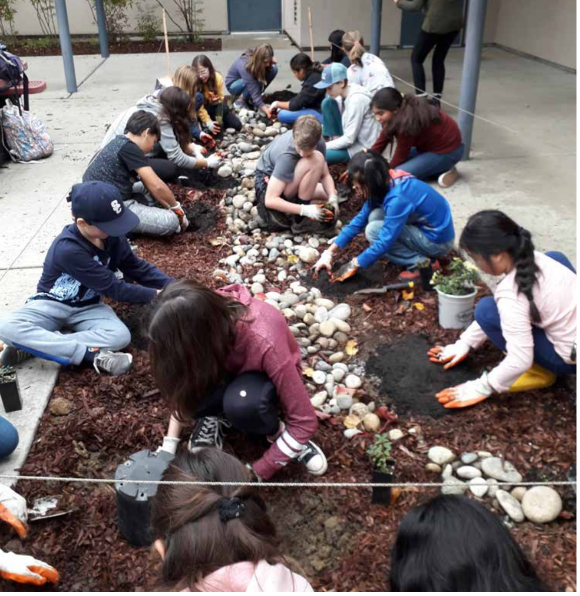
Photo Credit: Groundwork Milwaukee.

Neighborhood Rain Garden Installation.
Photo Credit: Milwaukee Metropolitan Sewerage District, WI.

Table 3 below provides links to useful resources for incorporating equity in GSI planning.

Table 3. Equity in GSI Planning Resources

GSI EQUITY RESOURCE	DESCRIPTION
Equity Guide for GSI Practitioners	Resource developed through the GILE by and for green infrastructure program managers offering a variety of tools to support practitioners in customizing community-informed equity work and evaluation plans.
Joint study by the Cary Institute of Ecosystem Studies and the Urban Systems Lab of 20 cities from across the U.S. assessing equity within GI Plans.	Key outputs from the project, including definitions for equity and green infrastructure, peer-reviewed publications, public presentations, and project-related web products.
GSI Toolkit for Equitable Investment – Georgetown Climate Center	How policymakers can design green infrastructure programs to prioritize environmental justice for communities facing disproportionate climate risk and pollution burden and resources that can be used to help fund projects in disadvantaged communities.
GSI Toolkit for Equitable Planning – Georgetown Climate Center	How to consider socioeconomic and other risk factors in green infrastructure planning.



Tierra Linda Middle School, San Carlos, CA. Photo Credit: City/County Association of Governments of San Mateo County

3.3 Public Engagement, Communication, and Outreach

Early and consistent public engagement is necessary for GSI project success and is especially important for improving GSI equity outcomes. Engaging the public as early as possible in program or project planning is important to continue to work towards different types of equity goals.[51] When thinking about how to make a case for considering climate change, resilience, and the role of GSI, program managers should consider the following factors:

- Leadership, buy-in, and partnerships
- Storytelling, messaging, and education
- Intergovernmental/ intragovernmental coordination
- Community infrastructure levels of service and performance targets

Participants in the CRRG roundtable for community-based organizations (CBOs), described in Section 3.5, discussed ways municipal agencies can better engage communities and align community and municipal goals. Underserved communities may mistrust municipal agencies when there has been a history of negative actions such as redlining and long-term disinvestment. Municipalities should also recognize that seemingly obvious technical benefits might not resonate for the local community. For example, trees and other vegetation installed for GSI might not be popular due to lack of municipal maintenance, leaf drop, improper growth, the possibility of falling over during storms and causing property damage.

To overcome these challenges, municipal agencies should engage communities in planning, siting, and design decisions. Messaging could also frame climate resilience and GSI goals in a way that focuses more on aesthetics and community pride, which are more commonly understood. Through partnerships with CBOs, municipalities can engage communities in co-creative and co-design processes with shared power in decision-making and building adaptive capacity. Municipal agencies should recognize that it may take years to build trust with the local communities.

Public Engagement Team Manager gives a stormwater tour, stopping at a combined sewer overflow on Cobbs Creek. Photo Credit: Philadelphia Water Department.

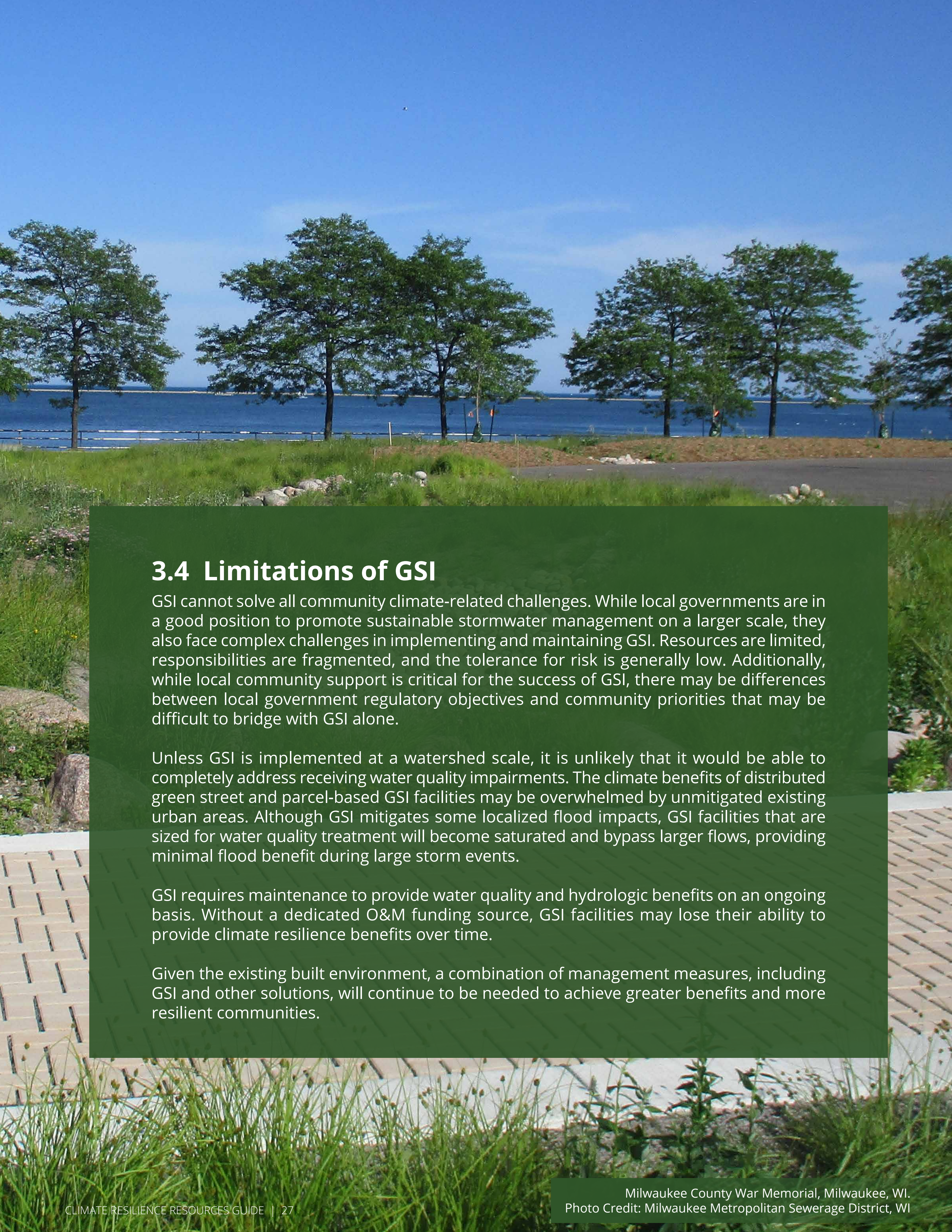
At a NOAA and Water Research Foundation workshop in 2020, the organizers noted that engaging neighborhood residents as ambassadors was mutually beneficial. The relationships provided common understanding between city staff, utility staff, and community members and helped connect communities to project funding resources. This community-based approach achieved triple-bottom-line benefits for social, economic, and environmental resilience. The partnerships succeed when:[52]

1. **Partners speak a common language.** Community members respond when they understand the impact of their behaviors on the environment. Water and climate professionals implement better resilient strategies when they understand community impacts and needs.

2. **The utility and the community work together.** If community members feel ownership of the project, they take pride in it, which is vital for long-term maintenance (e.g., green infrastructure).

3. **Community members have trusted relationships with agencies.** Relationships are a two-way street: they help planners and engineers understand what the community wants and needs, and they give community members a window into water infrastructure and climate issues – was well as a greater awareness of water careers.

Communication and outreach strategies for GSI may include a variety of platforms such as presentations and workshops, media campaigns, websites, written materials, inter-agency partnerships, and/or connections through CBOs. When working with multilingual communities, GSI practitioners should recognize language barriers and plan to produce materials in the language(s) of the target audiences. Other ways to promote accessibility and equity in the community engagement process include providing directions to a location from public transit, including contact information to request accommodations, holding meetings outside of typical working hours, and offering food or childcare. Community pop-up events and joining with pre- existing events (e.g., cultural festivals) can also be an effective means of community engagement and buy-in. Additional information on Communication Strategies for Green Infrastructure is available through the Georgetown Climate Center.



3.4 Limitations of GSI

GSI cannot solve all community climate-related challenges. While local governments are in a good position to promote sustainable stormwater management on a larger scale, they also face complex challenges in implementing and maintaining GSI. Resources are limited, responsibilities are fragmented, and the tolerance for risk is generally low. Additionally, while local community support is critical for the success of GSI, there may be differences between local government regulatory objectives and community priorities that may be difficult to bridge with GSI alone.

Unless GSI is implemented at a watershed scale, it is unlikely that it would be able to completely address receiving water quality impairments. The climate benefits of distributed green street and parcel-based GSI facilities may be overwhelmed by unmitigated existing urban areas. Although GSI mitigates some localized flood impacts, GSI facilities that are sized for water quality treatment will become saturated and bypass larger flows, providing minimal flood benefit during large storm events.

GSI requires maintenance to provide water quality and hydrologic benefits on an ongoing basis. Without a dedicated O&M funding source, GSI facilities may lose their ability to provide climate resilience benefits over time.

Given the existing built environment, a combination of management measures, including GSI and other solutions, will continue to be needed to achieve greater benefits and more resilient communities.

Milwaukee County War Memorial, Milwaukee, WI.
Photo Credit: Milwaukee Metropolitan Sewerage District, WI

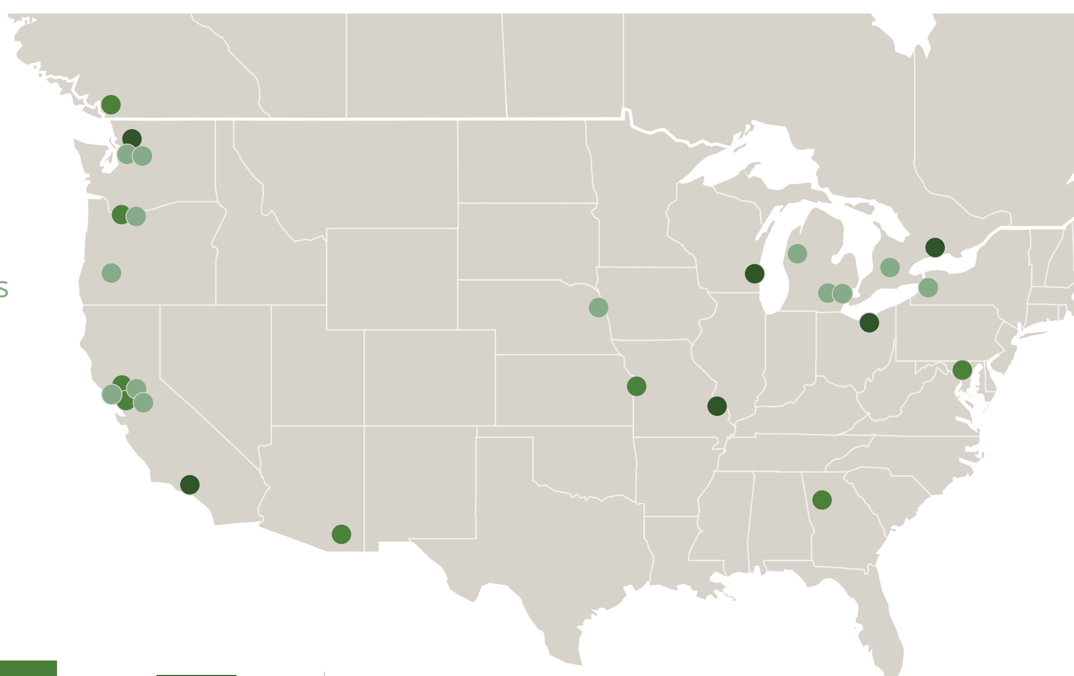
3.5 CRRG Outreach Summary

In developing this Guide, outreach efforts, including surveys, interviews, and roundtables, were identified as a key part of developing practical tools and step-by-step methods to implement decision-making for GSI and climate resilience. Outreach activities conducted included:

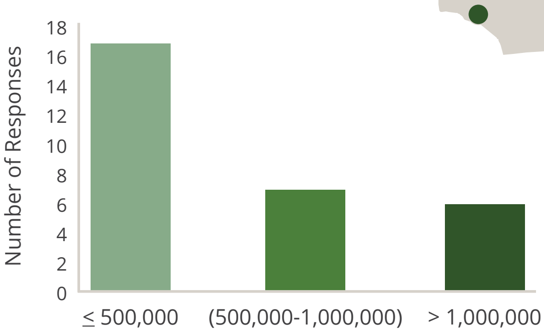
1. **CRRG Survey** – A 15 question outreach survey to identify the key decision-making processes that agencies currently use to implement GSI in the context of climate resilience was developed. The survey was shared with the GILE members (a total of 54 member organizations) and was open for approximately three weeks, from March 28, 2023, to April 14, 2023. Thirty agencies from across the U.S. and Canada responded to the survey. By population, respondents represented 5% of the U.S. and 10% of Canada.
2. **Municipal Roundtable** - One 2-hr municipal roundtable was held on May 8, 2023, and included representatives from seven agencies throughout the U.S. and Canada. The municipal roundtable participants were asked about their GSI policy, planning, design, and maintenance processes and the climate resilience-driven changes agencies are making to or planning for these processes.
3. **Community-Based Organizations Roundtable** - One 1-hr community-based organization (CBO) roundtable was held on May 25, 2023, and included representatives from three organizations throughout the U.S. The CBO roundtable participants were asked about the role of GSI in climate resilience, municipal agency actions needed to better engage with communities about resilience, and how to align community and municipal goals relating to climate resilience.
4. **Two Individual Municipal Interviews** - Two 30-minute municipal interviews were held on May 22 and 25 with representatives from the cities of Milwaukee and Tucson, respectively. The focus of the municipal interviews was similar to the municipal roundtable.
5. **Input received through these outreach activities** is referenced throughout the remainder of this Guide.

Results and Responses from CRRG 2023 Survey

30 responses from
12 U.S. states and
2 Canadian provinces



Service Population

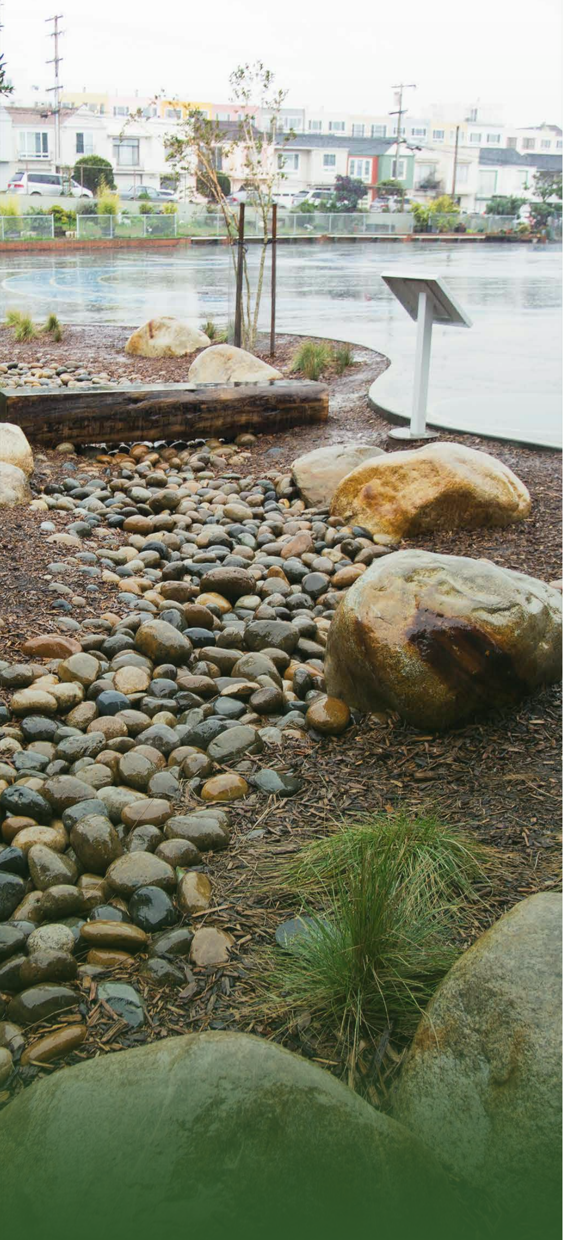


0 – 500,000
500,000 – 1,000,000
1,000,000+

4. GSI Policy for Climate Resilience

This section summarizes existing policies and regulations relevant to GSI and climate resilience and discusses the importance of incorporating resilience into future policies and regulations. This section also touches on the role of grants and funding options for infrastructure improvements that prioritize projects in disadvantaged communities and community partnerships.

Herron Avenue Garden, Pittsburgh, PA.
Photo Credit: City of Pittsburgh.



The San Francisco Green Infrastructure Grant Program includes application evaluation criteria for achieving a Climate Resilience co-benefit. These funding options also emphasize and/or require project implementation in underserved and more vulnerable communities.

Robert Louis Stevenson Elementary School, San Francisco, CA.
Photo Credit: San Francisco Public Utilities Commission.

4.1 Existing Policies and Regulations Concerning GSI and Climate Resilience

In the United States, the Federal Water Pollution Control Act was amended in 1972 to become the Clean Water Act (CWA). The CWA prohibits discharge of pollutants to waters of the United States from any point source unless the discharge complies with a National Pollutant Discharge Elimination System (NPDES) permit. A framework for regulating municipal, industrial, and construction stormwater discharges under the NPDES program was amended to the CWA in 1987.[iii] In 1990, USEPA published final requirements for storm water permits for municipal separate storm sewer (MS4s)[iv] serving a population of over 100,000 (Phase I communities). In 1998, USEPA published final requirements for MS4s serving populations under 100,000 (Phase II communities). Discharges from CSSs, combined sewer overflows (CSOs), are also regulated under NPDES permits.

Through these requirements, owners/operators of MS4s are required to develop, implement, and enforce a stormwater management program that includes post-construction runoff control along with other program areas. The post-construction runoff control program requires control of pollutant loads, volume, and flowrate impacts of stormwater runoff from development. Communities with CSOs must comply with the CSO Control Policy, which requires pollution prevention and other controls. NPDES permits across the country often require GSI to be implemented for new and redevelopment projects and some also require existing urban areas to retrofit drainage areas with GSI.

These regulations have not been amended to substantively address climate change resilience at the federal level. However, many state and local regulations and policies now focus explicitly on climate resilience and adaptation and are also relevant to stormwater management.

> CRRG Survey outcomes indicated that twenty percent of survey respondent organizations have policies or regulations with requirements to ensure GSI is more climate resilient. Over sixty percent of survey respondent organizations indicated that they are working on policy or regulatory updates to incorporate climate resilience.

Complimentary to the growing body of local or state-based GSI policies that consider climate change impacts, many local and state grant programs, and federal infrastructure funding options are focusing on climate resilience related to stormwater projects (for example, California Climate Resilience Package funds).[53]

[iii] under Section 402(p).
[iv] An MS4 is a conveyance or system of conveyances that is: owned by a public entity and discharges to waters of the US; designed or used to collect stormwater; not a combined sewer; and not part of a sewage treatment plant.

4.2 Incorporating Climate Resilience into Policies and Regulations

Municipalities and other local agencies may incorporate climate resilience into local policies and regulations in response to regional, statewide, or federal regulations and/or to protect infrastructure. Climate adaption touches on many municipal departments that might not have a history of working together and that may have competing interests. As such, interagency and interdepartmental coordination and collaboration at various levels of governance are critical.

Responses from the CRRG Survey demonstrated that the key drivers for agencies to update policies or plans to incorporate climate resilience are:

Results and Responses from CRRG 2023 Survey

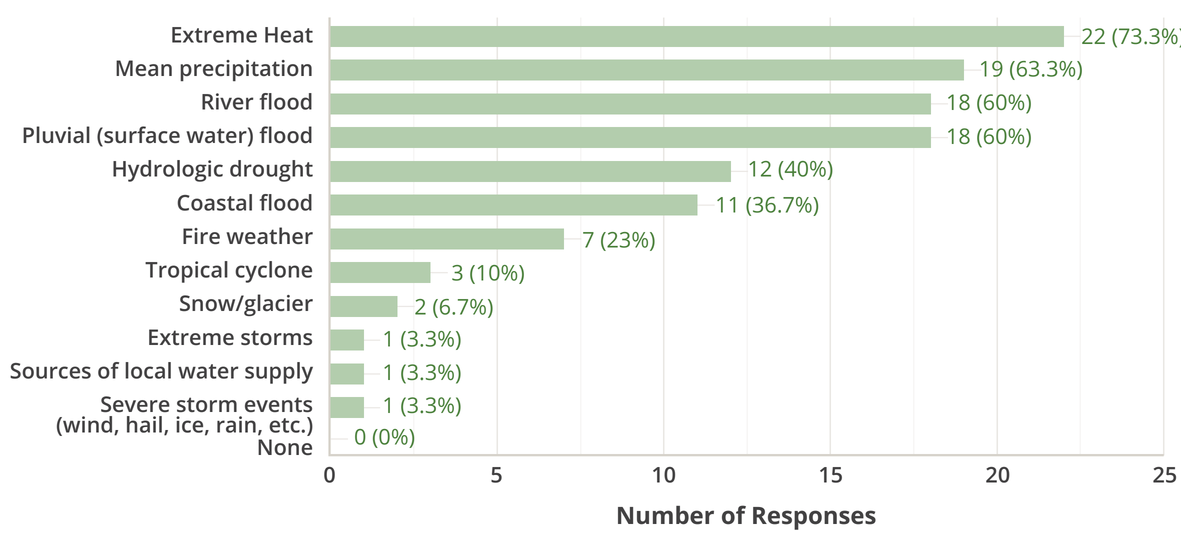
- **Public Health and Safety**
- **Community and Equity priorities**
- **Environmental Protection**

- State Regulatory Requirements
- Federal Regulatory Requirements
- Regional/ Local Regulatory Requirements
- Economic Concerns
- Other: drought, funding opportunities, public and private sector interests.

Responses from the CRRG outreach survey indicated that the types of climate impacts being observed and driving development of climate resilience policy primarily include extreme heat, increases in average rainfall, and flooding (surface water, river, and coastal flooding).

Results and Responses from CRRG 2023 Survey

What are the types of climate impacts that are being observed and driving climate resilience policy development for your organization?



A majority of respondents have observed extreme heat, increases in average rainfall, and flooding.

La Escuela Fratney Elementary School, Milwaukee, WI.
Photo Credit: Reflo Sustainable Water Solutions

4.2.1 CLIMATE RESILIENCE MANAGEMENT QUESTIONS

Climate resilience related policy, ordinance, or document updates should consider GSI appropriately to maximize the benefit of GSI with respect to part of the overall climate adaptation strategy at the local level. GSI can be incorporated into climate resilience strategies but should not be relied upon to be the only resilience solution. Management questions that could be considered during policy updates include:

1. **What impacts** have been experienced by the community because of climate change-related factors (e.g., flooding, urban heat)?
2. **How could GSI** mitigate these factors (e.g., reducing localized flooding, adding shade)?
3. **What design considerations** are needed for GSI if used as a climate resilience strategy (e.g., sizing facilities larger given current or future precipitation patterns, considering plant palettes)?
4. **What other infrastructure-related efforts** should be integrated with GSI during planning and design processes (e.g., integrating GSI with other "grey" infrastructure upgrades such as transportation flood mitigation, water supply, or wastewater)?
5. **What silos** are present that prevent more integrated resilience infrastructure and could be addressed through policy updates (e.g., required separation of private and public stormwater, silos between City departments or other local water-related agencies)?
6. **What adaptive management structures** should be put into place to ensure that infrastructure is updated as new climate trends are observed or projected?

4.2.2 EXAMPLES OF INTEGRATING RESILIENCE INTO GSI-RELATED POLICY

Using the management questions posed, local GSI-related policy and regulatory changes could be implemented that integrate climate resilience. Some examples of these may include but are not be limited to:

1. **Policy updates, for example:**
   - A requirement that the planning, design, and construction of projects and GSI facilities consider and incorporate resilience against climate change impacts for a specified climate change scenario and planning horizon. Such a requirement could require larger sizing of facilities; require specific treatment mechanisms, such as increased retention or detention; or set volume-based capture targets at the watershed scale. This requirement could also address resilience benefit considerations, such as requiring capture and reuse to be considered for certain locations or site uses and streamline approvals of nonpotable uses of captured stormwater.
   - For proposed GSI, a requirement to consider climate adaptation, mitigation, equity, and integration with other green or grey infrastructure (e.g., cloudburst management) for greater resilience in planning and implementation.
   - For existing GSI, a requirement to update asset management, operations and maintenance, system modeling, and assumed performance to address changing precipitation patterns, heat, and other climate risks to adequately understand system performance and maintenance needs. Depending on the outcomes of the updates, existing facilities may need to be retrofit or modified to better respond to changing conditions.
   - Flexibility to enable the mixing of private and public stormwater to allow common or regional GSI facilities to benefit from private development contributions and vice versa.
   - Requirements to integrate resilience planning across departments (i.e., stormwater compliance/public works, transportation, urban forestry/parks, climate adaptation planning, local hazard mitigation planning, water supply, sewer, etc.) and align environmental policies on resilience.

2. **Updates to ordinances, design guidelines, and standard details and specifications** for public and private new and redevelopment GSI, as well as other public infrastructure projects, to consider projected changes in precipitation patterns, sea-level rise, temperature, and other climate impacts. Such updates could require redundancy through multi-layered grey-green stormwater infrastructure systems for unpredictable volumes and flow rates.

3. **Adaptive management of policies and standards** to respond to and anticipate changing conditions due to climate change and its environmental impacts and confirm that existing policies do not result in unintended challenges with GSI implementation.

New climate resilience policy that is released by Federal, State, or Regional entities should also be considered in GSI planning and design processes. This is discussed further in Section 5.

4.3 Additional Considerations - Policy for GSI and Resilience

Additional development of GSI policy guidance in the context of climate resilience could include:

1. Methods for conducting risk assessment relating to GSI performance. Specifically, whether GSI can meet future and anticipated regulatory requirements given current implementation practices, including scenario planning to examine a potential range of outcomes.

2. Guidance for policy decision-making including options for addressing uncertainty with respect to climate change impacts to GSI and utilizing the outcomes of GSI risk assessments.

3. Development of model policy language to address opportunities for improving climate resilience in GSI planning and implementation.

4. Economic evaluation guidance relevant to GSI, including methods for GSI lifecycle assessments with consideration of different future climate-related standards. Economic/risk evaluation guidance could also consider how benefits from GSI could be incorporated into bond ratings that consider climate resilience and provide parameters for evaluating stormwater captured for other resilience needs, such as water conservation and water supply augmentation.

Construction of Orange Memorial Park Stormwater Capture Project, South San Francisco, CA.
Photo Credit: City/County Association of Governments.

5. GSI Planning for Climate Resilience

This section explores considerations for GSI planning related to climate resilience.

Bessie Carmichael Middle School, San Francisco, CA. Photo Credit: San Francisco Public Utilities Commission.

5.1 Considerations for GSI Planning for Climate Resilience

GSI planning entails several steps, including site and opportunities assessment, selection of GSI types, initial layout, conceptual design, and permitting. The scale at which GSI planning is conducted can range from a single property, block, neighborhood, or subwatershed to an entire City, County, or region. The full benefits of GSI may be better achieved when these measures are planned at the regional or watershed scale. Regional scale planning may also consider linkages to related municipal water and sewer infrastructure and land management activities aimed at achieving "One Water" outcomes. Public outreach should be included in early planning stages to provide project direction and garner support for planned GSI.

Future stormwater regulations may require incorporating resilience into GSI planning; however, even in the absence of specific regulatory drivers, stormwater agencies may want to consider the additional risk climate change impacts pose.

CRRG Survey outcomes indicated that fifty-seven percent of survey respondent organizations have plan(s) that address how to incorporate climate resilient into GSI planning or implementation. Examples of such plans include sustainable streets master plans, climate action and adaptation plans, green infrastructure plans, watershed plans, and asset management programs. Climate resilience should be considered in GSI planning when:

1. Climate change could impact GSI performance.
2. GSI has the potential to augment efforts to meet larger community resilience goals (e.g., by providing localized flood reduction, or drought resilience).

Considerations for these separate, but related, GSI planning goals are explored in this section.

Currently, GSI siting considerations and objectives considered in GSI planning assessments include those relating to:

- Ease of implementation, such as location, ownership, accessibility, physical and site use/programming constraints.
- Performance considerations, including hydrologic and hydraulic factors and favorable subsurface conditions.
- Potential benefits, including improved water quality, flood management, groundwater recharge, stormwater capture, and reuse, urban greening, equity, and biodiversity.
- Incorporating social data, such as benefits to disadvantaged and vulnerable communities.
- Funding sources and capital and maintenance costs.
- Cost-effectively complying with applicable regulatory requirements.

Results and Responses from CRRG 2023 Survey

Example plans that specifically address how to incorporate climate resilience into GSI planning or implementation from CRRG Survey respondents:

Vital Streets

Strategic Plan

Green Infrastructure Portfolio Standards

2030 Tacoma Climate Action Plan and Watershed Plan

Asset Management Program

Climate Ready DC

DC Clean Energy Plan

Sustainable DC 2.0

DC Stormwater Regulations

Sustainable Streets Master Plan

Tucson General Plan

OneWater 2100

Tucson Climate Action & Adaptation Plan

Tucson Million Trees

Green Infrastructure Plan

Papio-Missouri River Natural Resources District Regional Hazard Mitigation Plan

Toronto's First Resilience Strategy

KC Green Stormwater Infrastructure Manual

Climate Protection & Resiliency Plan

Integrated Water Resources Management Plan

Green Infrastructure Strategic Action Plan

GI Implementation Plan

Climate Resilience Plan

Energy Plan

Resilient Atlanta Plan


Leland Ave Rain Garden, San Francisco, CA.
(Left: A large storm inundated a facility at Leland;
Right: The event caused excessive sedimentation)

5.1.1 POTENTIAL IMPACTS OF CLIMATE CHANGE ON GSI PERFORMANCE

Projected climatic impact drivers, including changes to snowmelt, larger storm events, higher rainfall intensities, longer duration events, and increased soil moisture, are likely to reduce the effectiveness of GSI facilities[54] by reducing the proportion of runoff volume that may be captured and treated. Climate change may also impact the ability of GSI designed per current guidance to meet or partially meet current water quality or flood control targets. Higher temperatures cause greater stress to vegetation in GSI facilities. Projected sea and lake level rise may impact feasible locations for GSI due to inundation and rising groundwater levels.



Potential considerations for GSI planning processes to better incorporate GSI facility resilience could include:

1. **Locating GSI where climate change** is less likely to impact GSI performance (e.g., avoiding: rising groundwater or surface water levels, areas of increased flood ponding, increased heat and impacts to plants, reduced irrigation water supply, or microclimates in the region observed or projected to have more extreme precipitation or heat).

2. **Setting volume-based or flow-based runoff capture targets** to prevent inundation and erosion of GSI facility infrastructure where there are projections of increased frequency of intense precipitation. Such targets may differ from or exceed current local regulations.

3. **Selecting GSI facility types and plant palette** with consideration of projected changes to climate such as increased heat and drought.

Recommendations for the types of GSI facilities and design changes that could provide resilience to climate impacts are provided in Section 6.

5.1.2 OPPORTUNITIES FOR GSI TO INCREASE COMMUNITY RESILIENCE

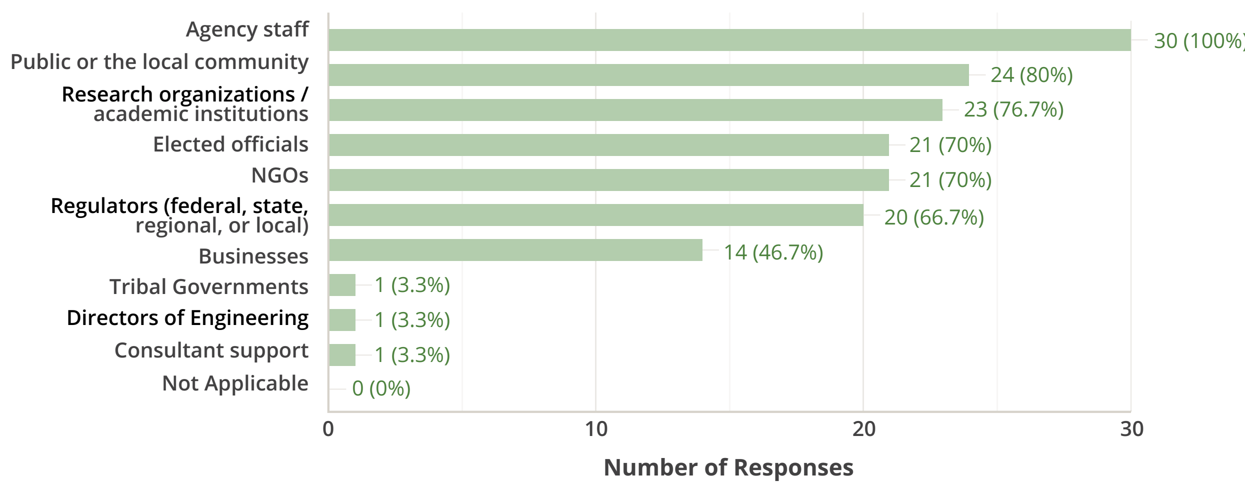
There are several opportunities for GSI to increase climate resilience as part of larger community planning efforts. Increased precipitation associated with larger storms under climate futures may have undesirable impacts on roadway and transit infrastructure, especially for vulnerable communities, where multi-scale GSI implementation at a watershed level may provide valuable relief to associated public infrastructure like streets and roads. Climate change may exacerbate other conditions that GSI is implemented to partially mitigate, such as the urban heat island effect, localized flooding, or impacts on underserved communities. GSI could become part of the toolbox in thinking more strategically about integrated water planning to address prolonged drought.

> Responses from the CRRG Survey indicate that 43% of organizations have constructed GSI projects where the primary driver was to increase community resilience in the face of climate change. Example projects included surface capture of water for irrigation, tree trenches, stormwater management ponds and basins, daylighting projects, and porous pavement. Other primary drivers of project implementation included flood mitigation, water quality and urban heat island effect. Survey respondents also indicated that input from agency staff, elected officials, and the public community were prioritized during project implementation.

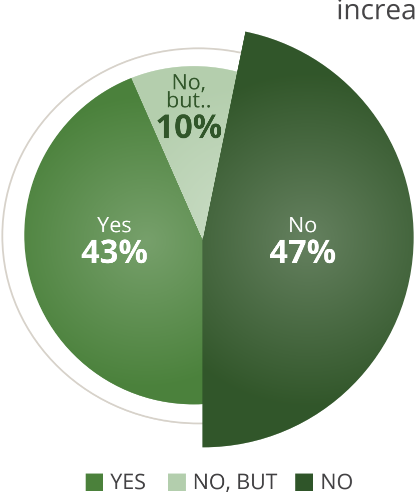
The remainder of this Guide is focused primarily on opportunities for GSI to increase community resilience as part of broader resilience efforts.

Results and Responses from CRRG 2023 Survey

Who is or would be involved in climate resilience policy development for your organization?



Has your organization constructed any GSI projects where the primary driver was to increase community resilience in the face of climate change?



YES, SUCH AS....

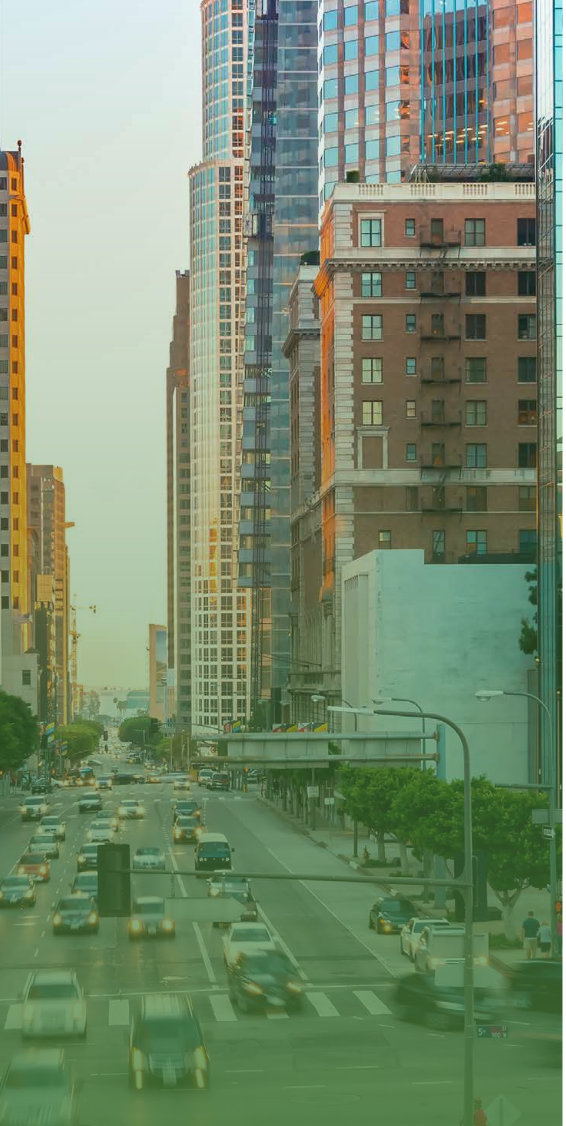
- Daylighting projects and porous pavement
- Detention basin
- Bioretention and underground detention tanks
- Orange Memorial Park multi-benefit project
- Tree trenches
- Surface capture for irrigation
- Stormwater management ponds

NO, BUT...

...we are in the development phase for projects like this.

...other things were considered the primary driver of the project, like...

- Water quality
- Flooding mitigation
- Urban heat island effect



CRRG ROUNDTABLE DISCUSSION

Climate Resilient Communities (CRC) in San Mateo County worked with residents to identify flooding and displacement as key community concerns in East Palo Alto. With community input, nature-based solutions were prioritized as a response to flood concerns. CRC was able to secure a grant to construct 25 rain gardens in the community to reduce localized flooding.

5.2 Integrating GSI Planning and Climate Resilience Efforts

Climate resilience objectives should be considered in the earliest phases of GSI planning and assessment. A flowchart, "GSI Planning for Climate Resilience" illustrating how to integrate GSI planning and climate resilience efforts is provided on the following page. A description of how to apply the flow chart is included in this section.

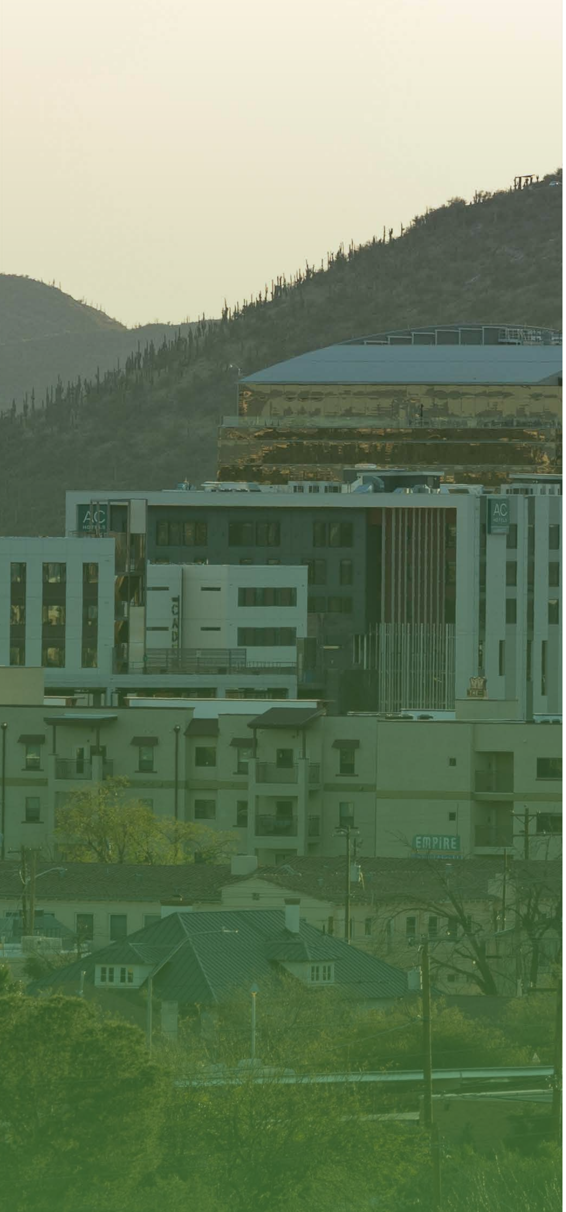
5.2.1 IDENTIFYING CLIMATE RESILIENCE OBJECTIVES FOR GSI

In initiating a local or regional planning effort related to GSI and climate resilience, an agency should first identify and define its Region of Interest. For a given Region of Interest, the following steps are recommended for planning GSI in the context of climate resilience:

STEP 1: Identify Climate Resilience Planning Objectives for GSI
Identify the range of climate resilience related objectives for the Region of Interest that may relate to GSI. These could include:

- **Regulatory drivers**, particularly where federal, state, or local governments have instated or plan to instate requirements for water quality, flood management, or climate resilience. Objectives could include complying with current requirements, or preemptively taking steps toward compliance with known upcoming regulatory changes or new standards.
- **Specific climate resilience concerns** relating to risks to public health and safety and infrastructure from climate change impacts including flooding, drought, heat, wildfires, intense storms, or extreme cold.

- **Community equity priorities** in historically disinvested communities, which are typically the most vulnerable and least resilient to effects from climate changes. Equity related climate resilience objectives should consider important factors like socioeconomic concerns and lack of safe and clean public spaces in addition to vulnerability to climate impacts. Because community improvements can result in an increased cost of living and displacement of the original residents, safeguards to prevent displacement should also be considered.
- **Water demands and supply reliability,** as affected by population growth, rising heat, and insufficient recharge of groundwater supply sources.



CRRG ROUNDTABLE DISCUSSION

With a key objective of reducing urban heat, Tuscon Clean and Beautiful has identified rebate programs offered by the local electric utility and water supplier to fund GSI with trees for their urban forestry initiative.

STEP 2: Prioritize Climate Resilience Objectives for GSI

Once the range of climate resilience objectives for GSI are identified, the objectives should be prioritized based on known urgency and support. Priorities should be determined using available data, studies, and input from other internal and external stakeholders. Coordination with other agencies can highlight critical health and safety risks, and review of data and research published by others can inform needs. Most importantly, outreach with key stakeholders, CBOs, and other community representatives can shed light on equity needs and how these can be addressed in conjunction with other climate resilience objectives for GSI.

STEP 3: Formalize Climate Resilience Objectives for GSI

The prioritized climate resilience objectives should be formalized by obtaining support from community members and decision makers and confirming alignment with other lead or partner agency plans and programs. Following buy-in from residents and community stakeholders, agency leaders, elected officials, and other key partners, agencies can develop actionable goals and identify potential funding opportunities focused on the objectives.

Broader partnerships and multi-disciplinary collaboration may be needed to formalize climate resilience objectives for GSI and pursue related actionable goals. GSI project implementation increasingly involves engaging with other regional landowners with different motivations and requirements, including but not limited to schools, recreation districts, water and sewer districts and utility agencies, and the private sector (e.g., developers).

In cases where funding has not been fully secured for GSI implementation, funding mechanisms including capital improvement programs, fees, taxes, and grants can be researched and pursued. Formalized climate resilience objectives for GSI can be used to focus messaging and target specific grant opportunities.

STEP 4: Identify and Select Project Opportunities

The lead agency can then identify various GSI project opportunities to address the formalized climate resilience objectives. Further guidance on identifying GSI project opportunities to meet climate resilience objectives is provided in the next section.

GSI Planning for Climate Resilience

Establishing Climate Resilience Objectives

Climate Resilience Objectives for GSI

1 Identify

- Determine **Regulatory Drivers** based on current or anticipated federal/state/local requirements and guidance for water quality, flood management, and climate resilience.
- Identify **Climate Resilience Concerns,** like infrastructure concerns, community health needs, and lack of green spaces.
- Include **Community Equity Priorities,** such as safety, socioeconomic concerns, and safeguards against displacement.
- Assess current and projected **Water Demands** and consider improvements for **Water Supply Reliability.**

2 Prioritize

- Identify critical **Health and Safety Risks** in coordination with other municipal agencies, such as combined sewer overflows, permit violations, climate impacts, water supply reliability, and urban heat.
- Conduct **Outreach** with key stakeholders and community-based organizations to understand and conceive ways to address identified needs and priorities in conjunction with water-related objectives.
- Review **Available Data and Research,** including watershed management plans, other planning documents, and results of local studies related to water challenges, climate impacts, and related concerns.

3 Formalize

- Obtain support from **Decision Makers,** including elected and appointed officials.
- Obtain **Community Support** through established relationships, tabling, surveys, meetings, workshops, etc.
- Confirm compatibility with **available funding** purposes, including fees, taxes, grant funding, etc.
- Confirm alignment with goals of **other plans and programs.**

4 Implement

- Identify project opportunities throughout the Region of Interest that could meet established objectives.
- Refer to **"GSI Project Siting for Climate Resilience".**

SW Marigold Street, Portland, OR. Photo Credit: City of Portland, courtesy Bureau of Environmental Services.

5.2.2 CLIMATE RESILIENCE OBJECTIVES TO ADDRESS KEY CLIMATE IMPACTS

Tools developed for this Guide focus on a few key climate resilience objectives that correspond with several of the climate impact drivers presented in Section 2.2.1. The linkage between the climate impact drivers and key climate resilience objectives, as well as how GSI relates to these objectives, is shown in the table provided.

Table 4. Climatic Impact Driver and Corresponding Climate Resilience Objective

CLIMATIC IMPACT DRIVER	CORRESPONDING CLIMATE RESILIENCE OBJECTIVE
Extreme heat	**Reduce Urban Heat** to reduce health impacts of extreme heat. Vegetated GSI can provide urban cooling benefits.
Heavy precipitation with pluvial flood	**Improve Stormwater System** to manage increases in precipitation, pluvial flooding, early snow melt, and extreme events Including cloudburst events. GSI could be part of the set of infrastructure solutions implemented to address these challenges.
Snow	
Hydrological drought	**Diversify Water Supply** to reduce the reliance on supply sources impacted by drought, or changes to snowpack or precipitation. Certain types of GSI can augment water supply.

An additional climate resilience objective of focus is to **benefit vulnerable communities.** This objective is not identified for any specific climate impact driver but instead would respond to climate impacts for target communities.

5.2.3 GSI PROJECT SITING FOR CLIMATE RESILIENCE

The first step in implementing projects that can meet formalized climate resilience objectives is to identify sites where GSI could provide benefits associated with those objectives. The climate resilience objectives of focus for this Guide, introduced on the previous page in relation to CIDs, include those described below. The "GSI Project Siting for Climate Resilience" tool provided on the next page provides an overview of site characteristics that correspond with these climate resilience objectives.

Benefit Vulnerable Communities

GSI projects that benefit underserved and climate-vulnerable communities are intended to reduce the impacts of climate change on those communities. While many of these projects would be located within the target community to provide, for example, urban cooling or mitigation of localized flooding, GSI projects located upstream of communities should also be considered. To increase the benefits provided to the community and garner support, GSI projects should be implemented in conjunction with other needed improvements identified by the residents, such as active transportation, recreation, or creation of green spaces, wherever possible.

Reduce Urban Heat

GSI implemented to reduce urban heat should be sited in communities currently affected by urban heat and/or projected to have increased heat impacts. These are typically areas with low vegetation cover and high imperviousness. The intended outcome of GSI implemented to address urban heat would be to increase vegetation and evaporative cooling.

Improve Stormwater System

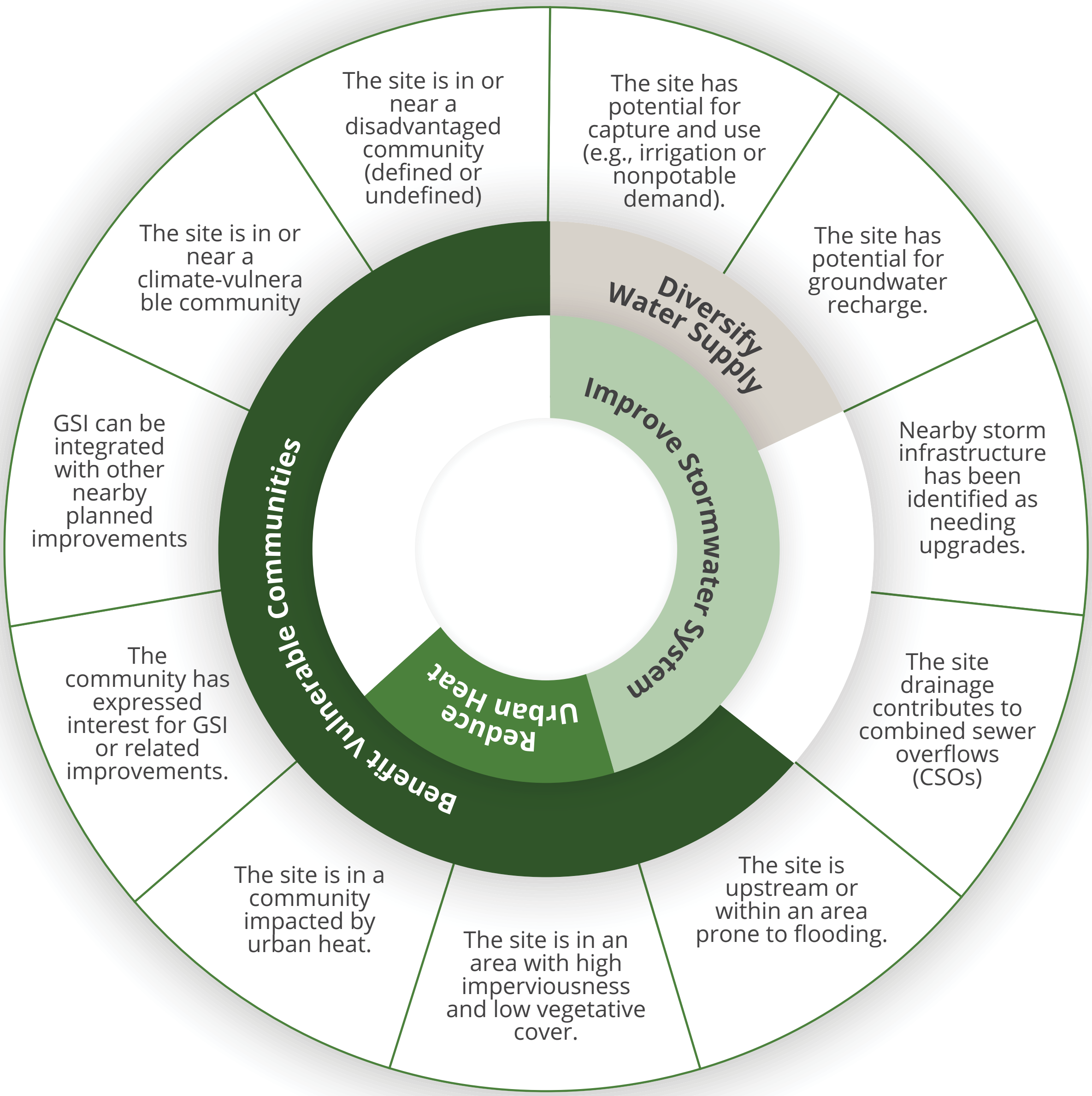
GSI projects can provide localized hydrologic benefits in areas of concern for existing storm system infrastructure, especially those prone to localized flooding or that contribute to combined sewer overflows downstream. The intended outcome of GSI implemented as part of stormwater system improvements is to manage a portion of stormwater flows through detention, retention (including infiltration or storage and use), or other diversion to reduce current or projected storm peak flows. GSI can also be implemented in combination with other grey improvements (for example, detention facilities or upsized pipes) to reduce flood flows and mitigate cloudburst events and can be designed in some cases to reduce the required capacity of grey improvements.

Diversify Water Supply

GSI projects intended to augment water supply can be used to provide groundwater recharge or store water for nonpotable use. Sites that have infiltrative soils and are overlying groundwater basins are potentially good candidates to provide groundwater recharge. Groundwater protection siting measures, including but not limited to locating the facility where there is at least 15 to 20 feet depth of soil separation, and adequate distance away from contaminated areas, septic fields, drinking wells, or geotechnical concerns, must also be considered. Sites that may have demand for nonpotable use, such as irrigation, water truck filling (e.g., for dust mitigation), or toilet flushing (where plumbing code allows) can be considered for stormwater capture and use.

GSI Project Siting for Climate Resilience

Select GSI project sites with characteristics that relate to established climate resilience objectives.



Intended Outcomes for Key Resilience Objectives:

Benefit Vulnerable Communities

Reduce community climate impacts

Reduce Urban Heat

Increase vegetation and evaporative cooling

Improve Stormwater System

Manage increased stormwater flows and retain stormwater

Diversify Water Supply

Retain stormwater for water supply

CRRG TUCSON INTERVIEW

During GSI Project Siting, the City of Tucson incorporates a Tree Equity Score, a tool created by American Forests, and incorporates tree canopy cover, climate, demographics, and socioeconomic data.

Photo Credit: City of Tucson, AZ

The GSI Project Siting for Climate Resilience tool is intended to help agency staff identify GSI project opportunity sites with characteristics that relate to formalized climate resilience objectives and inform prioritization of GSI project opportunities.

Recommended datasets for determining GSI priorities and objectives are shown in the box below.

Data Needs for: GSI Project Siting for Climate Resilience

Benefit Vulnerable Communities

- [ ] Community Demographic Data
- [ ] Park Need
- [ ] Outreach with community-based organizations and residents
- [ ] Other community planning documents

Reduce Urban Heat

- [ ] Land Cover / Land Use data
- [ ] Urban Heat Studies

Improve Stormwater System

- [ ] Rain Gauge Data and Isohyetal maps
- [ ] Subdrainage Areas
- [ ] Flood Risk Area
- [ ] H&H Modeling and Analysis
- [ ] Storm Drain Infrastructure

Diversify Water Supply

- [ ] Soil types / Geology / Geotechnical conditions
- [ ] Mapped contaminant plumes or contaminated sites
- [ ] Reservoirs
- [ ] Groundwater Basins
- [ ] Recycled Water Infrastructure
- [ ] Site Irrigation Demand

In addition to these considerations, it is important to consider the engineering feasibility of a GSI project during the planning phase. A checklist of data needs used to identify sites that may be suitable for GSI is provided in Appendix B.

CRRG MILWAUKEE INTERVIEW

Milwaukee Metropolitan Sewerage District (MMSD) has developed and implemented climate resilience metrics in project planning. MMSD has an existing green infrastructure retention capacity goal of 50 million gallons over the permit term. MMSD's 2035 Vision aims to create enough green infrastructure in its service area to capture 740 million gallons of water each time it rains.

5.3 Additional Considerations – Planning for GSI and Resilience

Additional development of GSI planning guidance in the context of climate resilience could include:

1. Detailed guidance on processes to locate GSI opportunities:
   - Describing logic-based geospatial analyses to identify beneficial GSI candidate sites and remove less-favorable opportunity locations.
   - Planning frameworks that address uncertainty (e.g., Robust Decision Making).
   - Methods to better integrate GSI with infrastructure planning, including street and drainage improvements.
2. Developing an evaluation framework to prioritize project opportunities to robustly capture considerations related to environmental performance, climate change risk, and social vulnerabilities and benefits, including developing benefit metrics and analyzing projects based on those metrics.
3. Developing cost-benefit analyses relating to GSI and climate resilience.

Milwaukee Area Technical College, Downtown Campus, WI. Photo Credit: Milwaukee Metropolitan Sewerage District.

6. GSI Design for Climate Resilience

This section considers facility-scale GSI designs and design improvements that can provide benefits toward climate resilience objectives.

Wightman Park, Pittsburgh, PA. Photo Credit: City of Pittsburgh

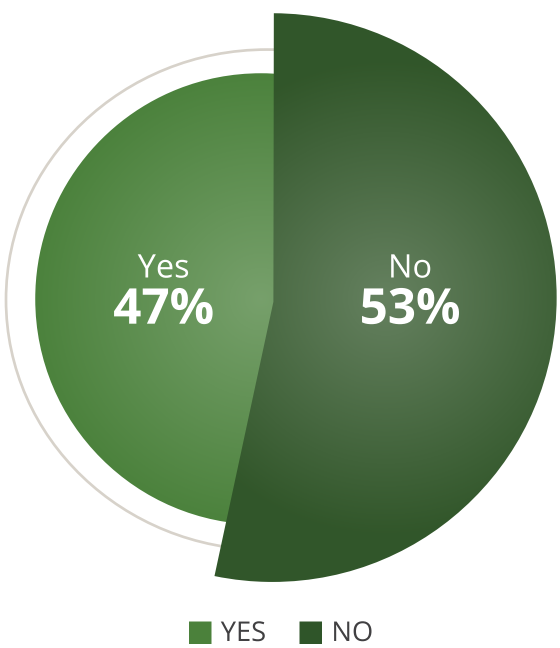
6.1 Considerations for GSI Design for Climate Resilience

Several CIDs related to GSI are projected to change in the future and will affect GSI design. These drivers include changing storm event characteristics such as the size, intensity, duration, and location of significant rain events,[55] along with flood and submergence from rising sea, riverine, and groundwater levels and extreme temperature.

Responses from the CRRG Survey indicate that 47% of organizations have modified how GSI projects are planned, implemented, or maintained based on climate change projections. Some examples are included throughout this section. Impacts are anticipated at different scales, and while there is a need for adaptation at the facility, project, and sub-watershed scale, the section below focuses on GSI design at the facility scale; however, the tools and resources in this section do provide guidance on a range of design considerations for different climate trends on a regional basis.

Results and Responses from CRRG 2023 Survey

Has your organization modified how GSI is planned, implemented, or maintained based on climate change projections and/or impacts?



"Climate change projections are informing priority areas for GSI and overall stormwater retrofit projects"

"GSI gets more advocacy and risk analysis in the planning process of our work specifically for its climate resilience value."

"Tree planting locations are chosen for greatest impact, and plant species are chosen for resilience."

"Climate change also affects design calculations and sizing."

"We modified our stormwater rules to require infiltration of the first flush of stormwater.

6.2 Climate Resilience Benefits of Different GSI Measure Types

Different GSI measure types provide different benefits relevant to climate resilience objectives. The matrix below can be used to select specific GSI types , sometimes referred to as GSI structural best management practices (BMPs), based on regionally and locally relevant climate resilient project and program priorities.

Addressing Climate Resilience Objectives using GSI

GSI Measure Types that could provide benefits for climate resilience objectives are identified in the matrix below.

GSI Treatment Category	GSI Measure Type	CLIMATE RESILIENCE OBJECTIVES			
		Improve Stormwater System	Reduce Urban Heat	Diversify Water Supply	Benefit Vulnerable Communities
Infiltration-Based	Drywells	●		●	●
	Infiltration basin	●	●*	●	●
	Infiltration trench	●		●	●
	Pervious pavement	●		●	●
	Subsurface infiltration system (gallery or vault)	●		●	●
Capture and Reuse	Rainwater harvesting (parcel-based)	●		●	●
	Stormwater capture and use (regional; vault-based)	●		●	●
Bioretention / Green Street Features	Bioretention (lined) or flow-through planter	●*	●		●
	Bioretention (unlined)	●	●	●*	●
	Engineered Tree Well	●*	●		●
	Suspended pavement systems (e.g., Silva Cells) with trees	●*	●		●
Stormwater Treatment	Media filter with vegetation (includes tree well filters and high flow rate biofiltration)		●		●
Detention	Extended detention basin	●			●
Other	Constructed wetlands		●		●
	Green roofs		●		●
	Vegetated swale		●*		●
Self-Treating Areas or Non-Structural BMPs	Conservation Landscaping		●		●
	Forested patches		●		●
	Soil Restoration		●		●

*depending on site and design

Wightman Park Phase 2 Construction.
Photo Credit: City of Pittsburgh, PA.

6.3 Incorporating Climate Resilience into GSI Design

This section introduces how climate resilience objectives can be considered in GSI sizing and design processes and how changes or enhancements to GSI design may provide additional climate resilience benefits.

6.3.1 GSI SIZING CONSIDERATIONS FOR CLIMATE RESILIENCE

While the climate impacts on GSI are expected to vary by region, location, and type of facility, larger storm events, higher rainfall intensities, longer duration events, and more saturated initial conditions are likely to reduce the effectiveness of GSI facilities.[56] Hydrologic changes due to climate change may necessitate updated GSI facility sizing requirements or guidance. Design standards are typically developed based on historical precipitation data, and GSI facilities are designed with the assumption that past rainfall-runoff patterns will persist over their design life. Climate change is anticipated to alter historic rainfall- runoff patterns, such as the proportion of smaller, low- intensity events versus larger, high-intensity events, as well as the duration of different storm sizes. These precipitation changes could cause damage to an undersized facility, or result in a smaller overall amount of runoff captured. In these cases, the facility may no longer provide the hydrologic or water quality benefits it was designed to provide.

To address the potential performance issues that could arise from facility sizing that is inconsistent with future precipitation patterns, several agencies in North America have or are considering changing GSI sizing standards. Seven agencies identified through CRRG outreach indicated that they have incorporated climate change projections into GSI sizing or sized facilities differently to account for changing precipitation patterns.

For further context on GSI sizing, the history of the established conceptual model for GSI siting, sizing, and design and how these standards may need to be modified to respond to climate change is summarized in Appendix C.

CRRG ROUNDTABLE DISCUSSION

The City of Vancouver has policies requiring consideration of climate resilience and has updated their intensity, duration, and frequency (IDF) curves for future rainfall.

City of Portland is updating their GSI soil specification after finding through monitoring studies that their current soil specification drains too quickly and can lead to poor plant outcomes, especially with increased heat.

Manage Increased Stormwater Flows (Improve Stormwater System): Changes to precipitation patterns may require GSI facilities to manage increased stormwater flows. In addition to simply increasing GSI facility storage volume, several design decisions can help accommodate larger or more intense storm peaks even when annual volume is not projected to increase. This can include designing the facility offline from the stormwater system, so only water quality flows are directed to the facility. Additionally, changes to the design and sizing of inlet, outlet, and overflow components may be needed. As the hydrologic regime shifts, an inlet design that previously captured sufficient volume and flow may no longer do so. Similarly, if a facility must be designed to capture more intense or larger storms, erosion and sediment control components, underdrain sizing, outlet sizing, and overflow operations may also need to be designed specifically to manage increased flows and volumes. When reconfiguring GSI designs to manage changing precipitation regimes, a designer must consider both maintaining facility performance (i.e., through increasing the amount of stormwater captured and treated and the water quality benefit provided) and protecting facility infrastructure from intense flows that could damage components.

Retain More Stormwater (Diversify Water Supply): Infiltration and capture and reuse GSI measure types retain stormwater by recharging it to the subsurface or storing it for later use. Water retained can be increased by increasing the storage volume of these facilities. Additionally, infiltration facilities can incorporate subsurface amendments or gravel layers that increase the amount of infiltration in the immediate subsurface or provide additional water quality treatment prior to percolating into groundwater below.

Increase Vegetation and Evaporative Cooling (Reduce Urban Heat): Vegetated GSI facilities, particularly those with trees, can provide urban cooling benefits. GSI facility vegetation must be carefully selected for fast draining soils. Plant and tree species selection may require more site-specific plant palettes that survive in harsh (including extreme dry and submerged) conditions in anticipation of rising temperatures and changing precipitation patterns. Approved species lists by municipalities should take into consideration how climate change will affect plant hardiness zones. The shifting of those zones over time (projected by the US Forest Service)[57] with rising temperatures and increased precipitation intensity and/or increased periods of intense drought will need to be considered when designing vegetated systems to last decades into the future. If trees are included, sufficient soil volume and composition must be included to support roots. Additional design improvements to enhance soil moisture retention and sustain plant health as temperatures increase include media amendments (e.g., biochar) that encourage water retention while maintaining drawdown rates, adding additional surface mulch, or changing irrigation types or frequency. GSI facility grades and hydrozone can be evaluated for optimizing plant health and selecting specific species for unique GSI configurations (i.e., stormwater planters with deeper uniform media vs. rain gardens with variable surface grades and elevations related to different hydrozones).

Consider Changing Subsurface Conditions: In nearshore locations with shallow groundwater, future groundwater levels should be considered when siting and designing GSI. These considerations will affect whether a GSI facility should incorporate an impermeable liner to prevent groundwater and/or seawater from infiltrating into the facility, impacting plant health and water quality.

Provide Benefit Vulnerable Communities: All types of GSI facilities sited appropriately and designed in collaboration with community members can provide benefits for vulnerable communities to varying degrees. GSI should be designed to consider specific climate resilience objectives and community needs or be included in concurrent community multi-benefit projects whenever possible, such as improvements to public transportation and recreation/park spaces. Projects may also be designed to achieve culturally relevant goals for communities, such as accounting for preferences for athletic versus open space or integrating artistic components.

6.3.2 GSI DESIGN IMPROVEMENTS FOR CLIMATE RESILIENCE

GSI facility design changes and improvements can provide benefits for specific climate objectives. Suggested design changes that could provide climate resilience benefits are included in the matrix below. GSI measure types that could be designed with the identified changes are checked for each category.

GSI Design Improvements for Climate Resilience

GSI Treatment Category	GSI Measure Type	MANAGE INCREASED STOMWATER FLOWS						RETAIN MORE STORMWATER		INCREASE VEGETATION AND EVAPORATIVE COOLING THROUGH IMPROVED PLANT HEALTH					CONSIDER CHANGING SUBSURFACE CONDITIONS
		Design facility offline from conveyance	Add or configure underdrain for larger flows	Design inlet for larger flows	Design outlet for larger flows	Add outlet controls	Sediment control forebay or erosion control for more intense flows	Increase storage volume	Subsurface Soil Amendments	Specify treatment media amendments	Incorporate Trees with appropriate soil volume and composition	Specify resilient, low-maintenance plant palette	Develop water-efficient irrigation schedule	Increase mulch layer	Install impermeable liner under facility**
Infiltration	Drywells	●		●				●	●						
	Infiltration basin	●		●			●	●	●						
	Infiltration trench	●					●	●	●						
	Pervious pavement	●						●	●						
	Subsurface infiltration system (gallery or vault)	●		●				●	●						
Capture and Reuse	Rainwater harvesting (parcel-based)	●						●							
	Stormwater capture and use (regional; vault-based)	●		●	●	●		●							●
Bioretention / Green Street Features	Bioretention (lined) or flow-through planter	●	●	●	●	●	●	●		●	●	●	●	●	●
	Bioretention (unlined)	●	●	●	●		●	●	●	●	●	●	●	●	●
	Tree wells (LID)	●	●	●	●		●	●		●	●	●	●	●	●
	Suspended pavement systems (e.g., Silva Cells) with trees	●	●	●	●		●	●		●	●	●	●		●
Stormwater Treatment	Media filter with vegetation (includes tree well filters and high flow rate biofiltration)	●	●	●	●		●			●		●	●		●
Detention	Extended detention basin	●		●	●	●	●	●							●
Other	Constructed wetlands	●		●	●	●	●	●			●	●			●
	Green Roofs	●								●		●	●	●	
	Vegetated swale	●	●	●	●		●			●		●	●		●
Self-Treating Areas/ Non-Structural BMPs	Conservation Landscaping Forested Patches Soil Restoration	** These practices may be sized differently to improve climate resilience. None of the listed design improvements are applicable for this category.													

**Requires proper consideration during design

CRRG ROUNDTABLE DISCUSSION

New York City, a CSO community, updated their GSI design standards to include a "cloudburst toolbox" to manage increased flows and worked with water and sewer operations to identify locations for enhanced GSI.

6.3.3 ADDITIONAL GSI DESIGN CONSIDERATIONS

GSI Treatment Trains and Active Treatment Mechanisms: Single GSI facilities that rely on fixed detention storage may fare worse than facilities that incorporate multiple treatment mechanisms (i.e., retention, infiltration, soil storage, evapotranspiration), especially where rainfall intensity, duration and frequency may be more dynamic or increase over time. In many regions, regardless of trends in heat and precipitation, multiple GSI facility types used together in a 'treatment-train' may provide more resilience than single facilities. Other potential options to increase GSI resilience to climate change impacts that are appropriate for regional-scale projects include using real-time control, adjustable outlet structures, stormwater capture and use, and GSI implemented with other large-scale nature-based solutions or cloudburst-type facilities.

CSO Communities: CSOs must manage increased volumes of water from both increased storm volumes and wastewater. CSO communities will require additional analysis to estimate the amount of upstream GSI-provided retention (e.g., infiltration) and detention needed to offset anticipated future runoff volume. The siting of upstream GSI and the volume provided may require adjustment to adequately prevent overflows given changing climate conditions. Because CSO systems are often older infrastructure and may not have been upsized with growing populations, these communities face compounded challenges in managing increased stormwater flows. Stormwater managers in CSO communities must collaborate closely with their wastewater counterparts to devise solutions.

GSI Facility Retrofit Needs: The performance of existing GSI facilities may decline because of impacts of climate change. Declining performance could include but not be limited to:

1. **Capturing a smaller proportion of average annual runoff** or a smaller total volume, resulting in increased occurrence of bypass and less proportional or total treatment.
2. **Erosion and sediment loading impacts** to GSI facility surface or hydraulic components.
3. **Other hydraulic issues** such as extended ponding or flooding near inlet, outlet, overflow with resultant vector issues, or downstream flooding.
4. **Subsurface impacts,** including groundwater intrusion into facility or export of pollutants to sensitive underlying groundwater basins; and/or
5. **Poor vegetation survival.**

Existing facilities may require re-analysis and retrofit of hydraulic components, installing a facility liner, replacing vegetation with better-suited species, enlarging facilities, or building additional facilities upstream or downstream.

6.4 Additional Considerations – Design for Climate GSI Resilience

Additional development of GSI design guidance in the context of climate resilience could include:

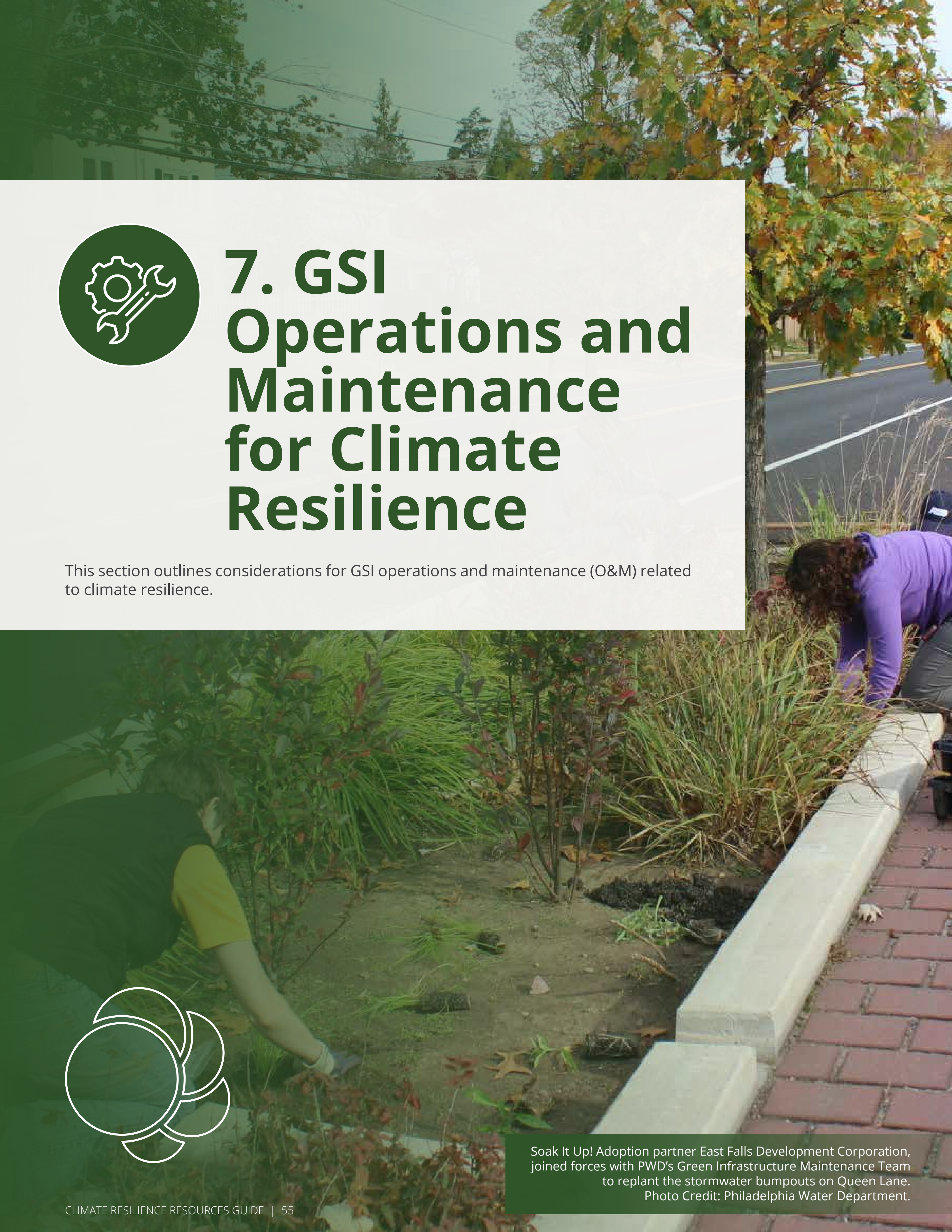
1. Methods to Develop New GSI Design Standards or Guidance – This could include a technical and/or decision-making methodology for identifying the changes needed for GSI volume or hydraulic design. The tool could incorporate the range of estimated GSI performance changes leveraging existing tools at the local or regional level. This would result in the GSI sizing factors or guidance that appropriately accounted for observed or projected changes in near-term precipitation and projected precipitation compared to long-term historic precipitation.

2. GSI design and retrofit changes needed for resilience can be further studied by comparing predicted future climate conditions to historical conditions and/or modeling GSI using a range of these. This analysis can provide insight into how the performance of GSI designed per current practices may be impacted and the specific changes to address those impacts.

Liberty Green Park, Pittsburgh, PA. Photo Credit: City of Pittsburgh

7. GSI Operations and Maintenance for Climate Resilience

This section outlines considerations for GSI operations and maintenance (O&M) related to climate resilience.



Soak It Up! Adoption partner East Falls Development Corporation, joined forces with PWD's Green Infrastructure Maintenance Team to replant the stormwater bumpouts on Queen Lane. Photo Credit: Philadelphia Water Department.

7.1 Considerations for GSI Operations and Maintenance for Climate Resilience

Typical O&M practices for GSI include routine and non-routine actions specific to each facility type.

Examples of GSI O&M practices and their frequency include:

1. **Frequent O&M needs:** irrigation, plant maintenance, trash and sediment removal.
2. **Post-storm O&M needs:** Inspections to examine damage including erosion, sediment loads, standing water/drawdown issues, and needed rehabilitation.
3. **Annual O&M needs:** mulch replacement, clean out of hydraulic components (inlet, outlet, or underdrain), addressing fine sediment accumulation.
4. **Infrequent O&M needs:** scarification of the top layer of media, plant replacement, replacement of hydraulic or structural components, replacement of media/mulch.

Several climate impact drivers, including changes to temperature, precipitation, flood, rising sea, riverine, and groundwater levels, and changes to snow patterns could impact O&M. Typical GSI O&M practices and frequency may require adjustment to maintain performance under future climate change.

Potential changes to these activities could include:

1. **Frequent O&M needs:** more frequent, longer term, or higher volume of irrigation or more frequent plant maintenance needs due to higher temperatures and/or changing precipitation patterns.
2. **Post-storm O&M needs:** More frequent inspections or rehabilitation (e.g., increased erosion caused by higher intensity storms).
3. **Annual O&M needs:** deeper or more frequent mulch application, increased frequency of sediment removal, and maintenance of hydraulic components to account for increased erosion and flooding.
4. **Infrequent O&M needs:** Plant or plant palette replacement due to drought conditions; retrofit/replacement of hydraulic components; replacement of media to provide adjusted/ needed filtration or drawdown rate.

Impacts of June 2021 heat dome at a GSI facility without shade in the City of Portland. Photo Credit: City of Portland, OR, courtesy of Bureau of Environmental Services.

In addition to the typical O&M practices listed, the impact of changes to regular maintenance practices of nearby infrastructure should be considered. This could include, for example, increased or different amounts of salt applied to adjacent roadways in response to snow and ice changes, or increased irrigation applied to adjacent landscaping in response to increased temperature. These adjacent O&M practices could generate runoff that may impact GSI facilities; responsive GSI O&M needs should be considered.

7.2 Incorporating Climate Resilience into GSI O&M

O&M programs should adapt as needed to keep pace with anticipated climate change, recognizing that severe impacts are often unpredictable and will occur more frequently. Adaptive management processes may require more frequent inspections to learn how enhanced O&M affects GSI performance. A flow chart illustrating how agencies could identify potential changes needed to GSI O&M practices is shown. To address climate resilience in their O&M processes, an agency should first assess their current O&M practices, including effort, equipment, schedules, and other resources. Based on this, the agency can identify seasonal and long-term trends and changes in the performance and condition of the GSI facilities under the current level of effort.

GSI Operations and Maintenance Changes for Climate Resilience

Examine Historic O&M Effort

- ☐ Inspection Documents
- ☐ Staff Time or Contractor Time Spent (by facility or site)
- ☐ Activities Conducted
- ☐ Equipment Used

Identify Trends in O&M

Analyze available data to identify seasonal and long-term trends and changes in:

- ☐ Site condition (e.g., less healthy vegetation; more erosion, effects of road salt)
- ☐ Maintenance staff time needs (e.g., more time spent with landscape needs; repairing erosion damage)
- ☐ Maintenance activities (e.g., replacing plants; replacing/adding flow dissipation)
- ☐ Maintenance equipment needs
- ☐ Irrigation demand and effectiveness

Use Trends to Adjust O&M Resources

- ☐ Revise guidance to reflect changes in maintenance activities and include retrofit options (e.g., if erosion more frequently observed, redesign/add more flow dissipation)
- ☐ Revise budget to account for changes in maintenance staff needs and equipment (e.g., increased budget to account for flow dissipation retrofits)
- ☐ Purchase additional needed equipment for staff

Over time, visual inspection data coupled with precipitation and temperature data could be used to examine trends in GSI performance with specific O&M practices; changes to those trends would indicate that updates to an O&M program are needed. Changes to the overall condition of the GSI facility, irrigation demand, the degree of maintenance activities needed such as cleaning and plant replacement, and what resources are needed to achieve best performance can be observed over time. Using these trends, modifications can be made to reflect the needed O&M activity or frequency changes and facility retrofits, and the agency can revise budgets and obtain additional resources and funding, as needed. In addition, increasing temperatures may affect the health of maintenance staff, requiring schedule adjustments.

A key component to adaptive management is a robust asset management strategy that can efficiently and consistently capture O&M-related data. Changes to asset management with consideration of climate resilience may also be needed. Lessons learned from changes to O&M practices should be documented such that they can be applied to future planned projects.

7.3 ADDITIONAL CONSIDERATIONS

A critical component for adapting GSI O&M programs includes communication, education, and training of GSI maintenance staff and personnel. Staff should be made aware of policy changes relating to GSI and potential changes to GSI performance based on scientific studies or community-specific analysis. Staff communication should be bidirectional and encourage the reporting of anecdotal evidence or observations of potential climate-related impacts on GSI facilities. A communication plan including education and training of staff, along with obtaining input from staff, should be developed to support and inform adaptive management of O&M practices.

Community involvement and partnerships can also be considered in the O&M phase. Many O&M tasks would require work by trained GSI maintenance professionals (e.g., addressing sedimentation/ erosion, replacement of soil media or structural components) or landscape professionals (e.g., mulching, pruning, planting, weeding). Work force development programs to train youth, underserved communities and others interested in GSI maintenance could build out long-term and sustained adaptive capacity while providing economic opportunities. In some neighborhoods with active community groups, the local community and residents can also provide stewardship of GSI through minor plant maintenance and trash and debris removal. Local community involvement can improve the potential for long-term success.

Additional development of GSI O&M guidance in the context of climate resilience could include:

1. Providing guidance on an education, training, and communication strategy that supports adaptive management of GSI O&M practices.
2. Identifying key components of asset management tools that may require update to adequately track climate trends and impacts (e.g., better linkage with preceding storm size, geospatial data needs, plant health rating scales, etc.).

PWD's Green Stormwater Operations team maintains GSI in 2021.
Photo Credit: Philadelphia Water Department.

8. Summary and Ongoing Updates

This Guide explores the intersection of GSI and climate change. It describes how GSI that is thoughtfully planned, designed, and implemented can be important for increasing resilience to climate risks. GSI can support climate change adaptation in the urban environment at a "broad brush level" for a variety of future climate change impacts anticipated throughout North America. GSI is part of the range of solutions that can manage urban flooding, erosion, and urban heat island impacts, and can also improve air quality, provide water supply augmentation, and provide ecosystem and human health benefits. Equitable implementation of GSI is more critical than ever, as vulnerable communities will feel climate change impacts first and worst, and GSI is often implemented when it is easy but not where it is needed most. Community engagement early and often, combined with meeting residents in their local communities, will improve the chances of long-term success.

GSI facilities are also vulnerable to climate change impacts. This Guide provides technical resources, tools, and considerations for improving the resilience of GSI planning, design, and implementation in the face of various climate change risks.

This Guide and its appendices are intended to be living documents for the GILE and its members to leverage for current use and to build from for future GSI program development as the science and community around resilience and GSI continues to evolve. Updates to the Guide content and attachments should be considered every five years or more frequently to keep pace with the rapidly evolving changes to the science, policy, and funding opportunities.

Lafayette Elementary School, San Francisco, CA. Photo Credit: San Francisco Public Utilities Commission.

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Appendices

SamTrans Lot Rain Garden, San Carlos, CA. Photo Credit: City/County Association of Governments of San Mateo County.

Title	Year	Authors	Resource Type	Priority Item (1 to 5)	Green Stormwater Infrastructure		Climate Change Impact								Focus on Equity	Web Link	Brief Summary
					Mention of GSI	Focus on GSI	Urban Heat	Precip	Snow-fall	Sea Level/ Lake/Riverine Rise	Water Stress	Bio-diversity	Tree/ Green Equity	Air Quality			
Milwaukee Metropolitan Sewerage District: Regional Infrastructure Plan	2013	Milwaukee Metropolitan Sewerage District	Plan	2	●	●		●			●			●		https://www.mmsd.com/what-we-do/green-infrastructure/resources/regional-green-infrastructure-plan	Milwaukee's green infrastructure plan; The "Green Infrastructure Benefits and Costs" section detailed the triple-bottom-line analysis (sustainable development).
San Mateo Countywide Sustainable Streets Master Plan	2021	C/CAG & Caltrans	Plan	2	●	●		●								https://ccag.ca.gov/countywide-sustainable-streets-master-plan/	General guideline on sustainable streets for San Mateo County.
EPA: Green Infrastructure for Climate Resiliency	2021	EPA	Website	2	●	●	●	●		●	●	●				https://www.epa.gov/green-infrastructure/green-infrastructure-climate-resiliency	General information how GSI can help build climate resiliency.
Philadelphia Water Department: Green City Clean Waters	2011	Philadelphia Water Department	Plan	2	●		●	●		●	●	●		●		https://water.phila.gov/green-city/	Philadelphia's Green City Clean Waters program, a 25-year plan to reduce the volume of stormwater entering combined sewers using green infrastructure and to expand stormwater treatment capacity with traditional infrastructure improvements.
City of Portland and Multnomah County Climate Action Plan	2015	City of Portland / Multnomah County	Plan	2	●		●	●	●							https://www.portland.gov/bps/climate-action/history-and-key-documents#toc-resiliency-and-preparation	Portland's climate action plan
Green Infrastructure and Climate Change Collaborating to Improve Community Resiliency	2016	EPA / Office of Watewater Management	Report	2	●	●	●	●			●					https://www.epa.gov/sites/default/files/2016-08/documents/gi_climate_charrettes_final_5082pdf	EPA convened charrettes, or intensive planning sessions in Albuquerque, Grand Rapids, Los Angeles, and New Orleans, to explore the ways in which green infrastructure could help cities become more resilient to climate change. Four different case studies are shown.
Reducing Damage from Localized Flodding - A Guide for Communities (FEMA)	2005	FEMA	Guide	2	●	●		●								https://www.fema.gov/pdf/fima/FEMA511-complete.pdf	FEMA's guide on reducing damage from localized flooding. GSI is suggested throughout the guide.
Developing the evidence base for mainstreaming adaptation of stormwater systems to climate change	2012	Gersonius et al.	Journal Article	3, 4, 5	●												The study introduced the mainstreaming method that can help enhance the understanding of the adaptive potential of stormwater systems.
Incorporating climate change into culvert design in Washington State, USA	2017	Wilhere et al.	Journal Article	3	●												Test culvert designs based on potential climate change impacts.
Flood loss avoidance benefits of green infrastructure for stormwater management	2015	Atkins & EPA	Report	2, 3, 4	●	●		●								https://www.epa.gov/green-infrastructure/flood-loss-avoidance-benefits-green-infrastructure-stormwater-management	This study generated an estimate of the monetary value of flood loss avoidance that could be achieved by using GSI; FEMA flood loss estimation model Hazus.
Economic assessment of green infrastructure strageties for climate change adaptation: Pilot studies in the Great Lakes Region	2014	Eastern Research Grou, Inc & NOAA	Report	2, 3, 4	●	●		●								https://coast.noaa.gov/data/digitalcoast/pdf/climate-change-adaptation-pilot.pdf	The purpose of this study was to assess the economic benefits of green infrastructure (GI) as a method of reducing the negative effects of flooding in Duluth, Minnesota, and Toledo, Ohio. A secondary purpose of the study was to develop an analytical framework that can be applied in other communities to 1) consider and estimate predicted changes in future precipitation, 2) assess how their community may be impacted by flooding with increased precipitation, 3) consider the range of available green infrastructure and land use policy options to reduce flooding, and 4) identify the benefits (as well as co-benefits) that can be realized by implementing GI.
Arid green infrastructure for water control and conservation; State of the science and research needs for arid/semi-arid regions	2016	EPA	Report	2	●	●					●					Arid Green Infrastructure for Water Control and Conservation State of the Science and Research Needs for Arid/Semi-Arid Regions | Science Inventory | US EPA	BMPs in arid and semi-arid regions; Policy initiatives and guidance to address drought and water sustainability through green infrastructure; current research in the application of GSI in arid and semi-arid regions.
The value of green infrastructure for urban climate adaptation	2011	The Center for Clean Air Policy	Report	2	●	●	●	●			●					Green Infrastructure FINAL (savetherain.us)	This report showed how each type of green infrastructure can help combat certain climate change impacts. It also suggested strageties for implementing each GI.
Smart Policies for a Changing Climate: The Report and Recommendations of the ASLA Blue Ribbon Pannel on Climate Change and Resilience	2018	American Society of Landscape Architects	Report	2, 4	●										●		The report provides design and planning solutions together with policy recommendations for five different areas (natural systems, community development, vulnerable communities, transportaion, and agriculture) that are important to building climate resilient community.
Green Infrastructure for Climate Resiliency	2014	EPA / Office of Water	Brochure		●	●	●	●		●	●						The brochure summarizes the climate change effects on cities and how GSI can help prepare cities to be resilient against flooding, drought, coastal damage and erosion, energy consumption, and urban heat island effect.
An Equity Review of the City of Calgary's Climate Resilience Strategy	2021	Toronto Environmental	Report	2									●		●		Equity-focused review of the Calgary Resilience Strategy: Mitigation and Adaptation Action Plans and provide support to the city as it undertakes an update of this strategy.
Climate Change and Stormwater in Portland, Gresham, and Clackamas County	2021	UW Climate Impacts Group	Report	1, 2	●			●									The purpose of this project was to develop projections of 21st century changes in precipitation that can be used to inform stormwater and wastewater management in the cities of Portland, Gresham, and Clackamas County. Use global circulation models to predict future precipitation.
BES Resiliency Master Plan and Climate Change Planning for CIP Projects	2017	Jennifer Belknap Williamson; Bureau of Environmental Services	Workshop	2	●		●	●									The pdf is a presentation on the resiliency master plan and climate change planning for CIP projects in Portland.
The Effects of Climate Change on Lake Tahoe in the 21st Century: Meteorology, Hydrology, Loading and Lake Response	2010	Tahoe Environmental Science Center	Report		●			●									The study examines the potential effects of changing meteorologic conditions (future air temp, amount and type of precipitation, stream discharge, sediment and nutrient loading characteristics, BMP performance, lake mixing and water quality response) using existing water resource models developed for the Lake Tahoe TMDL.
An Enhanced Climate-Related Risks and Opportunities Framework and Guidebook for Water Utilities Preparing for a Changing Climate	2021	Water Utility Climate Alliance	Report	2, 3, 4, 5	●												This is a supplement to the "Mapping Climate-related Risks and Opportunities to Water Utility Business Functions Framework" intended for water utility business function leads to use as they begin to assess the climate-related risk and opportunities associated with their critical business functions.
Re-imagining design storm criteria for the challenges of the 21st century	2020	Markolf et al.	Journal Article	3	●	●		●									This paper seeks to idenfity design practices and strategies that are well-suited for the increasingly complex and rapidly changing contexts (climate change and increasing complexity of our urban systems) in which our cities and infrastructure are operating. As the conclusion, at the scale of single components/sub-systems, return periods (or similar criteria) will likely remain a necessary element of the design process. At the scale of entire system(s), approaches like safe-to-fail, robust decision making, and enhanced sensing and simulation amight be more suitable.

Title	Year	Authors	Resource Type	Priority Item (1 to 5)	Green Stormwater Infrastructure		Climate Change Impact								Focus on Equity	Web Link	Brief Summary
					Mention of GSI	Focus on GSI	Urban Heat	Precip	Snow-fall	Sea Level/ Lake/Riverine Rise	Water Stress	Bio-diversity	Tree/ Green Equity	Air Quality			
Is green infrastructure a viable strategy for managing urban surface water flooding?	2020	Webber et al.	Journal Article	2	●	●		●									This paper seeks to understand the effectiveness of GI on intervene surface water flooding. As the result, intensive application of GI could substantially reduce flood depth and velocity in the catchment but that residual risk remains, particularly during extreme flood events. The best performing intervention strategy in the study area was found to be catchment-wide decentralized rainwater capture.
Making Nature's City: A science-based framework for building urban biodiversity	2019	San Francisco Estuary Institute	Report	5	●	●						●					The report synthesizes global research to develop a science-based approach for supporting nature in cities. It identifies seven key elements of urban form and function that work together to maximize biodiversity. The elements are shown through a case study in Silicon Valley.
What is the role of GSI in managing extreme precipitation events?	2020	McPhillips et al.	Journal Article	2, 3, 4	●	●		●									This paper reviewed GSI design storm requirments for the seven Urban Resilience to Extremes Sustainability Research Network cities in the United States (Atlanta, Baltimore, Miami, New York, Phoenix, Portland, Syracuse). The results indicate that GSI in most of the study cities are designed for smaller, more common precipitation events (1-year storm) considered by current wate rquality regulations. For GSI to contribute to climate change adaptation, it is critical to ensure that design guidelines align with that goal.
NOAA workshop series on improving climate and weather information delivery for small- to medium-size water systems to help build climate resilience (includes 4 resources: brochure, workshop, project summary and appendices)	2020	NOAA	Workshop	3, 4, 5				●	●		●		●		●		This workshop series aim to improve the delivery of climate and weather information resources for small- to medium- size water systems with the goal of building their resilience to climate change. It has a specific section about equity.
Building Urban Stormwater Resiliency by Incorporating Global Climate Change Projections to Local Runoff Modeling	2021	CASQA/2ndNature	Workshop	3	●	●		●								Building Urban Stormwater Resiliency by Incorporating Global Climate Change Projections to Local Runoff Modeling | CASQA - California Stormwater Quality Association	This presentation illustrates the process of incorporating climate change projections to a stormwater model designed for direct use by stormwater managers to inform GSI implementation planning and design.
The tree cover and temperature disparity in US urbanized areas: Quantifying the association with incrome across 5,723 communities	2021	McDonald et al.	Journal Article	2	●								●		●		In 92% of the urbanized areas surveyed, low-income blocks have less tree cover than high-income blocks. On average, low-income blocks have 15.2% less tree cover and are 1.5C hotter than high-income blocks.
Simulated sensitivity of urban green infrastructure practices to climate change	2018	Sarkar et al.	Journal Article	2, 3	●	●		●			●	●					This paper used the Regional Hydro-Ecologic Simulation System (a hydrologic and biogeochemical watershed model) to investigate sensitivity of different GI practices to climate changes.
Life cycle assessment of stormwater management in the context of climate change adaptation	2016	Brudler et al.	Journal Article	2, 3	●	●		●									Compared a stormwater management system (combined GSI and local retention measures with planned stormwater routing) with a traditional, sub-surface approach through life cycle assessment. Showed that the adaption plan has lower impacts than the traditional alternative.
Multiobjective optimization of low impact development stormwater controls	2018	Eckart et al.	Journal Article	4, 5	●	●											This paper introduces a coupled optimization-simulation model that links SWMM to the Borg Multi-Objective Evolutionary Algorithm. The coupled model is used to identify the optimal combination of LID controls.
Assessment of low impact development for managing stormwater with changing precipitation due to climate change	2011	Pyke et al.	Journal Article	2	●	●		●									This study considers the potential effectiveness of LID for reducing stormwater impacts on surface water under changing precipitation patterns. Results suggests LID help increasing resilience of communities to changing precipitation patterns.
Potential climate change impacts on green infrastructure vegetation	2016	Catalano de Sousa et al.	Journal Article	2	●	●		●			●						This study investigates the impacts of successive simulated droughts and floods on two plant species commonly installed in green infrastructure sites built in the urban NE USA.
Using rainfall measures to evaluate hydrologic performance of green infrastructure systems under climate change	2021	Cook et al.	Journal Article	2, 3	●	●		●									The study suggests that performance of GSI under climage changes can be tracked by using annual rainfall measures (e.g. max daily rainfall per year).
Planning, Designing, Operating, and Maintaining Local Infrastructure in a Changing Climate (includes 4 resources: toolkit, project overview, presentation, and guide)	2021	Baltimore Metropolitan Council & Baltimore Regional Transportation Board	Report & Toolkit	2, 5	●			●		●							Resource guide for departments of public works and transportation in the Baltimore region on potential future climate changes impacts and adaptation strategies and toolkits.
Colma Creek Hydrology and Hydraulic Modeling Analysis	2021	Paradigm Environmental & Northwest Hydraulic Consultants	Report	3, 4, 5	●	●		●		●							The report summarizes the results of hydraulic models of Colma Creek (SF Bay Area) under future climate conditions. Climate change causes higher intensity storms and increases flood risk. GI can mitigate the effects of smaller, more frequent storm events. Current 100-year storm with sea level rise also presents a major risk.
Is Green Infrastructure a Universal Good?	2022	Cary Institute of Ecosystem Studies / Urban Systems Lab	Website	2	●	●							●		●	GI Equity	This project aims to examine the equity of green infrastructure in the urban planning process. The major findings state that over 90% of city plans seek to rearrange the values and hazards of urban landscapes affecting the distributional equity of GI. However, only one in four city plans discusses equity issues. Very few cities acknowledge the potential negative impacts of uneven or disproportionate investment in greening, like green gentrification.
State of Equity Practice in Public Sector: Green Stormwater Infrastructure	2021	The Green Infrastructure Leadership Exchange	Report	2	●	●							●		●	https://giexchange.org/wpcontent/uploads/2022/01/State-of-Equity-in-Public-Sector-GSIBaseline-Report-FINAL.pdf	This report aims to help better understand the extent to which GSI leaders in the public sector are incorporating equity best practices into their work.
Communities and Utilities Partnering for Water Resilience	2022	EPA	Website	3, 4, 5	●											Communities and Utilities Partnering for Water Resilience | US EPA	EPA website on building water resilience in general.
Climate Change and Water Tools	2022	EPA	Toolkit	3, 4, 5	●											Climate Change and Water Tools | US EPA	EPA website on tools for building resilient water utilities including general adaptation strategy guide, maps, and case studies.
Build Flood Resilience at Your Water Utility	2022	EPA	Toolkit	3, 4, 5				●			●					Build Flood Resilience at Your Water Utility | US EPA	EPA website on providing tools for building flood resilience.
WaterNow Alliance: Tap Into Resilience	2022	WaterNow Alliance	Website	3, 4, 5	●											Tap into Resilience | from WaterNow Alliance	WaterNow Alliance's initiative on providing water leaders nationwide with tools and inspiration to scale investment in sustainable, localized water infrastructure.
Georgetown Climate Center Green Infrastructure Toolkit	2022	Georgetown Climate Center	Toolkit	2, 3	●	●		●					●		●	Green Infrastructure Toolkit » About This Toolkit - Georgetown Climate Center	Toolkit from Georgetown Law on Green infrastructure planning

Title	Year	Authors	Resource Type	Priority Item (1 to 5)	Green Stormwater Infrastructure		Climate Change Impact								Focus on Equity	Web Link	Brief Summary
					Mention of GSI	Focus on GSI	Urban Heat	Precip	Snow-fall	Sea Level/ Lake/Riverine Rise	Water Stress	Bio-diversity	Tree/ Green Equity	Air Quality			
Climate Resiliency Design Guidelines	2020	NYC Mayor's Office of Resiliency	Guide	3, 4, 5	●		●	●		●							The guide provides potential future climate outlook for NYC and provides toolkits to help assess and plan for resilient designs.
Water Utility Resilience Program	2021	State of Massachusetts	Program	3, 4, 5							●					Water Utility Resilience Program | Mass.gov	This program aim at helping water and wastewater utilities to identify helpful and practical resiliency resources, finding opportunities for local and regional partnerships, offering infrastructure mapping and adaptation planning assistance, and coordinating training opportunities. It also provides various tools.
Coastal Flood Resilience Design Guidelines	2019	Boston planning and development agency	Guide	4	●		●	●		●						Boston Planning and Development Agency Releases Coastal Flood Resilience Design Guidelines – NorthEndWaterfront.com	This guide aims to raise awareness of future coastal flood risk, offer strategies to reduce damage and disruption, and provide consistent standards for review of projects that fall within the proposed zoning overlay district.
Climate Resilient Neighborhood of Østerbro	2022	The City of Copenhagen	Website		●			●								Klimakvarter Østerbro	Case study of Copenhagen's first climate resilient neighborhood.
Dynamic Adaptive Policy Pathways	2016	Deltares	Website	3, 4, 5												Dynamic Adaptive Policy Pathways - Adaptation Pathways - Deltares Public Wiki	The webpage explains the dynamic adaptive policy pathways approach, which aims to support the development of an adaptive plan that is able to deal with conditions of deep uncertainties.
Climate adaptation app	-	Bosch Slabbers, Deltares, Sweco, KNMI, Witteveen+Bos, Climate Changes spatial planning	Website		●			●			●					Adaptive Solutions (climateapp.nl)	The app gives urban designers, engineers or others insight in feasible measures for a project with a specific climate adaptation goal. The app will generate a selection of feasible climate adaptation measures in less than a minute. If for instance, an urban development in a flood plain is to be prepared for river flooding, the app will rank feasible measures based on the local conditions and the user's input. The user guide can be found here.
Green Cities: Good Health	2010	Urban Forestry / Urban Greening Research	Program		●							●				Introduction :: Green Cities: Good Health (washington.edu)	The program support research in the area of showing how nature benefits the human health and well-being in the urbanized areas.
Water Utility Climate Alliance (WUCA) website	2022	Water Utility Climate Alliance	Website	2, 3, 4	●		●	●		●	●					https://www.wucaonline.org/	Website full of resources especially in relation to actionable science, e.g. climate change projections etc. See Plans and Publications and items under work plan, and Case Studies section as well.
Advancing Stormwater Resiliency in Maryland (A-StoRM) Maryland's Stormwater Management Climate Change Action Plan	2021	Maryland Department of the Environment	Report	3, 4, 5	●	●		●								https://mde.maryland.gov/Documents/AStorRMreport.pdf	The report proposes consideration of regulatory changes to include the use of the most recent NOAA Atlas 14 precipitation estimates in Maryland's Stormwater Design Manual and to develop draft updates to Maryland's stormwater design standards for ESD to MEP to capture increased stormwater runoff volume (e.g., 3.0 inches for the 1-year rainfall event) for new development and redevelopment based upon future climate projections.
Philadelphia Climate Action Playbook	2021	The City of Philadelphia Office of Sustainability	Report	4, 5	●		●	●		●		●	●	●	●	https://www.phila.gov/documents/philadelphia-climate-actionplaybook-resources/	The Philadelphia Climate Action Playbook outlines the actions Philadelphia is taking to respond to climate change through 2050. The Playbook also outlines how climate change will impact Philadelphia and where we need to go further to achieve our goals.
Managing Heavy Rainfall with Green Infrastructure: An Evaluation in Pittsburgh's Negley Run Watershed	2020	Fischbach et al	Journal Article	1, 2, 3, 4	●	●		●								https://www.rand.org/pubs/research_reports/RRA564-1.html	The researchers identified potential climate change impacts for the Negley Run watershed, where urgent flood-risk challenges are presented in the city. In the project, the researchers use simulation modeling (SWMM) to evaluate present and future risks in Negley Run from sewer overflows and flooding given future rainfall uncertainty. Then, the authors evaluate proposals for a phsed series of GSI investment. The study also showcases the recreational and other cobenefits of the GSI in addition to the stormwater benefits.
Quantifying the Uncertainty Created by Non-Transferable Model Calibrations Across Climate and Land Cover Scenarios: A Case Study With SWMM	2022	Sytsma et al	Journal Article	4												https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021WR031603	The paper attempts to quantify the error in model prediction that arises when the optimal calibrated value of effective parameters changes with model forcing. A case study with SWMM was conducted with the specific parameters of subcatchment 'width' and 'connected impervious area'. The authors concluded that variation across forcing parameters can result in significant prediction errors. These results point to a need for additional research to determine how to use urban hydrologic models to make robust predictions across future conditions.
Trees and Hydrology in Urban Landscapes	2021	Whipple et al; San Francisco Estuary Institute & The Aquatic Science Center	Report	1, 2	●	●										https://www.sfei.org/documents/trees-andhydrology-urbanlandscapes	This effort seeks to build links between stormwater management and urban ecological improvements by evaluating how complementary urban greening activities, including green stormwater infrastructure (GSI) and urban tree canopy, can be integrated and improved to reduce runoff and contaminant loads in stormwater systems. This work expands the capacity for evaluating engineered GSI and non-engineered urban greening within a modeling and analysis framework, with a primary focus on evaluating the hydrologic benefit of urban trees. Insights can inform stormwater management policy and planning.
Green Stormwater Infrastructure Maintenance Manual	2016	Philadelphia Water Department	Manual	1, 3	●	●										https://water.phila.gov/pool/files/gsimaintenancemanual.pdf	Philadelphia's GSI maintanence manual for various stormwater management practices.
Green Stormwater Infrastructure Landscape Design Guidebook	2020	Philadelphia Water Department	Guide	1, 3	●	●										https://water.phila.gov/pool/files/gsilandscape-designguidebook.pdf	Philadelphia's GSI landscape design guidebook.
Green Stormwater Infrastructure Planning & Design Manual	2021	Philadelphia Water Department	Manual	1, 3	●	●										https://water.phila.gov/gsi/planningdesign/manual/	Philadelphia's GSI planning and design manual.
Examples of Green Infrastructure Projects in San Francisco	2022	San Francisco Public Utilities Commission	Website	1	●	●										https://sfpuc.org/programs/san-franciscosurbanwatersheds/whatgreen-infrastructure	SFPUC's webpage explaining what is green infrastructre and showing examples of GI. The webpage also include monitoring reports for various existing GI in San Francisco.
FEMA: Nature-Based Solutions	2022	FEMA	Website	1	●											https://www.fema.gov/emergencymanagers/riskmanagement/naturebased-solutions	FEMA's risk management guide focusing on nature-based solutions.

APPENDIX A | Matrix 1. State of the Science: Resources Exploring the Intersection of Green Stormwater Infrastructure and Climate Change

Title	Year	Authors	Resource Type	Priority Item (1 to 5)	Green Stormwater Infrastructure		Climate Change Impact								Focus on Equity	Web Link	Brief Summary
					Mention of GSI	Focus on GSI	Urban Heat	Precip	Snow-fall	Sea Level/ Lake/Riverine Rise	Water Stress	Bio-diversity	Tree/ Green Equity	Air Quality			
Nature-based solutions for climate change mitigation	2021	United Nation Environment Programme (UNEP) & Internationl Union for Conservation of Nature (IUCN)	Report	1	●		●	●	●	●	●	●	●	●		https://www.iucn.org/theme/nature-basedsolutions	The report shows the benefits and challenges of using nature-based solutions to combat climate changes.
San Francisco Public Utilities Commission Green Stormwater Infrastructure Maintenance Cost Model	2018	San Francisco Public Utilities Commission	Model	1, 3	●	●										https://sfpuc.sharefile .com/dsd59402b587f4fe59	SFPUC developed this GSI maintenance cost model and have been sharing it with other municipalities. This would serve as a starting point of developing future maintenance cost model with climate resilience in mind.
Reimagining parks as stormwater infrastructure—stormwater parks of all sizes, designs, and funding sources	2019	Bryant et al	Article	1,3, 4, 5	●	●		●								http://www.newea.org /wpcontent/uploads/2019/03/NEWEAJournal_Spr19.pdf#page=19	This paper provides an overview of funding sources, design strategies, water quality improvements, and additional co-benefits provided by multi-objective green stormwater infrastructure in parks and public spaces. Example projects of all sizes from New York City, Atlanta, and Calgary are described, and an example of a successful Institute for Sustainable Infrastructure Envision verification and award process for a stormwater park is also be shared.
Cloudburst Resiliency Planning Study	2017	New York City Department of Environmental Protection & Ramboll	Report	1, 2, 4, 5	●	●		●								https://www1.nyc.gov/assets/dep/downloads/pdf/climate resiliency/nyccloudburst-study.pdf	This executive summary describes the process and fi ndings from the Cloudburst Resiliency Planning Study carried out by Ramboll in 2016. The methodology builds upon Ramboll's experience and city-to-city collaboration regarding cloudburst solutions development for the City of Copenhagen. The purpose of the project is to provide insight on ways to advance climate resiliency projects and traditional stormwater solutions to mitigate inland flooding and accommodate future increase in rainfall intensity through integration with ongoing urban planning and development.
New York City Stormwater Resiliency Plan	2021	NYC Mayor's Office of Resiliency	Plan	1, 2, 5	●	●		●								https://www1.nyc.gov/assets/orr/pdf/publications/stormwater resiliency-plan.pdf	The Stormwater Resiliency Plan (the "Plan") outlines the City's approach to managing the risk of extreme rain events. Truly holistic planning for rain-driven flooding involves consideration of both large storm events and the chronic worsening of average conditions. For this reason, the Plan addresses emergency response procedures as well as accounting for increasing rainfall in standard design and long term planning of stormwater infrastructure.
An unexpected item is blocking cities' climate change prep: obsolete rainfall records	2022	National Public Radio (NPR)	Article	4				●								https://www.npr.org/2022/02/09/1078261183/an-unexpected item-is-blocking-cities-	The article points out that the lack of rainfall data is a crital challenge for future planning of storm water infrastructure.
U.S. Climate Resilience Toolkit	2016	NOAA	Website		●		●	●	●	●	●	●	●	●	●	https://toolkit.climate.gov	
New Solutions for Sustainable Stormwater Management in Canada	2016	Sustainable Prosperity	Report		●												
Governor Newsom Signs Climate Action Bills	2021	Office of Governor Gavin Newsom	Press Release													https://www.gov.ca.gov/2021/09/23/governor-newsom-signsclimate-action-billsoutlines-historic-15-billion-package-totackle-the-climatecrisis-and-protectvulnerable communities/	

APPENDIX A | Matrix 2. Original Studies that Established the Conceptual Model for GSI Design

Title	Year	Authors	Resource Type	Priority Item (1 to 5)	Green Stormwater Infrastructure		Climate Change Impact								Focus on Equity	Web Link	Brief Summary
					Mention of GSI	Focus on GSI	Urban Heat	Precip	Snow-fall	Sea Level/ Lake/Riverine Rise	Water Stress	Bio-diversity	Tree/ Green Equity	Air Quality			
Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs	1987	Thomas R. Schueler for Washington Metropolitan Water Resources Planning Board	Manual	3	●	●										Controlling Urban Runoff | Metropolitan Washington Council of Governments (mwcog.org)	Manual provides detailed guidance on how to plan and design urban best management practices to remove pollutants and protect stream habitats
Design and Construction of Urban Stormwater Management Systems	1992	Water Environment Research Federation and American Society of Civil Engineers	Manual	3	●	●										https://ascelibrary.org/doi/-book/10.1061/9780872628557	
Stormwater: Best Management Practices and Detention for Water Quality, Drainage and CSO Management, 2nd Edition	1992	Urbonas and Stahre	Textbook	3	●	●										https://www.amazon.com/Storm-water-Management-Practices-Detention-1992-10-01/p/B01A65DCAS	
Surface Water Design Manual 1998	1998	King County Stormwater Services	Manual	3	●	●										https://your.kingcounty.gov/dnrp/library/water-andland/stormwater/surface-water-designmanual/1998-swdm.zip	
Stormwater Collection Systems Design Handbook	2001	Mays	Textbook	3	●	●										https://www.zuj.edu.j o/download/stormwat er-collection-systemsdesign-handbookpdf/	
Stormwater Treatment: Biological , Chemical, and Engineering Principles	2002	Minton	Textbook	3	●	●										https://books.google.com.books/about/Stormwater_Treatment.html?id=T5rRAAAACAAJ	
CASQA Stormwater BMP Handbook - New Development and Redevelopment	2003	CASQA	Manual	3	●	●											BMP manual from CASQA
Municipal Stormwater Management, 2nd Edition	2003	Debo and Reese	Textbook	3	●	●										https://www.routledge.com/Municipal-Stormwater-Management/Debo-Reese/p/book/97815 66705844	
Stormwater Best Management Practices Design Guide (Volume 1, 2, and 3)	2004	U.S. Environmental Protection Agency	Manual	3	●	●										https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryId=99739	

Title	Year	Authors	Resource Type	Priority Item (1 to 5)	Green Stormwater Infrastructure		Climate Change Impact								Focus on Equity	Web Link	Brief Summary
					Mention of GSI	Focus on GSI	Urban Heat	Precip	Snow-fall	Sea Level/ Lake/Riverine Rise	Water Stress	Bio-diversity	Tree/ Green Equity	Air Quality			
Effects of climate change on hydrology and water resources in the Columbia River Basin	1999	Hamlet & Lettenmaier	Journal Article						●								General climate impacts in the Columbia River Basin.
Effects of simulated climate change on the hydrology of major river basins	2001	Arora & Boer	Journal Article					●									The paper explore the potential effects of global warming on the hydrology of 23 major rivers. It focuses on runoff and discharges.
Hydrologic sensitivity of global rivers to climate change	2001	Nijssen et al.	Journal Article						●								Used GCMs to predict future climate impact on hydrology.
The effects of climate change on water resources in the west: Introduction and overview	2004	Barnett et al.	Journal Article														Accessment of the effects of climage change on water resources in the western United States. The assessment focues on the potential chances over the first half of the 21st centry on the Columbia, Sacramento/San Joaquin, and Colorado river basins.
Potential impacts of a warming climate on water availability in snowdominated regions	2005	Barnett, Adam, & Lettenmaier	Journal Article						●		●						With a modest increase in near-surface air temperature, the alterations of the hydrological cycle are expected to take place via seasonal shifts in stream-flow in snowmelt-dominated regions. This change can lead to regional water shortages in areas without adequate water storage capacity.
Changes toward earlier streamflow timing across Western North America	2005	Stewart, Cayan, & Dettinger	Journal Article						●								Changes in timing of snowmelt-derived streamflow from 1948 to 2002 were investigated through trend and principal component analyses.
Human-induced changes in the hydrology of the Western United States	2008	Barnett et al.	Journal Article														Used hydrological models together with global climate models to show that up to 60% of the climate-related trends of river flow, winter air temperature, and snowpack between 1950 to 1999 are human-induced.
Implications of 21st century climate change for the hydrology of Washington State	2010	Elsner et al.	Journal Article						●								Impacts of climate changes on the hydrological cycle in Pacific northwest; focus on the greater Columbia River watershed and Yakima River watershed; main parameters looked at are snow water equivalent, soil moisture, runoff, and streamflow under different emissions scenarios
Adapting to the impacts of climate change	2010	National Research Council	Report	5													General climate changes in the US and adaptation options and strategies.
Climate change effects on stream and river temperatures across the northwest U.S. from 1980-2009 and implications for salmonid fishes	2012	Isaak et al.	Journal Article									●					The team assembled 18 temperature time-series from sites on regulated and unregulated streams in the NW US to describe historical trends from 1980 to 2009 and assess thermal consistency between these stream categories.
Geomorphological records of extreme floods and their relationship to decadal-scale climate change	2014	Foulds et al.	Journal Article														Study of the geomorphological traces of extreme rainfall and floods occurrence between 1900 to 1960 in the Cambrian Mountains of Wales, UK.
Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations	2014	Salathe et al.	Journal Article					●									The paper shows substantial increases in future flood risk (2040-69) in many Pacific Northwest river basins in the early fall using a regional climate model simulation. Two primary causes: more extreme and earlier storms and warming temperatures that shift precipitation from snow to rain domincance over regional terrain
Local Enhancement of Extreme Precipitation during Atmospheric Rivers as Simulated in a Regional Climate Model	2018	Lorente-Plazas et al.	Journal Article					●									This paper examins the synoptic conditions that yield extreme precipitation in two regions with different orographic features, the Olympic Mountains and Puget Sound.
Integrated Vulnerability Assessment of Climate Change in the Lake Tahoe Basin	2020	CA Tahoe Conservancy & Catalyst Environmental Solutions	Report					●	●		●	●				tahoe.ca.gov/vulnerability-assessment	This report aims to provide residents, visitors, businesses, and public agencies with state-of-art information on how patterns of temperature and precipitation will change, and how these patterns will affect the things people care about.

To identify a site that is feasible for GSI siting, check all boxes below or identify another engineering solution:

	Known/Anticipated Site Conditions	Data Needs
Can the site be used for GSI?	☐ The land is owned by the public agency or other identified public or private partner. ☐ The land has not been used for operations resulting in pollution that exceeds stormwater regulations. ☐ The land is not being used or planned to be used for other projects/purposes	• Parcel data • Political and Municipal Boundaries • Right-of-way boundaries • Land Cover / Land Use data • Land use planning datasets
Is there sufficient space to site GSI?	☐ There is available open space to install GSI appropriately sized for the drainage area. ☐ There are no space-constraining utility conflicts or large and/or protected trees. ☐ There is a relatively flat slope.	• Building Footprints • Utility Records (substructures, sewers, storm drains, and overhead power) • Topography / existing surveys • Locations of large/protected trees
Can the site capture sufficient flows?	☐ The site is downstream of and could receive flows from the target drainage area. ☐ It is possible to convey flows to the site through existing or new conveyance infrastructure.	• Topography data or existing surveys • Watersheds • Rain Gauge Data and Isohyetal maps • Storm Drain Infrastructure • Existing or Proposed structural BMPs • Subdrainage Areas
Would there be adequate maintenance access to site?	☐ The site has adequate space for maintenance truck and/or personnel to safely access it. ☐ There is an identified responsible party who would handle the O&M of the project	• Known site conditions and uses

To identify a site that is feasible for infiltrating GSI , the boxes below should also be checked:

Would the site support infiltration? Or would the facility need to be lined?	☐ There is no known groundwater contamination near the site. ☐ There are no geotechnical concerns, such as liquefaction, below the site. ☐ The groundwater level is sufficiently deep enough to allow for infiltration. ☐ The soil type below the site is conducive to infiltration.	• Soil types / Geology / Geotechnical conditions • Groundwater Basins • Measured groundwater elevations • Liquefaction areas • Mapped contaminant plumes or contaminated sites • Nearby wells and septic systems

Established Conceptual Model for GSI

1.1 Established Conceptual Model for GSI Siting, Sizing, and Design

Following the adoption of federal requirements for stormwater management in the 1980s, researchers published findings on how post-construction stormwater volumes and loads could be appropriately controlled. The results of an early study by Schueler[1] were widely adopted by regulatory agencies and used in subsequent technical guidance. That study recommended that stormwater best management practices (BMPs) should be sited and designed to 1) reproduce the hydrologic conditions of the downstream receiving water; 2) provide a moderate level of removal for most urban pollutants; and 3) have a neutral impact on the natural and human environment.[2]

Many of these early studies focused on a general class of stormwater BMPs, including detention and non-biological filtration type facilities. Conventional detention-type stormwater BMPs capture stormwater from large storm events and release it over time to reduce runoff intensity. The use of low impact development (LID) and GSI was promulgated under subsequent NPDES stormwater permits in the late 2000s and early 2010s. LID requirements focused on mimicking a wider range of natural hydrologic functions beyond runoff discharge, including rainfall interception, shallow surface storage, evapotranspiration, and infiltration/groundwater recharge.[3]

LID technical guidance focused on siting GSI and other stormwater management facilities by considering physical constraints, including underlying soil or geotechnical characteristics, slope, depth to groundwater, proximity to wells or infrastructure, and anticipated pollutant loading into the BMP. Physical siting characteristics that increase the potential volume that can be retained by the facility (i.e., infiltration, capture and use, and evapotranspiration) were also incorporated.

1.1.1 STORMWATER FACILITY SIZING

For many locations and depending on the regulatory agency, sizing requirements for total runoff captured for conventional stormwater facilities and GSI have remained unchanged for the past two decades. GSI technical guidance also recommends maximizing the retention of captured stormwater.

When examining the percent of total average annual runoff captured and treated as a function of BMP size, a "knee of the curve" is evident for most sites. This change in the instantaneous slope of the curve represents the point at which increases in BMP size (and cost) yield diminishing returns in total runoff captured and treatment effectiveness. For example, in California, the "knee of the curve" occurs at approximately the 75th-85th percentile storm event, corresponding to approximately 80% of average annual stormwater runoff (Figure D1). When a flow-based facility is designed to capture a larger rainfall intensity, a similar "knee of the curve" is found (e.g., 0.1 – 0.25 inches per hour in California).[4] This pronounced knee of the curve for both volume and flow-based sizing approaches allows for GSI cost efficiency while providing sufficient stormwater capture to reduce runoff volumes and pollutant loads in downstream receiving waters.

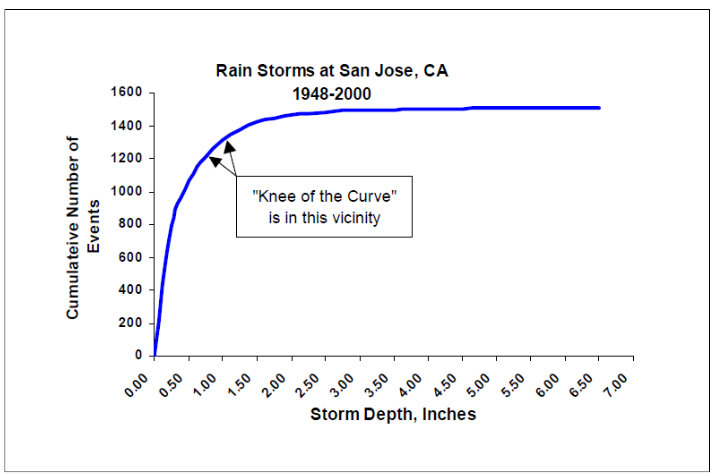


Figure D1. Example "Knee of the Curve" based on Historical Data[5]

1.1.2 GSI COMPONENT DESIGN

Technical studies of early GSI applications resulted in recommendations for typical GSI components. These components include GSI media, vegetation, and hydraulic elements (i.e., inlets, outlets, and underdrain).

Media

Following several studies identifying reduced infiltration of GSI facilities over time, media mixes were studied to identify how to avoid a decrease in performance. These studies identified that a fast filtration rate through the media (e.g., a minimum of 5 inches per hour in the San Francisco Bay Area) was required to prevent clogging. Faster drawdown of stored volume was also thought to prevent vector issues.

To provide these very fast infiltration rates, the proportion of clay in the media mix (for example, present in native topsoil used as a component) had to be greatly minimized or removed. Many regions adopted media mixes that were heavily sand-based and would therefore drain very quickly. This has resulted in benefits with reducing clogging potential but has resulted in other issues relating to plant health and irrigation requirements that are likely to be exacerbated with rising temperatures. This is particularly relevant for locations expecting to see increasing frequency, duration, and intensity of drought conditions.

Vegetation

Healthy vegetation is a key component of GSI performance. Plants provide biological treatment of pollutants, help maintain infiltration, and increase evapotranspiration. Given the harsh conditions in GSI facilities (i.e., episodic periods of submergence and desiccation), site-specific and more resilient plant palettes are needed.

Hydraulic Elements

GSI technical manuals often recommend that stormwater treatment facilities be designed to be “off-line” or installed such that only a portion of the total runoff is diverted to the facility. This avoids impacts of erosion and extended submerged periods that may occur otherwise. Inlets, underdrains, and outlets (including orifice-controlled outlets) are frequently sized to capture the required historic flow volume to meet water quality requirements.

1.2 Considerations for Updating the Conceptual Model for Climate Resilience

While the climate change impacts on GSI are expected to vary by region, location, and type of facility, larger storm events, higher rainfall intensities, longer duration events, and more saturated initial conditions are likely to reduce the effectiveness of GSI facilities.[6] Other climate change impacts, including rising groundwater and changes in temperature, may also affect GSI siting and performance.

1.2.1 HYDROLOGIC IMPACTS: PRECIPITATION CHANGE AND EARLY SNOWMELT

Design standards are typically developed based on multiple decades of historical precipitation data. GSI facilities are currently designed with the implicit assumption that past rainfall-runoff patterns will persist over their design life. Since climate change is anticipated to alter historic rainfall-runoff patterns, facilities may be in jeopardy of underperforming in the future. Climate change is projected and has already been observed to affect precipitation patterns. Rainfall is becoming more intense in many locations and less frequent in others. When the proportion of smaller, low-intensity events and larger, high-intensity events is altered, the amount of total stormwater runoff captured by a GSI facility may change. When this results in a smaller overall amount of runoff captured, the facility may no longer provide the hydrologic or water quality benefits it was designed to provide. In addition, the “knee of the curve” may be entirely shifted or become less pronounced. In the future, it may not be appropriate to preclude larger facility sizes for providing diminishing returns.

1.2.2 INCORPORATING CLIMATE MODEL PROJECTIONS INTO GSI SIZING

As described, hydrologic changes may necessitate updated GSI facility sizing guidance. This could include "dynamic sizing" approaches that more fully consider facility drawdown processes, as well as considerations of projected changes to local precipitation patterns.

Precipitation projections from Global Climate Models (GCMs) may be used in place of historic rainfall observations to design GSI facilities appropriately. However, most GCMs do not have an adequate spatial or temporal scale needed to represent urban stormwater. Most GCMs operate on a daily timestep, whereas urban storm events occur in minutes or hours. Several regions have begun to develop spatially and temporally downscaled models to provide refined precipitation datasets for stormwater managers. Local universities or state resources have often developed regionally downscaled models and identified GCMs that better represent their region. These downscaled models typically use GCM results as inputs to a regional weather forecasting model to provide more detail. The resulting precipitation data sets have a finer spatial and temporal resolution (e.g., 1-hour vs. 1-day).

While GCMs provide reliable results on a continental scale, they often suffer from both transient and system biases when compared to observed rainfall. Therefore, downscaled model outputs usually need to undergo bias correction before they can be used for planning. Additionally, regions with highly variable microclimates may require additional spatial downscaling or interpretation to be effectively used for facility sizing.

Selection of GCMs

GCMs are run for a historical period (hindcasting) and a future period (forecasting). Using the historical period, practitioners can compare GCM results with observed precipitation in the region. Different GCMs will vary in their potential applicability to a specific region. GCMs that perform poorly for the region, as tested by local researchers, universities, or state agencies, can be excluded.

Selection of Emissions Scenarios

The IPCC regularly selects and updates Representative Concentration Pathways (RCPs), reflecting the range of plausible future emissions scenarios (Table D1). Carbon emissions persist in the atmosphere for centuries and climate change predicted under higher RCPs is typically more severe, although precipitation impacts do not always scale with increased warming.

Table D1. Summary of IPCC Emission Scenarios (adapted from IPCC AR5, 2014)[7]

<table>
<tr><th rowspan="2">SCENARIO</th><th rowspan="2">CO_2-EQ CONCENTRATIONS IN 2100 (PPM)</th><th colspan="2">CHANGE IN CO_2-EQ EMISSIONS COMPARED TO 2010 (IN %)</th><th colspan="4">LIKELIHOOD OF TEMPERATURE CHANGE RELATIVE TO 1850-1900 REMAINING BELOW:</th></tr>
<tr><th>2050</th><th>2100</th><th>+1.5ºC</th><th>+2ºC</th><th>+3ºC</th><th>+4ºC</th></tr>
<tr><td>RCP2.6</td><td>430 – 480</td><td>-72 to -41</td><td>-118 to -78</td><td>More unlikely than likely</td><td>Likely</td><td rowspan="2">Likely</td><td rowspan="3">Likely</td></tr>
<tr><td>RCP4.5</td><td>580 - 720</td><td>-38 to 24</td><td>-134 to -50</td><td rowspan="3">Unlikely</td><td>More likely than not</td></tr>
<tr><td>RCP6.0</td><td>720 - 1000</td><td>18 to 54</td><td>-7 to 72</td><td rowspan="2">Unlikely</td><td>More unlikely than likely</td></tr>
<tr><td>RCP8.5</td><td>> 1000</td><td>52 to 95</td><td>74 to 178</td><td>Unlikely</td><td>More unlikely than likely</td></tr>
</table>

Although each RCP varies with respect to atmospheric carbon and long-term warming effects, climate change models suggest similar surface warming over the next 30-40 years (Figure D2). This period is equal to the design life of most GSI facilities. Therefore, projects implemented in this decade (i.e., the 2020s) can expect similar results regardless of the specific RCP.

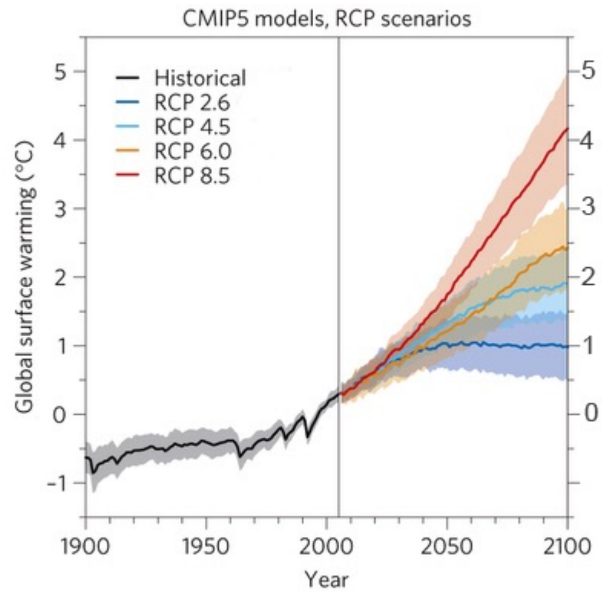


Figure D2. Projected global surface warming for different emissions scenarios[8]

The selected RCP scenario will have a more significant impact on projects with a longer design life or implemented in the second half of the 21st century. Considerations of risk and uncertainty should drive the selection of an RCP. For example, the highest emissions scenario, RCP 8.5, represents a more conservative analysis than lower emissions scenarios. Multiple RCPs may be chosen for a study to bracket the range of possible outcomes. If multiple scenarios are evaluated, they should be treated as independent outcomes and should not be aggregated or averaged.

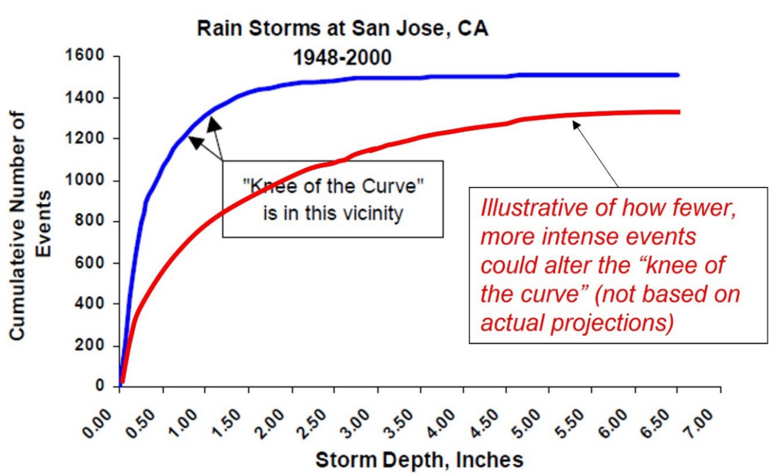
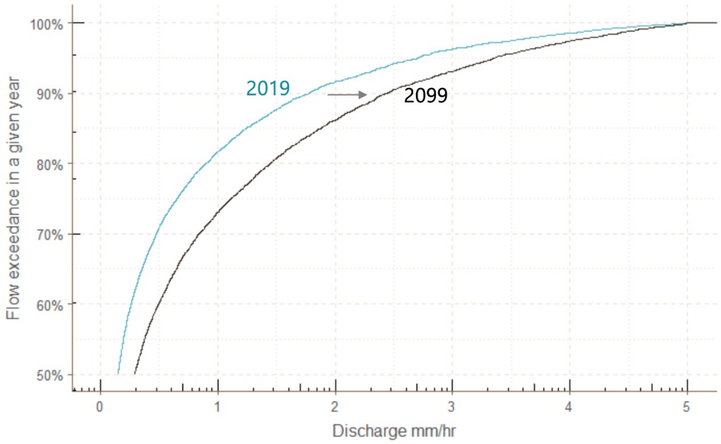


Figure D3. Altered "knee of the curve" sketch due to climate change impacts.

Based on modeling results from downscaled Global Climate Models[i] (GCMs) and hourly precipitation developed through an application of regional weather modeling for Western Washington, Figure D4 provides an actual example of an altered "knee of the curve."[9]

[i]Global Climate Models (GCMs) are a representation of the major climate system components - atmosphere, land, ocean, and sea ice – and their interactions. They are used for forecasting climate change.



Although each RCP varies with respect to atmospheric carbon and long-term warming effects, climate change models suggest similar surface warming over the next 30-40 years (Figure D2). This period is equal to the design life of most GSI facilities. Therefore, projects implemented in this decade (i.e., the 2020s) can expect similar results regardless of the specific RCP.

Figure D4. Actual altered "knee of the curve" due to climate change impacts in Western Washington.

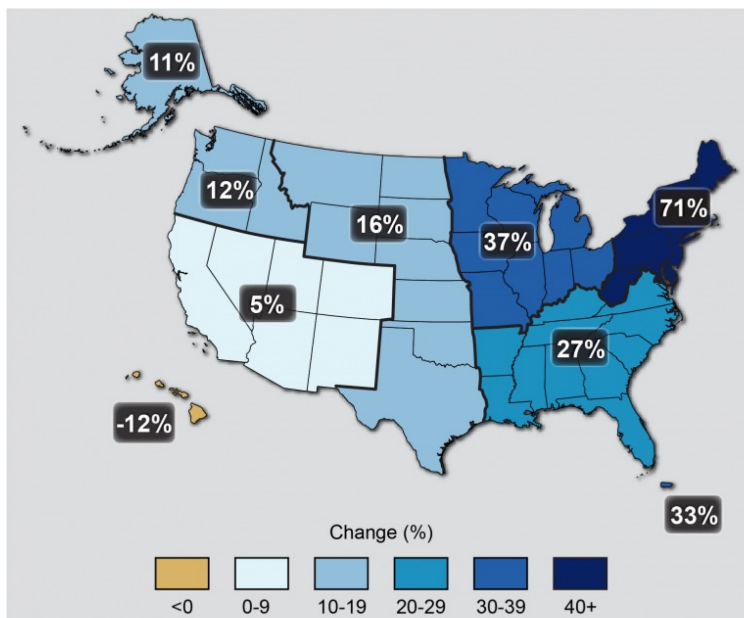


Figure D5. Map of the observed change in very heavy precipitation (defined as the top 1% of all daily events) from 1958 to 2012[10] in the U.S.

Beyond increased runoff from precipitation, conditions within the GSI facility itself may be impacted. When more storms occur in a shorter time, the ability of the GSI facility to drain, dry out, and capture the next storm is diminished, and runoff capture performance is reduced as systems bypass increased or cumulative flow. Communities with CSSs may see an increase in CSOs or combined sewer discharges (CSDs) with increased large storm events. The performance of GSI implemented to provide upstream retention and detention may be impacted and result in impacts to the downstream POTW.

Seasonal precipitation changes, such as an extended dry season or longer dry periods between storms, may result in reduced water quality performance for GSI facilities. These changes, which have already been observed in some locations, may cause an increase in pollutant accumulation on the landscape. In Portland, City staff have observed very dry soils in GSI facilities that shrink away from structural walls and become hydrophobic after the long dry summer season. This can result in short-circuiting of facilities with underdrains where flows cannot be absorbed and bypass the biotreatment soil media and/or cause premature overflows of first flush events. Higher concentrations of pollutants in seasonal first-flush events could impact GSI facility performance and may require additional pretreatment to maintain performance.

1.2.3 OTHER IMPACTS: TEMPERATURE AND SEA LEVEL RISE

Temperature changes may affect the performance of specific GSI design components. Some researchers have argued that increased temperature associated with climate change may lead to better performance of GSI due to reduced water viscosity and increased infiltration,[11] though temperature differences related to GSI performance vary by facility type with bioinfiltration showing more sensitivity than pervious pavement.[12] Media mixes with a high proportion of sand may dry out too quickly to maintain vegetative health when temperatures are higher. Vegetation that may have thrived in lower temperature fast-draining facilities may be increasingly stressed under higher temperatures.

Subsurface changes should also be considered for resilient GSI. Groundwater levels may rise due to increased nearby lake and sea levels. As sea levels rise, the risk of saltwater intrusion increases. As a result, areas with relatively shallow groundwater that were once suitable for GSI may no longer be appropriate. Groundwater level rise near freshwater lakes like Lake Ontario may also cause periodic sustained inundation of the root zones of GSI facilities, causing potential rotting of roots and plant failure. More resilient species selection and grading design will need to be incorporated to anticipate these potential climate impacts.

A technical and/or decision-making methodology for identifying the changes needed for GSI volume or hydraulic design could be developed. The proposed method would incorporate the range of estimated GSI performance changes leveraging existing tools at the local or regional level. This would result in the GSI sizing factors or guidance that appropriately accounted for observed or projected changes in near-term precipitation and projected precipitation compared to long-term historic precipitation.

1.3 Considerations for Climate Resilient Sizing Guidance or Tools

Additional analysis could be conducted to develop methods for changing existing design guidance for GSI components, including but not limited to:

1. Consideration of standards governing facility drawdown time and developing a method to examine potential impacts to drawdown with climate change.
2. Modeling analysis or methods to examine facility hydraulics (e.g., filtration rate, discharge rate) and associated performance changes for a range of drawdown times corresponding to different precipitation regime changes.
3. Developing factors or design changes to be incorporated into hydraulic components of facilities to address GSI performance modeling outcomes.
4. Quantifying uncertainty in design inputs.
5. Updating GSI plant palettes and resilient plant selection methods for different regions and their anticipated environmental changes. This could include guidance on hydrozone-specific plant placement geared towards specific GSI facility types to optimize vegetation health and facility resilience.

GSI design and retrofit changes needed for resilience can be further studied by examining the potential to mitigate the impacts of climate change and the extent of impacts on GSI facility performance. Comparing predicted future climate conditions to historical conditions and/or modeling GSI using a range of these conditions should be examined first. This analysis can provide insight into how the performance of existing GSI or GSI designed per current practices may be impacted.

GCMs could be identified for specific metropolitan areas, and their output could be examined for different RCPs compared to historical conditions (e.g., temperature and precipitation). Clear trends or changes identified through this comparison would provide high-level insight into potential GSI performance challenges. Developing more detailed GSI models incorporating regionally downscaled models would also provide more precise estimates of potential GSI performance issues.

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