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Climate Resilience Resources Guide: Part 1

August 2022

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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1. INTRODUCTION

This Climate Resilience Resources Guide (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 planning, design, and maintenance standards for GSI might leave this infrastructure at risk of not performing per current stormwater regulations or being damaged because of the impacts of a changing climate. This Guide explores potential changes to current GSI policy, planning, and implementation practices that could enhance the climate resilience benefits provided by GSI and considers how climate change could negatively impact GSI performance.

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.

This Guide examines decision-making processes for planning and implementing GSI based on climate resilience, public engagement, and equity considerations. The Guide references relevant resources throughout, including frameworks for considering equity in GSI planning and finding and utilizing downscaled climate model projections. A full matrix of resources is provided in Appendix A. The Guide and matrix are intended to be living documents that are updated and expanded over time. This Guide includes a roadmap for further advancing this work through the Green Infrastructure Leadership Exchange.

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.

2.1.1 Green Stormwater Infrastructure

Infrastructure is the basic equipment and structures essential for functional, healthy, and vibrant communities.[1] "Green" stormwater infrastructure (GSI) includes a range of measures that are engineered to passively capture and treat stormwater using natural processes. 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] The primary treatment mechanisms that GSI uses 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 media systems; 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;
- Practices to promote evapotranspiration, including tree planting, green roofs, and impervious surface dispersion;
- Rainwater harvesting (i.e., cisterns or rain barrels);
- Biofiltration, including bioretention, planter boxes, vegetated swales, vegetated filter strips, and proprietary biotreatment devices; and
- Biotreatment basins, such as wet detention basins and constructed wetlands.

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;
- 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.

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 practices 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 2.3.

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[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".

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 wastewater sources, 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) and are not of focus in this Guide. Other examples of nature-based solutions not covered in this guide include measures focused on mitigating the impacts of extreme, back-to-back rainfall or "cloudburst" events[ii]. Copenhagen, Denmark, and New York City have studied and implemented projects that store and convey water where it is favorable during extreme rain events.[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.

Landscape features, and other broad-scale, nature-based solutions may be explored in future versions of this Guide.

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. The implications of these impacts on GSI policy, planning, design, and operations and maintenance are discussed in Sections 4, 5, and 6, respectively.

2.2.1 Regional Climate-Related Impacts

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.

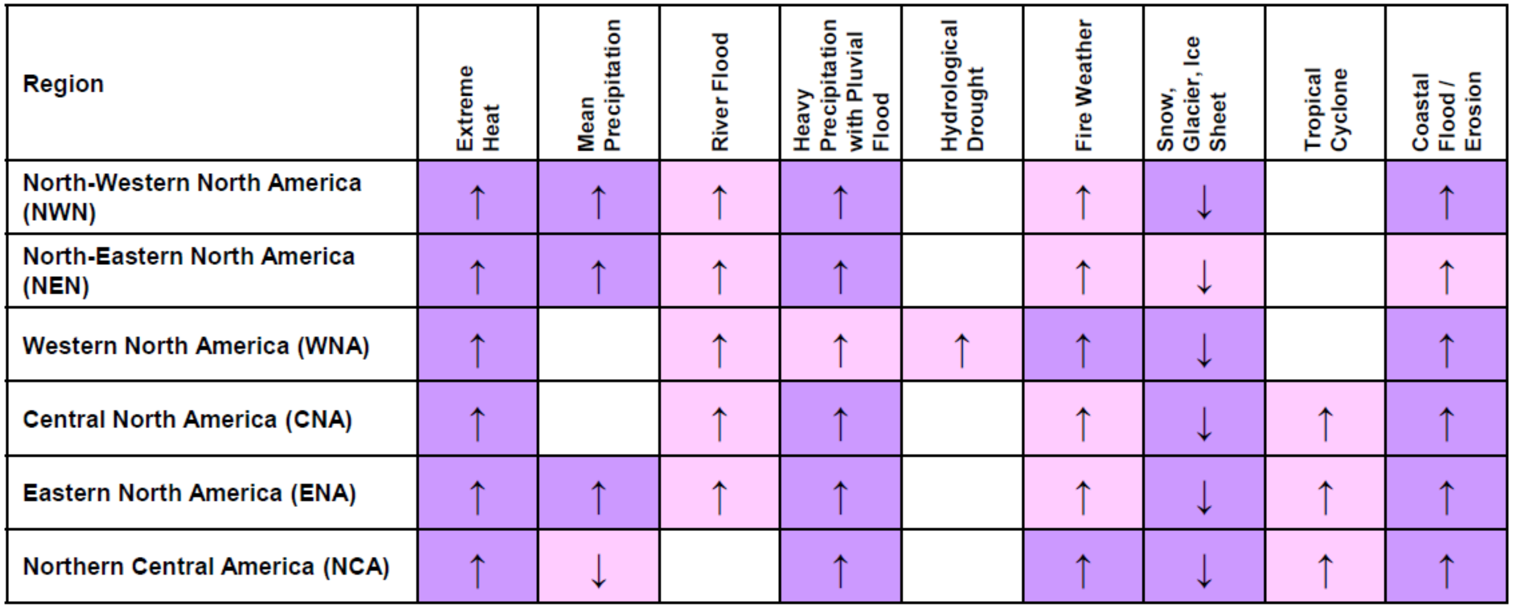
[ii] Cloudburst management is the management of extreme back-to-back rainfall events through intentional flooding, conveying, and storing water where it is favorable in the landscape.

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

Climatic Impact Driver	Explanation
Extreme heat	Temperature event of exceptionally high magnitude with a very rare occurrence, such as greater than the 90th percentile event.
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. The direction of change and confidence level is also shown in Figure 1. The future assessed changes refer to a 20 to 30-year period centered around 2050 and/or consistent with 2ºC (3.6ºF) global warming compared to a similar period within 1960-2014, except for hydrological drought, which is compared to 1850-1900.[11] In general, the northern, central, and eastern regions of North America are expected to have hotter and wetter extremes and, in some regions, more precipitation and fire weather. In western North America, future changes are expected to be hotter and drier, with wetter extremes in some regions.[12]

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

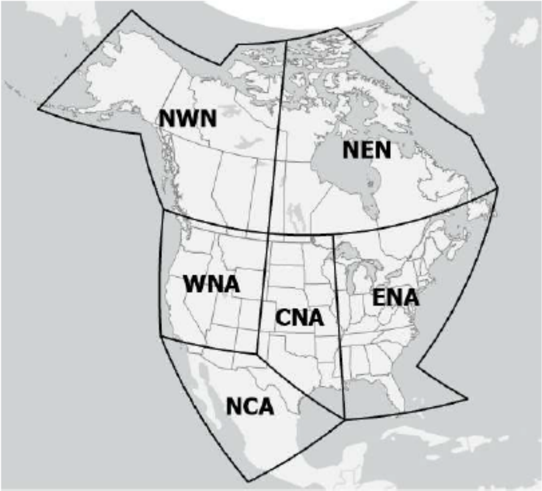


Region	Extreme Heat	Mean Precipitation	River Flood	Heavy Precipitation with Pluvial Flood	Hydrological Drought	Fire Weather	Snow, Glacier, Ice Sheet	Tropical Cyclone	Coastal Flood / Erosion
North-Western North America (NWN)	■ ↑	■ ↑	▨ ↑	■ ↑		▨ ↑	■ ↓		■ ↑
North-Eastern North America (NEN)	■ ↑	■ ↑	▨ ↑	■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

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/

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

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

Vulnerability is a function of the sensitivity of a system or population and the adaptive capacity of the same.[13] Examples of climate-specific vulnerabilities are described below.

Human Health and Vulnerable Populations

Climate affects all areas of human health. Changes in air, water, food, and the environment will result in changes in the health and well-being of people. Increased heat waves, changes in precipitation, and sea-level rise affect health via multiple pathways. Human health risks associated with climate change are expected to increase in the future.

Some populations will be at higher risk from climate change impacts than others. Low-income communities and some communities of color are currently affected by health disparities and are less resilient to the human health impacts of climate change. Existing health issues in native tribes across the U.S. and Canada are expected to be exacerbated by multiple climate-related factors, including the loss of traditional foods and practices, community displacement, flooding, decreased food security, and new infectious diseases.[14,15] Children, older adults, low-income communities, some communities of color, and communities that experience discrimination are disproportionately affected by extreme weather and climate events.[16] Other groups that may experience disproportional impacts from climate change include outdoor workers, residents of areas with poor environmental quality, and poorer communities, especially in rural areas.[17] Communities with less access to information or support may be less able to avoid the health risks of climate change.[18]

Biodiversity

Biodiversity and species conservation is important for ecosystem balance and human populations (e.g., pollination of food crops). As the climate changes, many species are beginning to exhibit evolutionary adaptations in response.[19,20,21] However, projections suggest that climate change may occur too rapidly for some species to adapt. The capacity for adaption varies by species and even among populations of the same species.[22]

Changes in species ranges have been observed as a response to warming temperatures[23] as well as changes to migration patterns or life cycle events.[24] Climate change may increase invasive or non-native species,[25] leading to non-native species outcompeting native ones. Current and future stressors are projected to reduce the capacity of ecosystems to recover from extreme events like floods and fires. Climate change is projected to lead to losing iconic species from certain regions or becoming extinct altogether.[26]

Urban Heat Island

The urban heat island effect refers to the tendency for urban areas to absorb and release solar heat,[27] 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 humid regions (primarily the eastern United States) and cities with larger and denser populations.[28] 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. Factors associated with climate change include changes in the quantity and quality of water supplies, changes in soil moisture, sea-level rise, and the frequency of extreme events.[29] Human systems that interact with these impacts include the vulnerability of water infrastructure, water withdrawals, and water-use efficiency. The vulnerability of water supplies to climate change is currently unknown since risks depend on future decisions and actions.

2.3 GSI for Climate Resilience

“Resilience”, as defined by the U.S. Climate Resilience Toolkit,[30] 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.

2.3.1 Managing 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.[31] When GSI is implemented in coordination with other landscape features connecting urban hydrologic and vegetations systems, significant benefits can be achieved.

2.3.2 Preventing and Reducing Erosion

GSI implementation can provide benefits in mitigating creek and coastal erosion. Projected future increases in flooding can cause increased runoff volumes and flow rates, leading to creek erosion, bank incision, degradation, and related water quality issues in downstream receiving waters. In reconnecting the natural water cycle through runoff retention and infiltration in an urban watershed, GSI can reduce downstream hydrologic impacts. This can be implemented through GSI facilities at multiple scales, including street trees and green roofs, which can mitigate hydrologic effects in highly urban settings. Some erosive impacts related to sea-level rise and storm surges can be reduced through GSI facilities incorporating natural functions. Additional GSI benefits include improved habitat, water quality, and carbon sequestration.[32]

2.3.3 Reducing Urban Heat Impacts

Communities can reduce heat island impacts through GSI including vegetation and trees providing natural heat-regulating services, such as shading, evapotranspiration, and thermal insulation of buildings.[33] Planting urban trees that focus on urban hot spots can appreciably reduce urban heat impacts.[34] Strategies targeting buildings such as cool roofs or green roofs can reduce heat absorption while reducing the energy needed to cool buildings and improve stormwater runoff.[35] 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.[36]

2.3.4 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.[37] Some evidence suggests that increased leaf area associated with certain GSI solutions can improve air quality by air pollution preferentially depositing onto vegetation.[38] 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.[39]

2.3.5 Water Supply Augmentation

Stormwater harvesting and groundwater replenishment from GSI can increase local water supplies, buffer against droughts, and reduce energy requirements and emissions associated with importing water from other locations.[40] 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.[41] For example, the Orange Memorial Park Regional Stormwater Capture Project Park in South San Francisco will divert flow from a creek for water quality treatment, beneficial reuse (e.g., irrigation), and local flood reduction.[42] 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.

2.3.6 Human Health Benefits

GSI has been shown to improve human health outcomes across various categories[43] 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 greens 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.[44]

Tree density and proximity to passive and active green spaces have been shown to provide physical, mental, and behavioral benefits.[45] Direct physical benefits of green space include improved cardiovascular health, reduced respiratory diseases, and reduced obesity.[46] Mental health benefits are associated with a reduced risk of depression, anxiety, and mood disorders.[47,48] Other benefits include a reduction in anti-social behaviors such as property and violent crime[49] and an improvement in helpful and generous behaviors.[50] 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.[51,52]

2.4 GSI and Equity

The effects of climate change disproportionately impact low-income and minority 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.[53,54] In a recent study, McDonald et al.[55] 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, minority neighborhoods are often at low elevations, vulnerable to sea-level rise and aging or failing stormwater infrastructure. These communities will disproportionally feel impacts from rising temperatures, urban heat island effects, poor air quality, and flooding, further contributing to inequity in health and well-being.[56]

By providing green spaces and a means for improved stormwater management, implementation of GSI in low-income and minority communities can help alleviate the negative impacts of climate change such as poor air quality, severe heat, and localized flooding. 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.[57] 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.[58] As presented in the Equity Guide for GSI Practitioners,[59] well-designed green infrastructure programs can make direct contributions to equity in the following ways:

- Expand nature in communities,
- Increase resilience to climate hazards,
- Improve properties,
- 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 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.[60] 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.[61]

> *"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, and 5) there is lower tree canopy coverage that could benefit from increased urban greening."*

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 Green Infrastructure Leadership Exchange 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.

2.5 Public Engagement, Communication, and Outreach

Early and consistent public engagement is necessary for success in GSI projects 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.[62] 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; and
- Levels of service and performance targets factoring in climate change impacts and system constraints (asset management project outcomes may address this).

It may seem that providing facts and unbiased information to people would lead them to make decisions in the same way. However, social science experiments have demonstrated that information alone is not the solution. People tend to interpret facts strongly in the direction of their past experiences. Rather than solely providing facts, meeting people where they are, finding common ground, and building partnerships through regular contact and communication is critical.

At the NOAA and the 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:[63]

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.
3. Community members have trusted relationships with the utilities. 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—as well as 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 community-based organizations. When working with minority 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.

2.6 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.

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.

Similarly, although GSI can assist in mitigating 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 continue to provide water quality and hydrologic benefits. 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.

3. POLICY AND REGULATORY REQUIREMENTS

This section summarizes existing policies and regulations relevant to GSI and climate change 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.

3.1 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 (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 stormwater permits for 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.

Climate change resilience has not been substantially amended to these regulations at the federal level. However, some state and local regulations and policies focus on

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[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.

resilience and are also relevant to stormwater management. In the United States, for example, the NPDES permit issued in 2022 by the San Francisco Bay Regional Water Quality Control Board requires that permittee's Green Infrastructure Plans are consistent with climate change adaption plans. The permit also requires long-term green infrastructure implementation to consider linkages to climate change impacts and resilience.[64] All permittees must complete a Climate Change Adaption Report by 2026, identifying potential climate change-related assets and appropriate adaptation strategies.

Canada does not have national regulations for stormwater similar to the US NDPES requirements. However, Canadian provinces and cities do have to meet other environmental and infrastructure requirements and goals in a sustainable manner.[65] An example of a local resilience standard in Canada includes the Toronto City Council's adopted Version 4 of the Toronto Green Standard (July 2021). This Standard addresses resilience through, "enhanced green infrastructure to manage stormwater runoff, reduce urban heat island impacts and promote biodiversity (including more extensive and higher performance green roofs), bioswales, rain gardens, native pollinator species plantings and a new requirement for "green streets" (roads or streets that incorporate green infrastructure)."[66] These standards apply to new development applications beginning May 2022.

Complimentary to the growing body of GSI regulations that consider climate change impacts, many state grant programs, and federal infrastructure funding options are focusing on climate resilience related to stormwater projects (for example, California Climate Resilience Package funds).[67] These funding options also emphasize and/or require project implementation in disadvantaged communities.

3.2 Incorporating Resilience into Policies and Regulations

Municipalities and other local agencies may incorporate 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 for resilience. In addition, broader partnerships and multi-disciplinary collaboration will be needed. More specifically, GSI project implementation increasingly involves the private sector (e.g., developers) and schools, requiring partnerships between landowners with different motivations and requirements. Engaging local communities and addressing equity issues to collaborate and realize a unified vision will also be essential.

Local GSI-related policy and regulatory changes that integrate climate resilience may include:

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 or require specific treatment mechanisms, such as increased retention or detention.
    - 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.

3.3 Next Steps

Additional development of GSI policy guidance in the context of climate resilience could be incorporated into future parts of this Guide. This 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. Potential management questions to be addressed in policy updates for climate resilient GSI planning and design.
4. Development of model policy language to address opportunities for improving climate resilience in GSI planning and implementation
5. 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.

4. GSI PLANNING

This section explores considerations for GSI planning related to climate resilience and incorporating climate resilience into GSI planning. As equity considerations and community engagement are important throughout the GSI implementation processes, these components are touched on below.

4.1 Considerations for GSI Planning Related to Climate Resilience

GSI planning entails several steps, including site and opportunities assessment, selection of GSI types, initial layout, permitting, and conceptual design. 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 planning to provide project direction and garner support for planned GSI. GSI siting considerations and objectives that may be considered in 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 identifying disadvantaged and vulnerable communities.
- Funding sources and capital and maintenance costs.
- Cost-effectively complying with applicable regulatory requirements.

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. Climate resilience should be considered in GSI planning when:

1. Climate change could impact GSI performance, or
2. GSI has the potential to improve community resilience (e.g., providing flood reduction or drought resilience).

Considerations for these separate, but related, GSI planning goals are explored in the sections below.

4.1.1 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[68] 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 changes to or considerations of how GSI planning processes can 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 runoff capture targets to prevent inundation and erosion of GSI facilities. Such targets may differ from or exceed current local regulations.
3. Recommend GSI types and general plant/tree selection considerations with consideration of projected changes to climate.

4.1.2 Opportunities for GSI to Increase Community Resilience

There are a number of opportunities for GSI to increase climate resilience, as described previously in section 2.3. 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 also exacerbate other conditions that GSI is implemented to partially mitigate, such as the urban heat island effect, localized flooding, or impacts on disadvantaged communities. GSI may also become part of the toolbox in thinking more strategically about integrated water planning to address prolonged drought.

Potential changes to or considerations of how GSI planning processes can incorporate climate resilience provided by GSI could include:

1. Locating GSI to more optimally meet anticipated climate-related regulations or policy.
2. Setting volume-based runoff capture targets to target projected localized flooding or water quality concerns, which may differ from or exceed current local regulations.
3. Locating GSI to provide additional climate-related resilience benefits (e.g., localized flooding benefits, urban heat island benefits, water supply benefits, combined park and water storage opportunities, community resilience, and active transportation options).
4. Including social and infrastructure data to understand community climate-related vulnerability, including in underserved communities, identify where climate-related improvements are most needed, and locate GSI where it can address some of these needs.
5. Considering GSI projects across scales to assess potential benefits to the greater green infrastructure and natural heritage system, improving landscape connectivity and system resilience.
6. Recommending GSI types and general plant/tree selection considerations to maximize climate resilience-related benefits in the planning stage.

In addition to the planning considerations above, larger-scale water quality and pollutant loading changes resulting from climate change should be considered. These include but are not limited to:

1. Rising temperatures resulting in increased water temperatures in receiving water bodies; and
2. Increases in eutrophication, especially in shallow water bodies.

GSI facilities or planning strategies previously developed to meet specific water quality goals may require updating as other water quality impacts become evident and/or are included in regulations.

4.2 Incorporating Climate Resilience into GSI Planning

Additional objectives and siting considerations may be needed to incorporate these climate-resilience considerations in the earliest phases of GSI planning and assessment. Incorporating climate resilience considerations into a community's GSI planning may entail stakeholder and municipal interdepartmental meetings to identify and prioritize climate-related objectives. This may also entail additional steps, data, desktop, or field studies when performing GSI opportunity analysis (i.e., identifying locations to implement GSI). Suggested approaches for how to incorporate climate resilience considerations in GSI planning are provided in this section.

Planning and decision-making processes to incorporate climate-resilience considerations into GSI opportunity analyses may entail:

1. Identifying management priorities relating to GSI planning and design in the context of climate resilience, including:
    - Compliance with new regulatory requirements or policies relating to climate change;
    - Implementation or retrofit to achieve more resilient GSI; and
    - Optimization of GSI locations and capacity at a subwatershed scale to maximize resilience-related benefits.
2. Identifying when in the planning process to consider climate resilience, such as:

- Formation of planning objectives, prioritizing those facilities that can comply with resilience requirements or provide enhanced climate resilience.
- Developing partnerships with stakeholders and community members to implement GSI for climate resilience goals, including "One Water" type strategies.
- GSI siting, to account for future potential impacts of climate change (e.g., hydrologic, temperature, and groundwater level changes) on GSI performance.
- Identification of GSI types, and extent and types of landscape/vegetation and trees, to maximize the resilience benefits provided as well as performance (adapting tree and plant species to changing climate conditions)
- Integration and coordination with other infrastructure and community plans to incorporate GSI or avoid conflict with other larger-scale climate resilience efforts.

3. Identifying planning-level climate resilience data or projections to consider for GSI implementation, for example:
    - Watershed-level quantitative targets (i.e., reduced flows or volume) for resilience.
    - The range of projected changes to precipitation patterns (e.g., calculated predictions for future floods, design storm frequencies) and potential design changes (as available and appropriate) for successful GSI performance.
    - Location and frequency of minor localized flooding or large flooding events.
    - Changes to groundwater level, including locations and frequency of flooding due to surfacing groundwater.
    - Areas, timing, and duration of urban heat stress.
    - Opportunities for groundwater recharge or capture and reuse.
    - Land use and ownership characteristics that may streamline or hinder GSI implementation or performance.
    - Relevant equity indicators.

  - Community goals, concerns, and priorities for GSI and climate resilience.

4.3 Next Steps

Additional development of GSI planning guidance in the context of climate resilience could be incorporated into future parts of this Guide. This could include:

1. Guidance on decision-making processes to establish community climate resilience priorities for GSI, including:
    - Compiling regulatory requirements and how they may be achieved through GSI.
    - Establishing a comprehensive list of multi-benefit objectives.
    - Identifying relevant stakeholders and performing outreach.
    - Developing cost-benefit analyses relating to GSI and climate resilience.
    - Planning in response to adjusted requirements or design standards that consider climate change.
2. Guidance on suggested data, indicators, and metrics to locate and prioritize GSI, for example:
    - Identifying data needs relating to GSI and climate resilience (such as projected temperature changes, projected precipitation changes, flood modeling output, water quality data and/or modeling output, etc.).
    - Developing benefit metric increments that could be used to identify whether a specific location and type of GSI could provide climate resilience.
    - Description of the geospatial, other modeling, and calculation methods that could be used to analyze benefit metrics and drive implementation targets.
3. Guidance on geospatial processes to locate GSI opportunities:
    - Listing GSI opportunity analysis data needs in the context of climate resilience, such as land use, ownership, physical properties including soil, depth to groundwater, utility conflicts, etc.
    - 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).

4. Guidance on incorporating needs and priorities of disadvantaged communities, identifying successful approaches for community engagement, and encouraging the equitable implementation of GSI to achieve long-term success in the context of a changing climate.
5. Developing an evaluation framework to prioritize project opportunities to robustly capture considerations related to environmental performance, climate change risk, and social vulnerabilities and benefits.

5. GSI DESIGN

Several climatic impact drivers related to GSI are projected to change in the future and would likely affect GSI design. These drivers include precipitation, including changing storm event characteristics such as the size, intensity, duration, and location of significant rain events,[69] along with flood and submergence from rising sea, riverine, and groundwater levels and extreme temperature. 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. This section introduces the established approach (i.e., that is currently in use) for GSI siting, sizing, and design, describes climate-related considerations that may be needed, and suggestions on how to incorporate changes to GSI siting, sizing, and design approaches given climate trends.

5.1 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[70] 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.[71]

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.[72]

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.

5.1.1 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 2). 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).[73] 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.

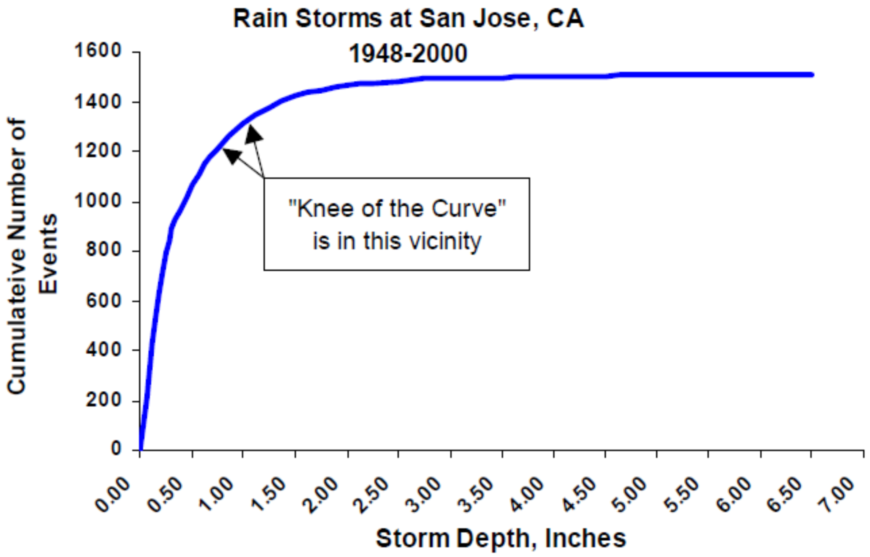

Figure 2. Example "Knee of the Curve" based on Historical Data[74]

5.1.2 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 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.

5.2 Considerations for GSI Related to Climate Resilience

While the 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.[75] Other climate change impacts, including rising groundwater and changes in temperature, may also affect GSI siting and performance.

5.2.1 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.

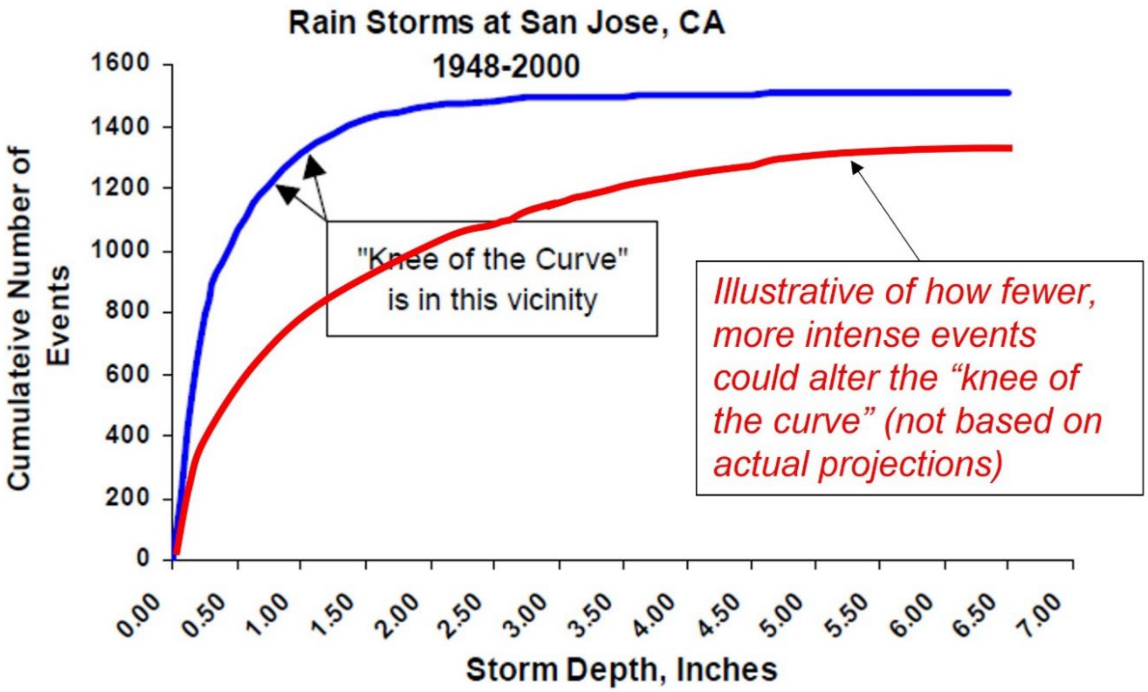

Figure 3. Altered "knee of the curve" sketch due to climate change impacts.

Based on modeling results from downscaled Global Climate Models[v] (GCMs) and hourly precipitation developed through an application of regional weather modeling for Western Washington, Figure 4 provides an actual example of an altered "knee of the curve."[76]

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[v] 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.

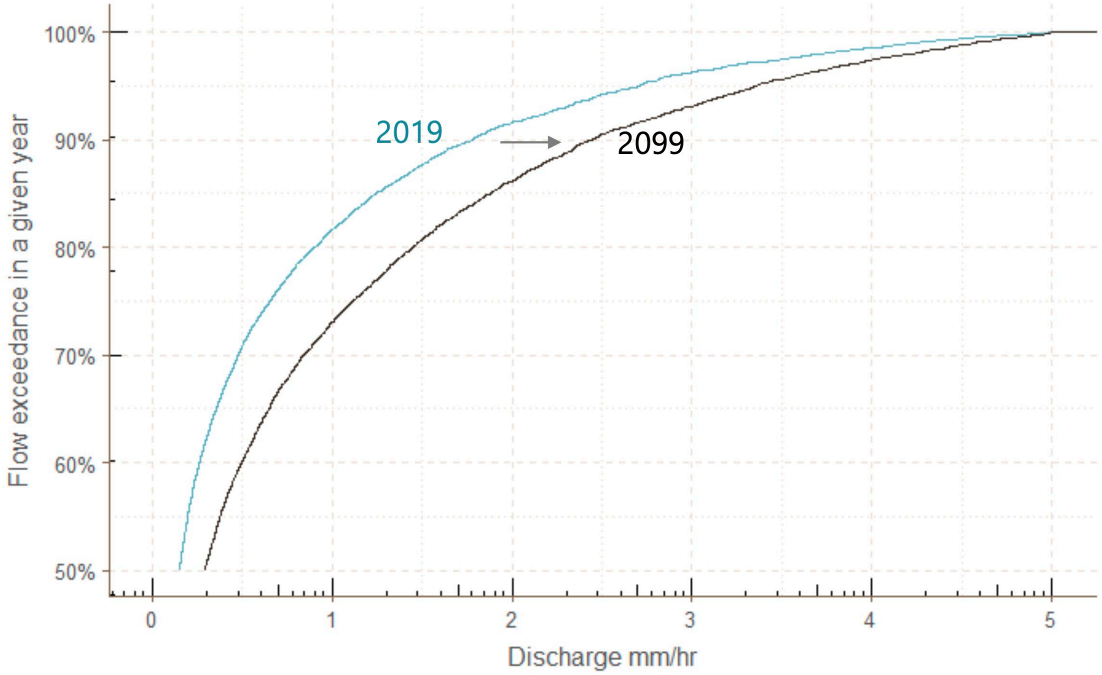

Figure 4. Actual altered "knee of the curve" due to climate change impacts in Western Washington.

In addition, more intense, less frequent storm events and other precipitation changes could affect facility performance. For example, an increased frequency of intense "back-to-back" winter storm events and atmospheric rivers has been observed in the western United States, while the eastern United States has seen an overall increase in very heavy precipitation (defined as the top one percent of all daily events) (Figure 5).

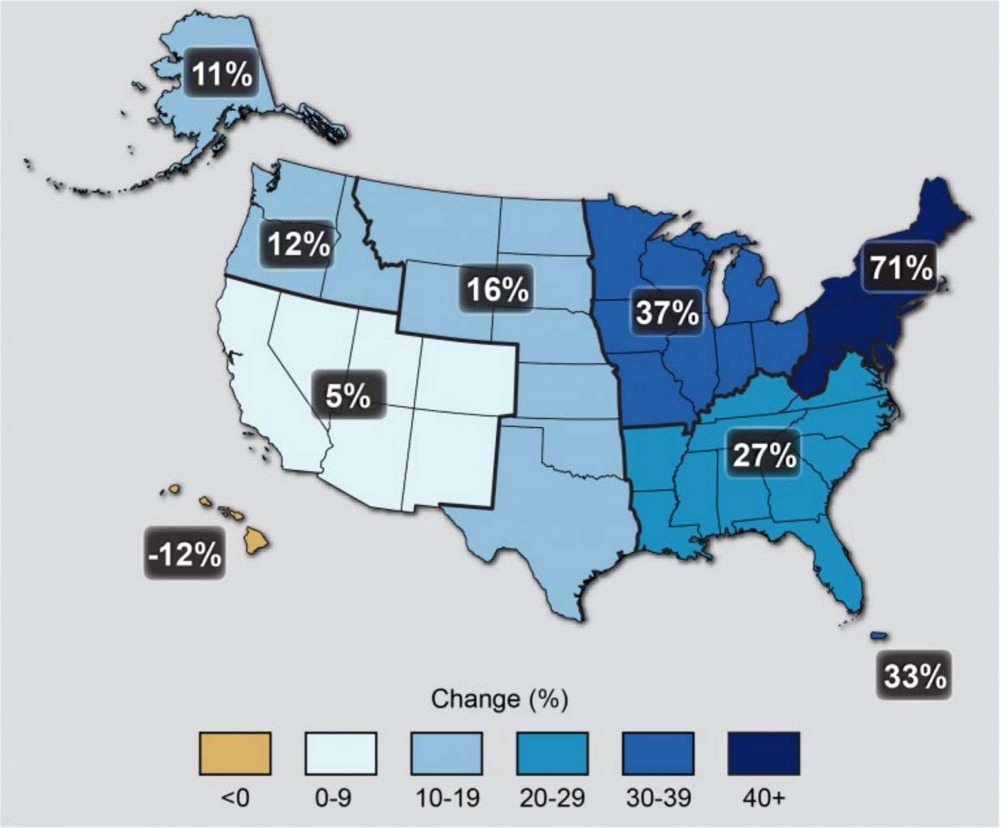

Figure 5. Map of the observed change in very heavy precipitation (defined as the top 1% of all daily events) from 1958 to 2012[77] in the U.S.

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. These changes, which have already been observed in some locations, may cause an increase in pollutant accumulation on the landscape. Higher concentrations of pollutants in seasonal first-flush events could impact GSI facility performance and may require additional pretreatment to maintain performance.

5.2.2 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,[78] though temperature differences related to GSI performance vary by facility type with bioinfiltration showing more sensitivity than pervious pavement.[79] 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.

5.3 Incorporating Climate Resilience into GSI Sizing and Design

The challenges described suggest the need for an updated approach to sizing and designing resilient GSI. Details of how climate resilience could be incorporated into GSI sizing and design are introduced in this section.

5.3.1 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 4). Climate change predicted under higher RCPs is typically more severe, although precipitation impacts do not always scale with increased warming.

Table 4. Summary of IPCC Emission Scenarios (adapted from IPCC AR5, 2014[80])

Scenario	CO_2-eq Concentrations in 2100 (ppm)	Change in CO_2-eq emissions compared to 2010 (in %)		Likelihood of temperature change relative to 1850-1900 remaining below:			
		2050	**2100**	**+1.5°C**	**+2°C**	**+3°C**	**+4°C**
RCP2.6	430 – 480	-72 to -41	-118 to -78	More unlikely than likely	Likely	Likely	Likely
RCP4.5	580 - 720	-38 to 24	-134 to -50	Unlikely	More likely than not		
RCP6.0	720 - 1000	18 to 54	-7 to 72		Unlikely	More unlikely than likely	
RCP8.5	> 1000	52 to 95	74 to 178			Unlikely	More unlikely than likely

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 6). 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.

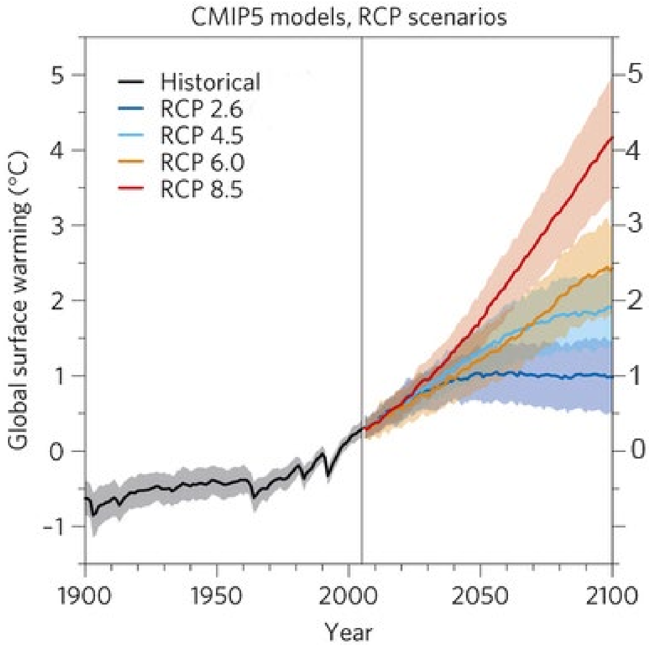

Figure 6. Projected global surface warming for different emissions scenarios[81]

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.

5.3.2 GSI Types

In addition to standard GSI performance changing for a range of different precipitation outcomes, different GSI types may perform better or worse depending on regional climate trends. Guidance for identifying the GSI types or combinations (including with other types of stormwater management approaches) that provide increased climate resilience would be a valuable tool for communities.

Single GSI facilities that rely on fixed detention storage, for example, may fare worse than facilities that incorporate multiple treatment mechanisms (i.e., retention, infiltration, soil storage, evapotranspiration), especially in regionally wet/cool and wet/warm climates 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 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.

5.3.3 GSI Hydraulic Components

Changes to the design and sizing of inlet, outlet, and overflow components may also be needed to adapt GSI facilities to climate change. 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, underdrain sizing, outlet sizing, and overflow operations may also need to be revisited. Analyzing inlet, underdrain, and outlet performance with projected climate change can provide insight into potential design changes.

5.3.4 Media and Vegetation Considerations

Other GSI design components, such as media, vegetation, subsurface, liners, and structural elements may be affected by climate change and require additional design changes.

For example, media amendments (e.g., biochar) that encourage water retention while maintaining drawdown rates may be needed to sustain plant health as temperatures increase. Plant and tree species selection will need to adapt to more site-specific plant palettes that survive in harsh (including extreme dry and submerged) conditions in anticipation of rising temperatures and changing precipitation patterns, as well as potential changes in groundwater levels. Approved species lists by municipalities will need to take into consideration how climate change will affect plant hardiness zones. The shifting of those zones over time (projected by the US Forest Service)[82] with rising temperatures and increased precipitation will need to be taken into account when designing vegetated systems to last many decades into the future.

In nearshore locations with shallow groundwater, future groundwater levels should be considered. These considerations will affect the design of a facility as well as specific features (e.g., whether a GSI facility should incorporate an impermeable liner). Additional considerations include selecting appropriate plant palettes under future climate change and selecting appropriate media. 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).

5.3.5 Additional Considerations for CSO Communities

CSO communities may 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.

5.3.6 GSI Facility Retrofit

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

1. Capture of 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 impacts to GSI facility surface or hydraulic components.
3. Other hydraulic issues such as extended ponding or flooding near inlet, outlet, or overflow with resultant vector issues.
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.

5.4 Next Steps

Additional development of GSI design guidance in the context of climate resilience could be incorporated into future parts of this Guide. Potential future guidance topics are provided below.

5.4.1 Quantifying the Potential Extent of Climate Impacts to GSI

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.

5.4.2 Resilience of GSI Measures and Components

Using the results of the analysis described in section 5.4.1, or through literature studies, guidance could be developed to inform which designs or GSI measures are most resilient to anticipated climate changes. This could include a tool, such as a matrix or a flowchart, which identifies GSI measures and design changes (e.g., media amendments, facility liner, constructing facility off-line, etc.) that are best suited to manage specific climate impacts. This guidance could also be used as a planning tool once developed.

5.4.3 Methods to Develop New GSI Design Standards or Guidance

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.

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.

6. GSI OPERATIONS AND MAINTENANCE

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

6.1 Considerations for GSI Operations and Maintenance Related to Climate Resilience

Typical operations and maintenance (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 removal.
2. Post-storm O&M needs: Inspections to examine damage including erosion, 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.

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.

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.

6.2 Incorporating Resilience into GSI O&M

To incorporate resilience into GSI, 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.

6.2.1 Climate Change Education & Training

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 can also be considered in the O&M phase. While some O&M tasks would require work by trained professionals (e.g., replacement of soil media or structural components), the local community and residents could do other tasks, such as plant maintenance and trash removal. This type of community buy-in would improve the potential for long-term success.

6.2.2 Adaptive Management

Adaptive management processes may require more frequent inspections to learn how enhanced O&M affects GSI performance. 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. Results from such an evaluation would be useful to identify staff or contractor training needs, tools, and resulting funding requirements. 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.

6.3 Next Steps

Additional development of GSI O&M guidance in the context of climate resilience could be incorporated into future parts of this Guide. This could include:

1. Providing guidance on an education, training, and communication strategy that supports adaptive management of GSI O&M practices.
2. Developing a stepwise process for examining current maintenance practices and estimating the potential required changes with projected climate impacts. In addition to examining individual activities, the stepwise approach could include suggestions for exploring staffing, tools, and cost impacts.
3. 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.).

7. CLIMATE RESILIENCE RESOURCES GUIDE ROAD MAP – SUGGESTED NEXT STEPS

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, and climate change adaptation in the urban environment at a "broad brush level" and for a variety of future climate change impacts anticipated throughout North America. GSI is part of the range of solutions that can help manage urban flooding, erosion, and urban island heat 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 and considerations for improving the resilience of GSI planning, design, and implementation in the face of various climate change risks.

This Guide and its appendix of GSI-related climate resilience references are intended to be living documents for the GI Leadership Exchange 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. Topics to consider for future additions to this Guide are outlined and prioritized below in Table 5.

Table 5. Prioritized Topics for Future Iterations of this Guide

Section	Next Step
Policy and Regulations	Methods for conducting risk assessment and scenario planning.
	Guidance for policy decision-making with uncertainty.
	Potential management questions in climate-resilient planning and design.
	Model policy language for climate resilience relating to GSI.
	Economic evaluation guidance relating to GSI.
GSI Planning	Guidance on decision-making processes to establish climate resilience priorities and goals, including community benefits and equity.
	Guidance on suggested data, indicators, and metrics to locate and prioritize GSI, as well as select GSI type.
	Guidance on geospatial processes to site GSI.
	Evaluation framework to prioritize project opportunities.
GSI Design	Quantifying the potential extent of climate impacts to GSI.
	Flowchart or tool to guide which designs or GSI measures are most resilient to anticipated climate changes.
	Methods to develop new GSI design standards or guidance.
GSI O&M	GSI O&M communication, education, and training strategy.
	Process to estimate potential required changes to maintenance activities, staffing, tools, and cost impacts.
	GSI O&M asset management guidance.

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APPENDIX A

Matrix of Existing GSI Resilience Resources

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

Title	Year	Author(s)	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	X	X		X			X			X		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	X	X		X								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	X	X	X	X		X	X	X				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	X		X	X		X	X	X		X		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	X		X	X	X							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	X	X	X	X			X					https://www.epa.gov/sites/default/files/2016-08/documents/gi_climate_charrettes_final_508_2.pdf	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	X	X		X								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	X												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	X												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	X	X		X								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	X	X		X								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	X	X					X					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	X	X	X	X			X					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	X										X		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	1, 2	X	X	X	X		X	X						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									X		X		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		X			X									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	X		X	X									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 Centry: Meteorology, Hydrology, Loading and Lake Response	2010	Tahoe Environmental Science Center	Report		X			X								-	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	X												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	X	X		X									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.

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

Title	Year	Author(s)	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	X	X		X									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	X	X						X					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	X	X		X									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				X	X		X		X		X		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	X	X		X								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 increome across 5,723 communities	2021	McDonald et al.	Journal Article	2	X								X		X		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	X	X		X			X	X					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	X	X		X									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	X	X											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	X	X		X									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	X	X		X			X						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	X	X		X									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	X			X		X							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	X	X		X		X							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	X	X							X		X	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	X	X							X		X	https://giexchange.org/wp-content/uploads/2022/01/State-of-Equity-in-Public-Sector-GSI-Baseline-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	X											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	X											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				X			X					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	X											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	X	X		X					X		X	Green Infrastructure Toolkit » About This Toolkit - Georgetown Climate Center	Toolkit from Georgetown Law on Green infrastructure planning

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Climate Resiliency Design Guidelines	2020	NYC Mayor's Office of Resiliency	Guide	3,4,5	X		X	X		X							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							X					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 assisstance, and coordinating training opportunities. It also provides various tools.
Coastal Flood Resilience Design Guidelines	2019	Boston planning and development agency	Guide	4	X		X	X		X						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		X			X								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		X			X			X					Adaptive Solutions (climateapp.nl)	The app gives urban designers, engineers or others insight in feasible measrues 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		X							X	a			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	X		X	X		X	X					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	X	X		X								https://mde.maryland.gov/Documents/A-StorRMreport.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	X		X	X		X		X	X	X	X	https://www.phila.gov/documents/philadelphia-climate-action-playbook-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	X	X		X								https://www.rand.org/pubs/research_reports/RRA564-1.html	The researchers identified potential climate change impacts for the Negley Run watershed, where urgant 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	X	X										https://www.sfei.org/documents/trees-and-hydrology-urban-landscapes	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	X	X										https://water.phila.gov/pool/files/gsi-maintenance-manual.pdf	Philadelphia's GSI maintanence manual for various stormwater management practices.
Green Stormwater Infrastructure Landscape Design Guidebook	2020	Philadelphia Water Department	Guide	1, 3	X	X										https://water.phila.gov/pool/files/gsi-landscape-design-guidebook.pdf	Philadelphia's GSI landscape design guidebook.
Green Stormwater Infrastructure Planning & Design Manual	2021	Philadelphia Water Department	Manual	1, 3	X	X										https://water.phila.gov/gsi/planning-design/manual/	Philadelphia's GSI planning and design manual.
Examples of Green Infrastructure Projects in San Francisco	2022	San Francisco Public Utilities Commission	Website	1	X	X										https://sfpuc.org/programs/san-franciscos-urban-watersheds/what-green-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	X											https://www.fema.gov/emergency-managers/risk-management/nature-based-solutions	FEMA's risk management guide focusing on nature-based solutions.

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Nature-based solutions for climate change mitigation	2021	United Nation Encironment Programme (UNEP) & Internationl Union for Conservation of Nature (IUCN)	Report	1	X		X	X	X	X	X	X	X	X		https://www.iucn.org/theme/nature-based-solutions	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	X	X										https://sfpuc.sharefile.com/d-sd59402b587f4fe59	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	X	X		X								http://www.newea.org/wp-content/uploads/2019/03/NEWEA-Journal_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	X	X		X								https://www1.nyc.gov/assets/dep/downloads/pdf/climate-resiliency/nyc-cloudburst-study.pdf	This executive summary describes the process and findings 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	X	X		X								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				X								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		X		X	X	X	X	X	X	X	X	X	ttps://toolkit.climate.gov	
New Solutions for Sustainable Stormwater Management in Canada	2016	Sustainable Prosperity	Report		X												
Governor Newsom Signs Climate Action Bills	2021	Office of Governor Gavin Newsom	Press Release													https://www.gov.ca.gov/2021/09/23/governor-newsom-signs-climate-action-bills-outlines-historic-15-billion-package-to-tackle-the-climate-crisis-and-protect-vulnerable-communities/	

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

Title	Year	Author(s)	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	X	X										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	X	X										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	X	X										https://www.amazon.com/Stormwater-Management-Practices-Detention-1992-10-01/dp/B01A65DCAS	
Surface Water Design Manual	1998	King County Stormwater Services	Manual	3	X	X										https://your.kingcounty.gov/dnrp/library/water-and-land/stormwater/surface-water-design-manual/1998-swdm.zip	
Stormwater Collection Systems Design Handbook	2001	Mays	Textbook	3	X	X										https://www.zuj.edu.jo/download/stormwater-collection-systems-design-handbook-	
Stormwater Treatment: Biological , Chemical, and Engineering Principles	2002	Minton	Textbook	3	X	X										https://books.google.com/books/about/Stormwater_Treatment.html?id=T5rRAAAACAAJ	
CASQA Stormwater BMP Handbook - New Development and Redevelopment	2003	CASQA	Manual	3	X	X											BMP manual from CASQA
Municipal Stormwater Management, 2nd Edition	2003	Debo and Reese	Textbook	3	X	X										https://www.routledge.com/Municipal-Stormwater-Management/Debo-Reese/p/book/9781566705844	
Stormwater Best Management Practices Design Guide (Volume 1, 2, and 3)	2004	U.S. Environmental Protection Agency	Manual	3	X	X										https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryId=99739	

Matrix 3. Regional-Focused Impacts and Global Hydrologic Impacts of Climate Change

Title	Year	Author(s)	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						X								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					X									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						X								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 snow-dominated regions	2005	Barnett, Adam, & Lettenmaier	Journal Article						X		X						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						X								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						X								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									X					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					X									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					X									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					X	X		X	X				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.