Green Stormwater Infrastructure for Urban Flood Resilience:

Opportunity Analysis for Dallas, Texas

The Nature Conservancy

Texas A&M AgriLife Extension

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LEFT: Parking lot bioretention area at the Texas A&M AgriLife Research and Extension Center-Dallas. © Kathy Jack/ TNC

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LEFT: Rain garden. © Charriss York/Texas A&M AgriLife.

Executive Summary

Dallas-Fort Worth is the fastest growing metropolitan area in the United States (U.S. Census Bureau, 2020). With rapid and widespread conversion of natural land cover to impervious surfaces, stormwater management—for water quality and urban flooding—is an important challenge for municipalities in the region. This challenge is expected to be exacerbated by climate change. Cities across the world are increasingly utilizing green stormwater infrastructure (GSI) practices, engineered plant and soil systems that recreate natural hydrological processes, to enhance stormwater management in urbanized watersheds. In addition to improving water quality,GSI can provide an important and cost-effective tool to enhance urban flood management.

This study utilized hydrologic modeling and spatial analysis to help answer the overarching research question: Where can green stormwater infrastructure (GSI) most effectively enhance urban flood management within the City of Dallas, Texas, when considering capacity, cost, and future impacts of climate change. The focus was on evaluating opportunities to enhance flood management where the existing drainage network may be limited. Therefore, the study was limited to areas with complete stormwater drainage system data, and included a total of 118,418 acres, or 53% of watershed area within the City.

The U.S. Environmental Protection Agency's Storm Water Management Model (EPA SWMM v. 5.1) was used to identify and evaluate potential stormwater system "hotspots"—specific locations where the drainage network is undersized and likely to contribute to inlet overflows and areal flooding, under a variety of storm conditions. Models were run for the 2-year (50%), 10 -year (10%), and 100-year (1%) 24-hour storms, for "current conditions"[1] and forecasted "climate change" scenarios for 2045 (RCP 8.5).[2]

The "challenged subwatersheds"[3] draining to system hotspots were spatially evaluated for potential sitesto deploy three types of green stormwater infrastructure—bioretention areas, rain gardens, and rainwater harvesting cisterns. For the selected current conditions storms, the capacity and costs were estimated for managing stormwater with the "maximum implementation scenario" of these GSI practices, and compared to "gray"[4] infrastructure for the 100-year design storm.[5] Finally, a desktop pre-and post-GSI analysis was performed to determine the potential flood management benefits from the maximum GSI implementation scenario.

1 The "current conditions" scenarios include models run with current Atlas 14 (Perica, Pavlovic, & Laurent, 2018), using precipitation data for the 2-, 10-, and 100-year,24-hour storms. Throughout this report, the terms"current conditions" or "current conditions storms" refer to these models.

2 Climate change precipitation scenarios are described in Section 2.3.5. Throughout this report, mentions of"future", "forecasted" and "climate change conditions" refer to these models.

3 "Challenged subwatersheds" are defined in section 2.3.2.

4 "Gray" infrastructure refers to traditional stormwater infrastructure, often made with concrete.

5 City of Dallas (City of Dallas, 2019b)requires that any upgraded gray stormwater infrastructure be designed to meet the 100-year (1%)storm; therefore, cost comparison is most equivalent for this "design storm."

Key findings include:

- Larger amounts of precipitation will lead to more, and more severe, system hotspots and contributing subwatersheds—for larger return period storms, and with the increased precipitation forecasted for 2045 (RCP 8.5).
- Climate change will result in an average increase in the number of system hotspots (+26%) and area of challenged watersheds (+30%), compared to current conditions for the three return period storms studied.
- Precipitation amounts and the resulting hotspots for the 10-year storm forecasted for 2045 resemble those for today's 100-year storm.
- Substantial cost-effective opportunities have been identified to deploy GSI for improved stormwater management in Dallas—particularly within the Joes' Creek, Cedar Creek, and Five Mile Creek Watersheds, and portions of the White Rock Watershed.
- GSI was found to reduce modeled overflows for all storms (17-31% reduction) and to delay peak flows which can reduce areal flooding as well as creek flows and overbank flooding.
- GSI was found to be 77% less costly than upgrading gray infrastructure alone, to meet modeled overflows, and a combination of green and gray provides the maximum cost-effective benefits.
- Of the systems studied, bioretention areas—particularly in parking lots—represent the "biggest bang for the buck," with the most widely available siting opportunities.
- Rain gardens and cisterns, as well as bioretention areas in parks and planting strips, also offer substantial opportunities for distributed benefits.
- GSI practices—together with additional "greening" interventions—can support community health and resilience within the City of Dallas, by enhancing urban flood management, improving water quality, reducing urban heat island impacts, and improving ecological function of city landscapes.

While this study focused on GSI systems likely to achieve the greatest volumetric capture for the cost, it is important to consider the stormwater management benefits of additional GSI practices and urban "greening" interventions—along with the co-benefits—when planning in the urban landscape. When combined with additional data and planning objectives, the findings may help to prioritize interventions to achieve multiple goals, including community health and resilience, improved water quality, urban heat island mitigation, and ecological function.

The results of this analysis will be shared with the City of Dallas and integrated into The Trust for Public Land (TPL)'s Smart Growth for Dallas (SGD)[6] Decision Support Tool for consideration with additional data, such as: City data on channel flooding, customer service calls, and upcoming streets and parks projects; Federal Emergency Management Agency (FEMA) flood plain maps; and data on water quality, equity, and land use types, available within TPL's SGD tool. It is our hope that these results will support planners, policymakers, and investors in Dallas to consider GSI as an important—and cost effective—tool for enhancing urban flood management.

[6] TPL's "Smart Growth for Dallas Decision Support Tool is an interactive geo-mapping platform that draws upon over one-hundred GIS-based datasets to target nature-based investments that can best serve the communities in the City of Dallas. Pairing community-articulated priorities with health, social, and environmental data, the Decision Support Tool was made available to the public in 2018 and updated with new layers in July 2020." (TPL, 2021)

1. Introduction

Dallas-Fort Worth is the fastest growing metropolitan area in the United States (U.S. Census Bureau, 2020). With rapid and widespread conversion of natural land cover to impervious surfaces, stormwater management—for water quality and urban flooding—is an important challenge for municipalities in the region. This challenge is expected to be exacerbated by climate change. Cities across the world are increasingly utilizing green stormwater infrastructure (GSI) practices, engineered plant and soil systems that recreate natural hydrological processes, to enhance stormwater management in urbanized watersheds.

GSI is conventionally viewed as a water quality solution, and those cities with comprehensive strategies to encourage GSI tend to be challenged by meeting federal water quality regulations (U.S.Environmental Protection Agency [EPA], 2014a; EPA, 2014b). More recently, GSI has garnered interest for its potential to reduce urban flooding (Kourtis, Tsihrintzis, & Baltas, 2020; Lourenço et al., 2020; Pour et al., 2020). In addition to improving water quality—GSI may provide an important—and cost effective—tool to enhance urban flood management.

This study utilized hydrologic modeling and spatial analysis to help answer the overarching research question: Where can green stormwater infrastructure (GSI) most effectively enhance urban flood management within the City of Dallas, Texas, considering capacity, cost, and future impacts of climate change. The focus was on evaluating how best to enhance flood management where the existing drainage network may be limited. Therefore, the study was limited to areas with complete stormwater drainage system data. After exclusions, a total of 118,418 acres, or 53% of watershed area within the City limits, were included in this analysis.

The U.S. Environmental Protection Agency's Storm Water Management Model (EPA SWMM v. 5.1) was used to identify and evaluate potential stormwater system "hotspots"—specific locations where the drainage network is undersized and likely to contribute to inlet overflows and areal flooding, along with the "challenged" subwatersheds draining to hotpots. Models were run for the 2-year (50%)[7], 10-year (10%), and 100-year (1%) storms, for "current conditions"[8] and for forecasted "climate change conditions"[9] for 2045 (RCP 8.5).

The "challenged subwatersheds"[10] draining to system hotspots were spatially evaluated for potential sites to deploy three types of green stormwater infrastructure—bioretention areas, rain gardens and rainwater harvesting cisterns. For the selected current conditions storms, the stormwater management capacity and the associated costs were estimated for the "maximum implementation scenario" of these practices. The capacity and cost figures were also compared between green and "gray"[11] infrastructure for the 100-year design storm.[12] A desktop pre- and post-GSI analysis was performed, citywide and for a neighborhood-scale sub-study, to determine the potential flood management benefits from the maximum GSI implementation scenario. Finally, recommendations are presented for applying the study results, together with additional data and planning criteria, to guide policy, planning, and investment decisions.

7 The probability of that event being equaled or exceeded within one year: in any given year, there is a 1% chance that a 100-year storm will be equaled or exceeded, a 10% chance that a 10-year storm will be equaled or exceeded, and a 50% chance that a 2-year storm will be equaled or exceeded.

8 The "current conditions" scenarios include models run with current Atlas 14 (Perica, Pavlovic, & Laurent, 2018), using precipitation data for the 2-, 10-, and 100-year, 24-hour storms. Throughout this report, the terms "current conditions" or "current conditions storms" refer to these models.

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1.1. Dallas: The Trinity River, Urban Flooding, and Green Stormwater Management

All stormwater in Dallas flows into the Trinity River. This section includes background on the Trinity and some of the regulatory and planning context relevant to considering widespread GSI implementation in Dallas.

Situated just below the convergence of the West and Elm forks of the Trinity River, the City of Dallas receives most of its drinking water from, and releases all of its treated wastewater and untreated stormwater into, the Trinity River. Over time, the river's regular large-scale floods have redefined the landscape and have caused billions of dollars in damages (North Central Texas Council of Governments, 2007) and loss of life. Water quality and water quantity issues are of concern in the Dallas region, and for the City of Dallas.

Managing seasonal Trinity River floodwaters through large-scale dam and levee systems continues to be a priority for Dallas and other communities in the Upper Trinity watershed. Additionally, the rapid conversion of natural land cover to impervious surfaces in the region has resulted in challenges with urban flooding. According to the U.S. Global Change Research Program's 2018 Fourth National Climate Assessment (NCA4), "Changing precipitation frequency and increases in the magnitude and frequency of heavy precipitation will place more stress on existing water resource infrastructure (U.S. Global Change Research Program, 2018)," in the Southern Great Plains, including North Texas. This will put pressure on the aging large-scale floodway and distributed stormwater infrastructure, alike.

Both Dallas Water Utilities (DWU) and the City's Office of Environmental Quality and Sustainability (OEQS) interact extensively with regional, state, and federal planning and regulatory agencies for water supply, quality, and floodway management. DWU manages stormwater drainage and flood control within the City, as regulated by the U.S. Army Corps of Engineers, the Federal Emergency Management Agency (FEMA), and the Texas Commission on Environmental Quality (TCEQ). The City maintains ongoing compliance of the municipal separate storm sewer system (MS4) under the Texas Pollutant Discharge Elimination System (TPDES),[13] the Federal Clean Water Act, and the Texas Water Code (see Figure 1).

ABOVE: Dallas flooding. © milehightraveler/istock

[13] Permit number is WQ0004396000 (Texas Commission on Environmental Quality, 2019).

Historically, GSI initiatives within the City have targeted water quality goals. For example, under its MS4 TPDES permit, the City is required to implement and enforce stormwater control measures to minimize discharge of pollutants from areas of new development and of significant redevelopment (City of Dallas, 2020c). To help meet these requirements, the City implemented the regional integrated stormwater management guidelines (called iSWM, and discussed below) into the updated 2019 design manuals for paving, streets and stormwater drainage (see Figure 1). Furthermore, the City's 2012 and 2017 Bond Propositions for facility, roadway, and park projects all specified use of GSI as a part of the project scope; as a result, the City typically implements 15 to 20 projects per year that include GSI as a critical part of the design (City of Dallas, 2020c).

b. MCM 2, Post-Construction Stormwater Control Measures.

i. The permittees shall continue implementation and enforcement of the controls to minimize the discharge of pollutants from areas of new development and significant redevelopment after construction is completed. The goals of such controls must include the following:
   - A) limiting increases in erosion and the discharge of pollutants in stormwater as a result of new development; and
   - B) reducing erosion and the discharge of pollutants in stormwater from areas of redevelopment.

iv. The permittee shall assess the impacts on the receiving water(s) for all flood control projects. Where feasible, new flood control structures must be designed, constructed, and maintained to provide erosion prevention and pollutant removal from stormwater. If applicable, the retrofitting of existing structural flood control devices to provide additional pollutant removal from stormwater shall be implemented to the maximum extent practicable.

Figure 1. Excerpt from the City of Dallas MS4 Permit, Post-Construction Stormwater Minimum Control Measures from Texas Center for Environmental Quality, 2019

A 2014 assessment of *Green Infrastructure Barriers and Opportunities in Dallas, Texas* led by the U.S. Environmental Protection Agency with the City of Dallas (EPA, 2014), aimed to support a more comprehensive approach to GSI across departments, ordinances, and codes. In addition to improved water quality, the assessment identified "preserving natural features, minimizing impervious surfaces ... carbon sequestration, energy efficiency, water conservation, and heat island mitigation" as additional benefits of GSI. Potential flood mitigation benefits, however, were not directly included in this assessment.

Since 2007, the City of Dallas has also worked as part of an effort at the North Central Texas Council of Governments (NCTCOG) to develop and implement a regional green infrastructure methodology, Integrated Stormwater Management (iSWM), to reduce the impact of urban design on local drainage infrastructure (NCTCOG, 2007).

ABOVE: Inundated stormwater inlet. © Kathy Jack/ TNC

City GSI Initiatives.

- In 2009, the City of Dallas adopted the iSWM Manual to be used on a voluntary basis for all Dallas projects
- In 2013, the City participated in a process led by the U.S. Environmental Protection Agency to identify *Green Infrastructure Barriers and Opportunities in Dallas* (EPA, 2014).
- In October 2015, the City adopted an impervious surface-based stormwater fee schedule (City of Dallas, 2015).
- January 2016, the City adopted the *Complete Streets Design Manual*—which includes a Green Streets component, and promotes green infrastructure "wherever feasible" on future bond-funded streets projects (City of Dallas, 2016).
- In 2018, the City adopted the *Resilient Dallas* plan, developed under a grant with the Rockefeller 100 Resilient Cities program (City of Dallas, 2018b). Included in this plan was an initiative to "promote partnership efforts to implement green infrastructure in neighborhoods disproportionately vulnerable to the impacts of urban heat island- effects, poor water quality and poor air quality", and features the work with TNC, Texas A&M AgriLife and TPL to "compile existing flooding and drainage analyses across the City into a comprehensive map to identify gaps and nature-based solutions to reduce flooding (7A.2)."
- In October 2019, the City adopted new design criteria manuals that integrated the regional green infrastructure design criteria into the *Paving, Street and Drainage Design Manuals.* These manuals outline opportunities for implementation and encourage their use in all projects in Dallas (City of Dallas, 2019a).
- In 2020, the City adopted the *Dallas Comprehensive Environmental and Climate Action Plan* (CECAP) that included actions to incorporate green infrastructure to mitigate adverse impacts of development (WR10), establish an urban greening factor that quantifies how new development projects contribute to urban greening for stormwater runoff, increase and improve access to green spaces within vulnerable communities to reduce impact of urban heat island, localized flooding and improve public health (EG1), and to assess opportunities for blue-green-gray infrastructure in the public realm to reduce flood risk (EG2) (City of Dallas, 2020b).

Figure 2. City of Dallas Green Stormwater Infrastructure Initiatives

1.2. Goal of This Study

As a part of a 2017 Environmental Health Opportunities Analysis, *Building a Cool, Clean Resilient Dallas* (The Nature Conservancy [TNC], 2018), led by TNC and conservation partners at The Trust for Public Land (TPL) and the Texas Trees Foundation (TTF), City staff and researchers from Texas A&M AgriLife Research Extension identified that GSI could also support City flood management, especially in flood prone neighborhoods; however, the following knowledge gaps were noted: 1) identification of the specific areas prone to urban flooding under current conditions and conditions anticipated with climate change; 2) quantification of the technical effectiveness and practicality of green infrastructure interventions in those locations; and 3) specification of the cost benefits of various green infrastructure interventions.

As in many cities, the stormwater drainage system in older portions of Dallas was designed for previous conditions, and in some areas is undersized for current drainage needs. This challenge will only be further exacerbated as storms become more frequent and intense as a result of climate change. DWU is currently planning for substantial capital investment to upgrade stormwater infrastructure throughout the City. Researchers hope that the scientific data and analysis in this study will support the City's consideration of GSI as a tool to enhance management of stormwater flooding in Dallas, now and into the future.

2. Methods

2.1. Overview

The analysis is composed of two main sections, each designed to help answer the overarching research question: Where can green stormwater infrastructure (GSI) most effectively enhance stormwater flood management within the City of Dallas, considering capacity, cost, and future impacts of climate change. A total of 118,418 acres, or 53% of watershed area within the City limits, were included in this analysis.

Part I is dedicated to identifying areas of Dallas where the existing gray stormwater network may be undersized for current conditions, and thus likely to contribute to urban flooding for a variety of rainfall events. The U.S. Environmental Protection Agency's Storm Water Management Model (EPA SWMM v. 5.1) was used to identify stormwater system hotspots—specific locations where existing gray stormwater infrastructure as modeled is under capacity during simulated storm events. Hotspots were indicated by stormwater inlets that overflowed during simulations for the 2-year (50%), 10-year (10%) and 100-year (1%), 24-hour storms under current and forecasted future conditions. The contributing subwatersheds were also identified to further evaluate opportunities for use of GSI.

In Part II, the subwatersheds contributing to system hotspots were spatially evaluated for opportunities to deploy three green stormwater infrastructure practices considered relevant for cost-effective urban stormwater flooding management—bioretention areas, rain gardens, and rainwater harvesting cisterns. The maximum potential stormwater management capacity, and the associated costs, were estimated for implementing these GSI practices in challenged subwatersheds, within the study area, for selected current conditions storms. The City of Dallas *Drainage Design Manual* (City of Dallas, 2019b) currently requires that any upgrades to the stormwater drainage network shall meet the 100-year (1%), 24-hour storm event; therefore, capacity and cost comparisons between green and gray "upgrades" as well as the potential for combined upgrades are described within that context. A desktop pre-post analysis was performed citywide and at the neighborhood level to determine the impact of GSI on challenged subwatersheds from the maximum implementation scenario. Finally, recommendations are presented for applying the study results, together with additional data and planning criteria, to guide policy, planning, and investment decisions.

2.2. Study Limitations

This study focused on identifying opportunities to enhance urban flood management with GSI in areas where the existing gray stormwater network may be under capacity and likely to contribute to urban flooding for a variety of rainfall events. EPA SWMM v 5.1 model was used to simulate the stormwater network flow in the City of Dallas for various storms, to identify areas of potential network limitations, and to assist with identifying areas to implement GSI.

Modeling studies, such as this one, have inherent limitations and uncertainties. The certainty of the results of the study will reflect the accuracy of the input data, including the drainage network data (locations, sizes, elevations, and missing data), and the resolution of input maps (i.e., elevation maps, land use/land cover maps, channel and stream maps). The model was used to identify overflowing inlets but does not calculate the areal flooding that might result in these areas.

Additionally, this study did not address flooding from bank overflow of existing streams. Note that capturing upstream runoff would have an impact on streambank overflows, but these data were not modeled in this study.

Finally, the analysis is limited to areas with complete stormwater drainage system data. The following were excluded from the study: areas that did not properly delineate into subwatersheds due to inadequate data, and drainage network sections that seemed incomplete and did not drain to a stream or lake. A total of 104,285 acres, or 47% of the total city area, was excluded from the analysis (see section 2.3.2 for additional details).

2.3. Part I Methods: Identify System Hotspots, and Challenged Sub-watersheds

2.3.1. Summary

Dallas Water Utilities (DWU) maintains a municipal separate storm sewer system (MS4) designed to collect and drain precipitation runoff through a piped network into the Trinity River or its tributaries (Figure 3). While such systems avoid Sanitary Sewer Overflow (SSO) pollution events that challenge combined sewer and stormwater networks when inundated, MS4s face water quality challenges from non-point source pollution and littered waterways. These systems also experience challenges with urban flooding where the drainage system is older and/or under capacity. The focus of this analysis is on identifying opportunities to enhance stormwater flooding management with GSI in areas where the drainage capacity may be limited.

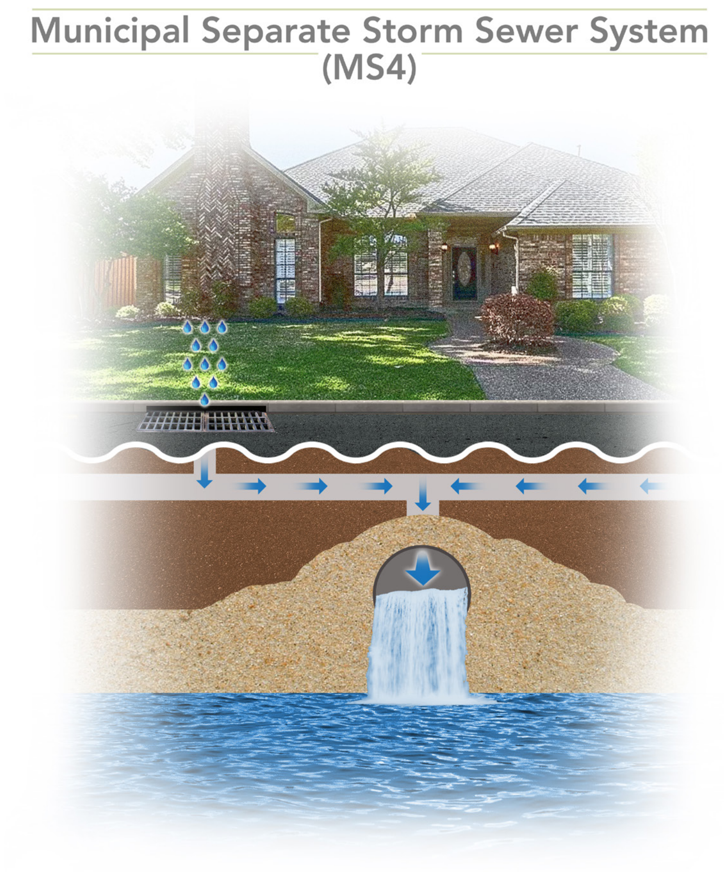

Figure 3. Diagram of a Municipal Separate Storm Sewer System (MS4)

The U.S. Environmental Protection Agency's Storm Water Management Model (EPA SWMM v. 5.1) (Rossman, 2015) is used to identify system hotspots—areas where existing gray stormwater infrastructure as modeled is under capacity during simulated storm events. SWMM models are used to identify stormwater inlets that overflow during simulations for the 2-year (50%), 10-year (10%), and 100-year (1%), 24-hour storms under current and forecasted future conditions.

Figure 4. Stormwater Inlet © Kathy Jack/ TNC

This **hydrologic model** was chosen for its ability to simulate storm drain flow as well as surface flow, making it ideal for urban hydrology.

> **Hydrologic models** use equations to conceptually and simplistically represent the flow and movement of water through the environment, including surface runoff, subsurface flow, evapotranspiration and channel flow. These simulations assist with understanding, forecasting and planning for hydrologic processes in the real world (Singh, 2012).

2.3.2. Dallas Watersheds

The City of Dallas was divided into 10 watersheds for analysis, as defined by the City and consistent with prior modeling done for FEMA[14]. Watersheds that had a substantial surface area outside the City of Dallas (including the Park Cities) were excluded from this study due to lack of data on the stormwater network. This resulted in the exclusion of 47,462 acres (see gray shading in Figure 5). In addition, areas with limited or problematic stormwater network data, were also excluded, resulting in the additional exclusion of 58,293 acres. Appendix 1 shows the breakdown of the areas excluded from the analysis at the watershed and city level. Once delineated, each watershed was further divided into subwatershed areas, each with a single, well-defined inlet into the stormwater system. A total of 118,418 acres, 53% of watershed area within the City limits, were included in this analysis.

[14] The watersheds used for FEMA analyses may not conform to the U.S. Geological Survey HUC-12 definitions.

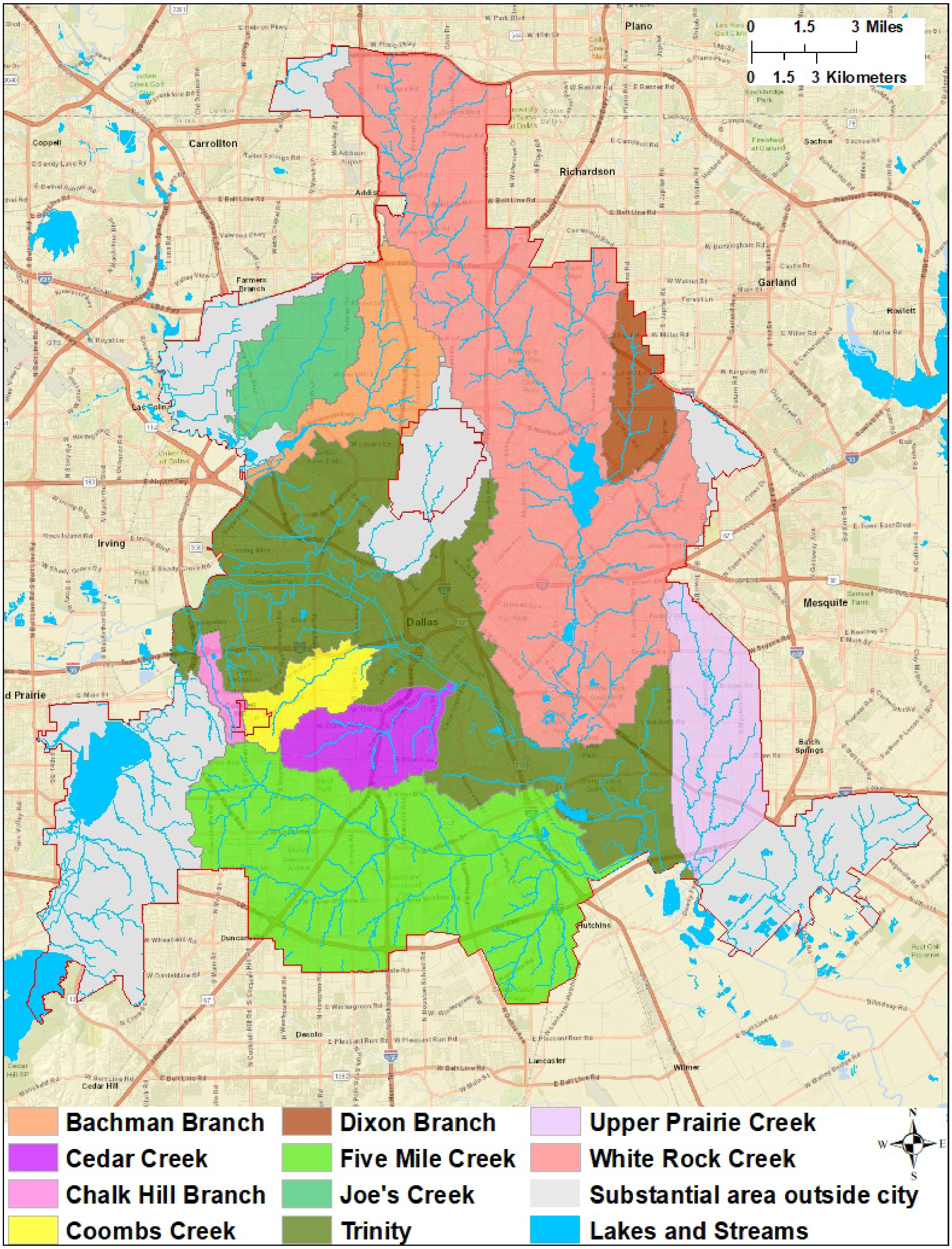

Figure 5. City of Dallas Watersheds, as Defined by the City and Consistent with Prior Modeling.

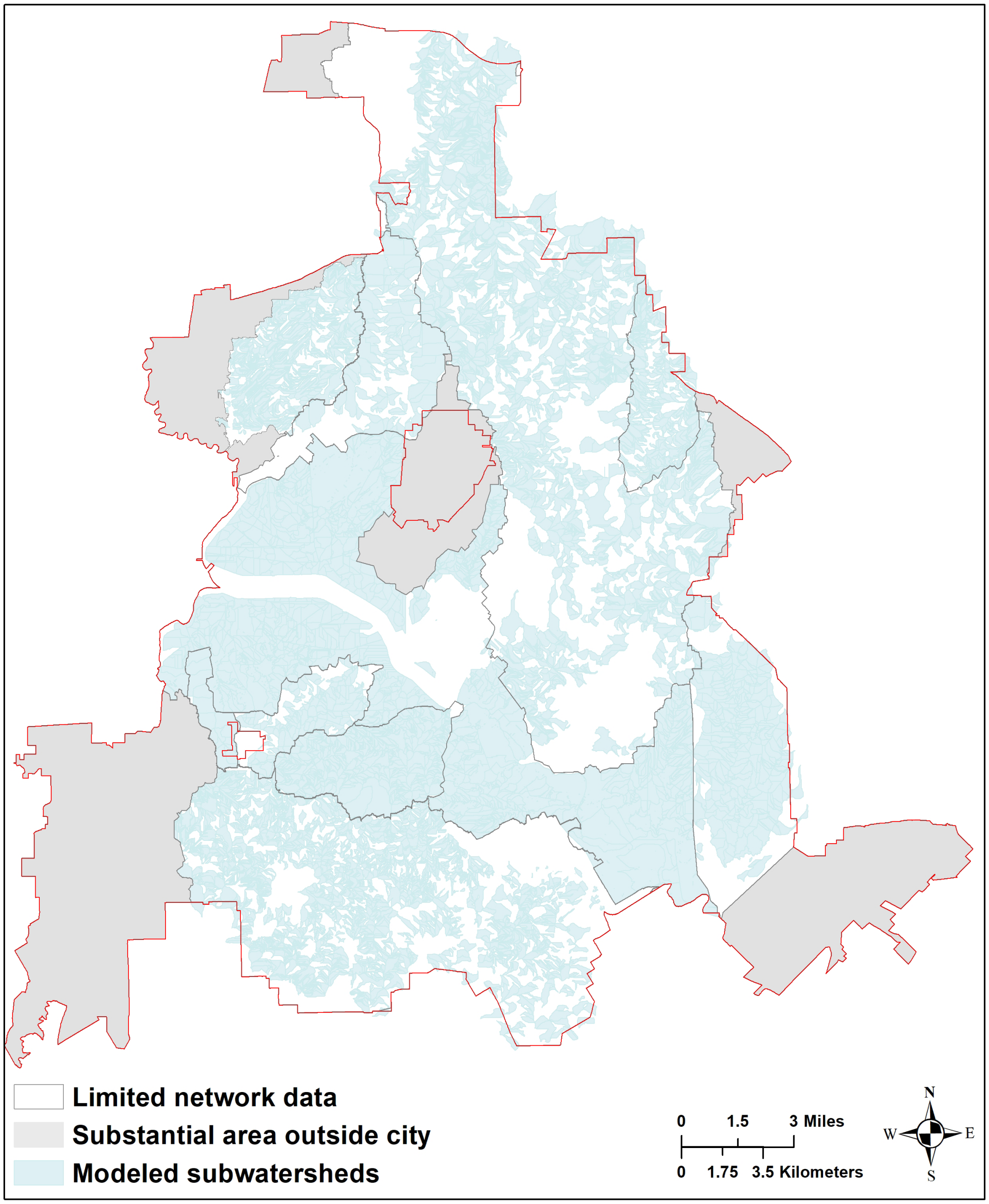

Figure 6. City of Dallas Subwatersheds Included in Models

2.3.3. Building the SWMM Models: Inputs and Parameters

SWMM models were developed for each watershed within the City of Dallas as determined, above. Several "input" files and parameters were established to build and run the SWMM models.

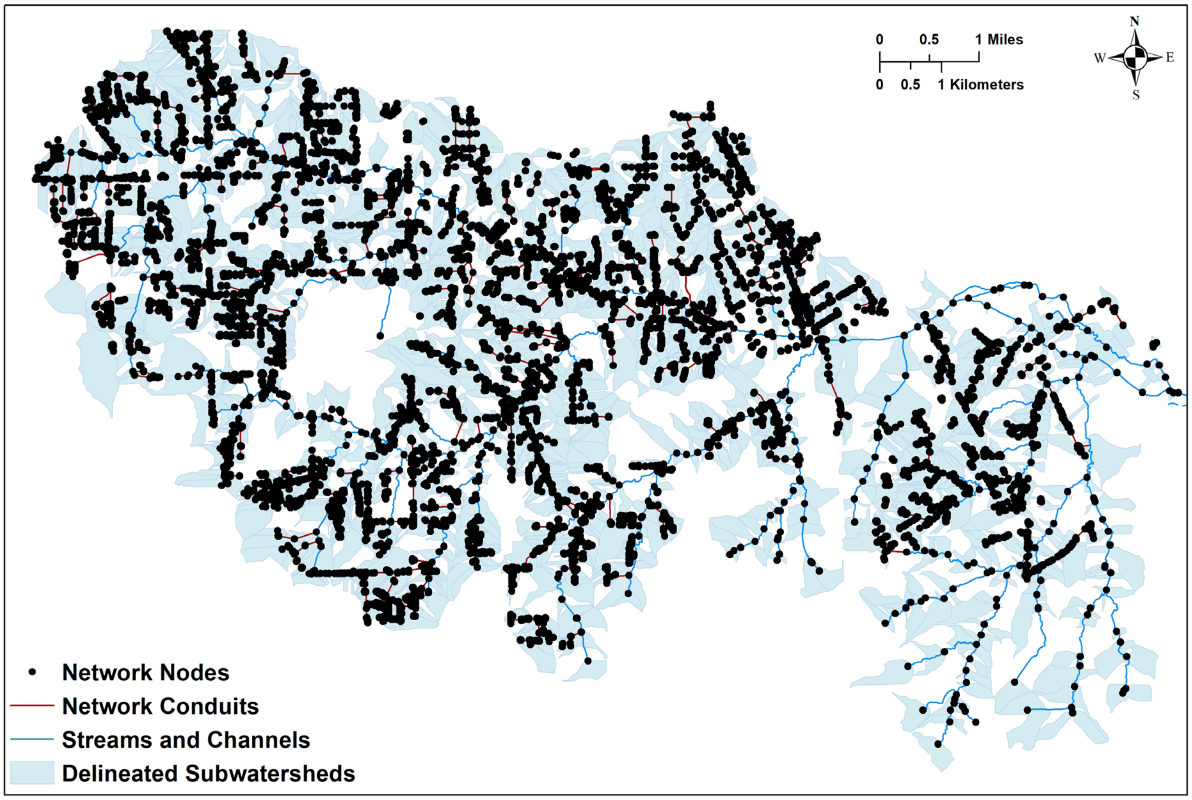

Figure 7. Digitized Stormwater Network, Five Mile Creek Watershed.

INPUT FILES:

- Stormwater network: A complete, digitized stormwater network file was created for each watershed. Each file included data on: stormwater network nodes (the inlets and junctions of a stormwater network); stormwater pipes (their size and length); and inlet geometry. These files were constructed from two sources provided by the City: stormwater engineering plats and pre-constructed ArcGIS layers of the stormwater systems. The stormwater network data in the plats were digitized into ArcGIS format, and where available, the City's ArcGIS files were used to improve on the digitized plat files.[15]
- Digital Elevation Model: A Digital Elevation Model (DEM) is an electronic topographic map used to help determine how surface water flows in a watershed. DEMs with a 10-meter resolution were downloaded from the U.S. Geological Survey portal (U.S. Geological Survey portal [USGS], 2021) and were used to delineate the watersheds and to compute the surface elevation of their inlets and channels.
- Land Use/Land Cover map: This Land Use/Land Cover (LULC) data was used to compute the impervious area of the delineated subwatersheds. The map was downloaded from the USGS portal (USGS, 2016).
- Flowlines: Channel and river flows were extracted from the USGS National Hydrography Dataset (USGS, 2018) to assign surface water flow routes in the model.

[15] When data was missing from both sources, assumptions were made for pipe-to-pipe offsets, total depth of inlets, and inlet surcharge depths based on averages of the data available in the engineering plats. The result was a complete digitized stormwater network for all the watersheds in the City of Dallas that incorporates information on pipe size and inlet depths.

2.3.4. Selecting "Return Period" Storms: Current Conditions

A **return period storm** refers to the estimated time interval between rain events of a similar size and duration, in a particular location, and is usually based on historical trends. The term can also be defined as the probability of that event will being equaled or exceeded within one year: in any given year, there is a 1% chance that a 100-year storm will be equaled or exceeded, a 10% chance that a 10-year storm will be equaled or exceeded, and a 50% chance that a 2-year storm will be equaled or exceeded. Such storms are usually defined for a specific duration (30 minutes, 1 hour, 24 hours, etc.) The 24-hour duration storm was used in this study. See National Oceanic and Atmospheric Administration (NOAA) Atlas 14 for more details (Perica, Pavlovic, & Laurent, 2018).

In order to assess the problem and opportunity areas associated with more frequent "nuisance" flooding and more intense and extreme rainfall events, the 2-year (50%), 10-year (10%) and 100-year (1%), 24-hour return period storms were selected for modeling at current and forecasted future precipitation levels. For this report, all references to the 2-, 10-, or 100-year storms refer respectively to the 50%, 10%, and 1%, 24-hour storms. The current 24-hour rainfall data for these return period storms was obtained from NOAA's Atlas 14 (Perica et al., 2018) , and translated into hourly storm data for SWMM using the U.S. Department of Agriculture's Natural Resources Conservation Service Type III rainfall distributions (U.S. Department of Agriculture's Natural Resources Conservation Service [USDA-NRCS], 2015). The City of Dallas Drainage Design Manual (City of Dallas, 2019b) requires that any upgrades to the gray stormwater network be designed to meet the 100-year (1%), 24-hour storm event; therefore, data for the 100-year (1%) return period storm is particularly helpful for comparing overflow reduction and costs between green and gray options.

2.3.5. Climate Change Precipitation Scenarios

The impacts of climate change on urban flooding and system resiliency are modeled within SWMM, based on precipitation changes estimated through widely accepted climate change models.

The Intergovernmental Panel on Climate Change (IPCC)'s Coupled Model Intercomparison Project Phase Five (CMIP5) produces global daily climate data—including precipitation totals—for three emissions scenarios (low, medium and high), which are available for further analysis by climate scientists (Flato et al., 2013). Using the high emissions scenarios (RCP 8.5) in the IPCC CMIP5, Villarini et al. (2013) estimated the rainfall distribution for the 10-year (10%) and 100-year (1%) return period storms in 2045 using daily forecasted data from 2006-2045 for the Central U.S. (including Texas). While originally dubbed as a "worst case scenario," the RCP 8.5 was found to be the closest approximation of historical CO2 emissions data as well as forecasted emissions, based on current policies (Schwalm, Glendon, & Duffy, 2020). Schwalm et al. (2020) argue that RCP 8.5 is best for assessing climate risk and impacts to 2050.

The total daily precipitation estimates obtained by Villarini et al. (2013) for the 10-year (10%) and 100-year (1%) return period storms were translated into hourly storm data using the NRCS Type III rainfall distributions (USDA-NRCS, 2015), and were entered into SWMM for future scenario climate change simulations. Villarini et al.'s methodology was used to forecast the 2-year (50%) storm. The daily precipitation totals were forecasted using CMIP5, through 2045; then, the distribution for the daily precipitation values was computed as above. The 50th percentile of these distributions represents the 2-year (50%) storm for 2045. Future land use changes were not included as a part of the forecast conditions.

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2.3.6. Model Simulations and System Hotspots

In cities with MS4 systems, inlets can overflow and result in localized areal flooding where the drainage network is under capacity to manage flow. SWMM models were used to identify those stormwater inlets that may overflow for various return period storms across the City. "Overflowing inlets" were defined as those inlet nodes for which the water depth within the inlet exceeded the capacity of the inlet structure at any point during a simulation. The overflowing inlets were then categorized by overflow severity into five groups (*very low, low, medium, high* and *very high*), based on the degree of modeled depth exceedance.[16] Inlet overflow maps were created for each watershed, for each return period storm being considered, and for current and forecasted future conditions (see Figure 8 and Appendix 2).

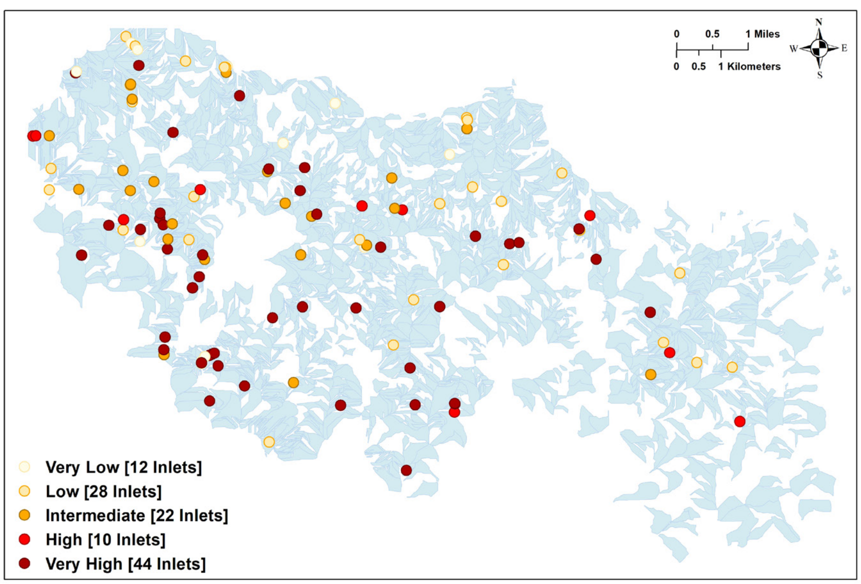

Figure 8. Overflowing Inlets, as Modeled for Five Mile Creek Watershed, 2-year (50%) Storm (4 inches), Current Conditions

[16] Depth exceedance in this study is an indicator of severity and does not represent depth in areal flooding; therefore, depth exceedance values were classified by severity rather than reported as absolute values. Depth exceedance ranges are consistent within each class across watersheds.

2.3.7. Challenged Subwatersheds

As a first step in determining potential "opportunity zones" for deploying green stormwater infrastructure, we identified those subwatersheds that contributed to inlet overflows modeled for each scenario. Each subwatershed is associated with one overflowing inlet. GSI placed in these challenged subwatersheds would have an immediate impact on reducing the flow to modeled system hotspots; therefore, these watersheds were determined to provide the most potential benefits from GSI for urban flood management. Part II of this study estimated suitable capacity for select GSI practices, within each of these subwatersheds.

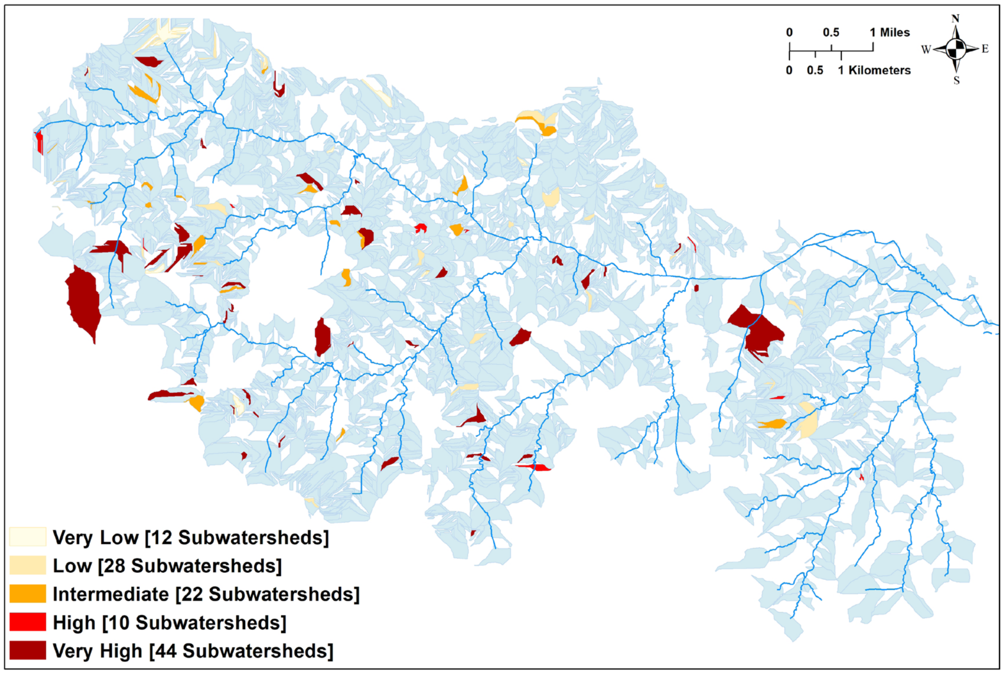

Figure 9. Challenged Subwatersheds Classified by Inlet Overflow Severity, as Modeled for Five Mile Creek Watershed, 2-year (50%) Storm (4 inches), Current Conditions

ABOVE: Dallas flooding. © Steven Luu

2.4. Part II Methods: Identify and Quantify Green Stormwater Infrastructure Opportunities

2.4.1. Summary

In Part II, the subwatersheds contributing to system hotspots for each of the current conditions storms were spatially evaluated for opportunities to deploy three types of green stormwater infrastructure—bioretention areas, rain gardens, and rainwater harvesting cisterns. The opportunity analysis in Part II was based on current conditions storms due to uncertainties related to future land use changes and emissions scenarios. However, findings from Part I indicated that focusing on opportunities to address hotspots from current conditions storms will likely translate to benefits in the scenarios for the 2- and 10-year climate change conditions. Focusing on the potential for GSI in current conditions provides decision makers with actionable near-term options, and with higher certainty of impact.

Generally, the design and sizing for specific GSI systems reflects site-specific considerations including cost, regulatory requirements, and aesthetics. However, for the purposes of a citywide analysis, standard designs and spatial criteria—described below—were developed for application across all studied watersheds. These areas represent the estimated maximum potential for deploying these GSI practices in each subwatershed. Additionally, the costs and overflow reduction capacity for using GSI was estimated for each return period storm and compared to gray infrastructure for the 100-year, (1%) storm.[17]

ABOVE: Rain garden with curb cut. © Texas A&M AgriLife

[17] The City of Dallas (City of Dallas, 2019b) requires that any upgraded gray stormwater infrastructure must meet the 100-year (1%) design storm; therefore, cost comparison is most equivalent for this design storm.

2.4.2. GSI Practices and Design and Spatial Criteria

For this analysis, bioretention areas, rain gardens, and rainwater harvesting cisterns were included. Additional GSI practices (for example, tree boxes) also can provide meaningful stormwater management benefits, including urban flood management and improved water quality (Tarrant Regional Water District, 2018; EPA, 2020).[18] The three practices modeled were selected for their cost efficiency and their ability to improve infiltration when distributed throughout urban watersheds. For the purposes of a citywide analysis, the following standard designs were applied across all watersheds.

A **rain garden** is a mulched vegetated depression designed to capture and infiltrate a portion of surface stormwater runoff before it leaves a property. Rain garden vegetation—usually wetland "facultative"[19] plants—contribute to water infiltration and water treatment. For the purposes of this study, the rain gardens were designed to be 0.5 ft deep vegetated depressions.

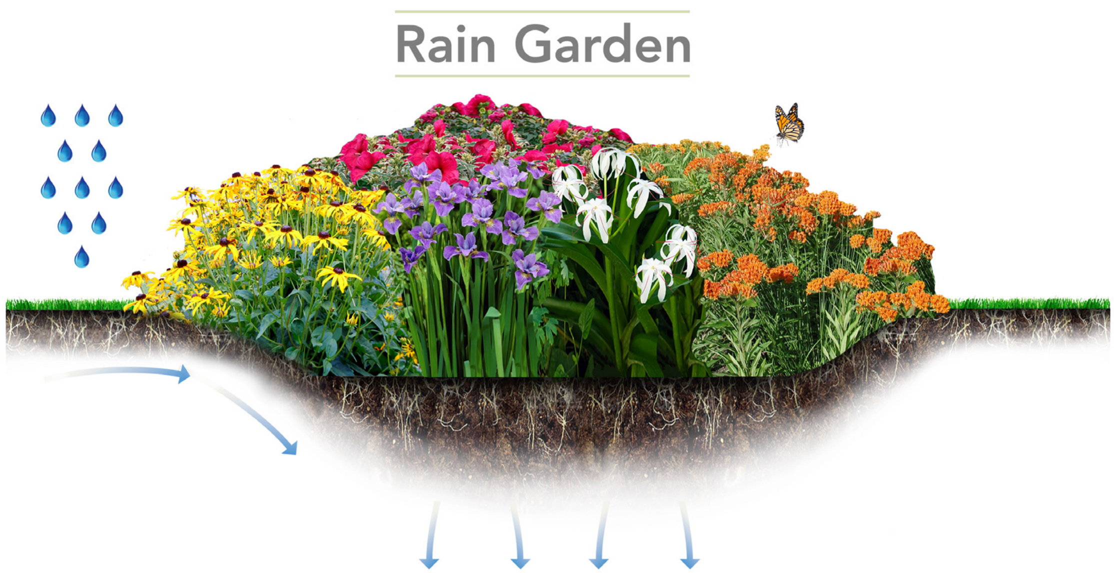

Figure 10. Rain Garden Schematic

A **bioretention area** is essentially a sophisticated rain garden, usually involving the removal of native soil that is replaced with a high infiltration engineered soil mix. Bioretention areas often include a perforated pipe midway through the total depth to facilitate drainage during consecutive storms. These systems are often integrated into parking lots and planting strips. For the purposes of this study, the bioretention areas were designed to be 3 ft deep, with an engineered soil mix (of 40% porosity) and a perforated pipe placed at 1.5 ft below the bioretention surface. The bioretention surface was in a 0.5 ft depression and was planted with wetland facultative plants.

[18] See Appendix 3 for a more comprehensive list of GSI practices.

[19] Wetland facultative plants usually occur in wetlands but may occur in non-wetlands (USDA-NRCS, 2014).

Bioretention Area

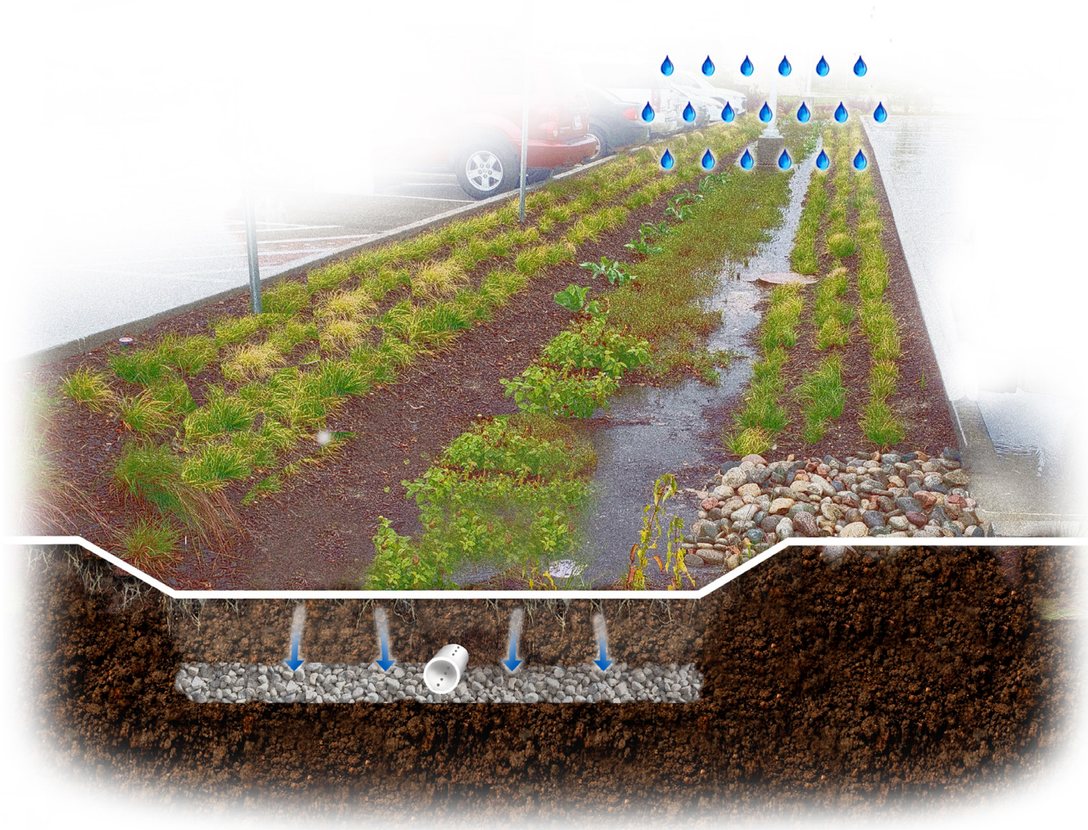

Figure 11. Bioretention Area Schematic

A **rainwater harvesting cistern** is a collection tank connected to the downspout of a structure to collect runoff from the rooftop. The water can be later used for irrigation or, where permitted, for other water uses. Tanks can also be designed to slowly release water (City of Austin, 2018) so that they are relatively empty when a storm occurs. For the purposes of this study, rainwater cisterns were designed to meet stormwater management goals (Brodie, 2008; Debusk, Hunt, & Wright, 2013; Herrmann & Schmida, 2000; Rain Catcher Austin, 2020), by including 1,000-gallon-tanks designed with a passive release at 25% capacity. Therefore, these systems will have a minimum average capacity of 750 gallons for stormwater capture.

Rainwater Harvesting Cistern

Figure 12. Rainwater Harvesting Cistern Schematic

In order to estimate the potential volume of runoff that could be managed by GSI in a storm event, the challenge subwatersheds were first assessed for the maximum available space to place selected GSI practices. As stated, the design and sizing for GSI practices generally reflects site-specific considerations including cost, regulatory requirements, and aesthetics. However, for the purposes of a citywide analysis, standard spatial criteria were developed for application across all watersheds within ArcGIS to identify the potential opportunity sites for these GSI practices. Spatial rules were applied to ArcGIS layers provided by the TPL and the City of Dallas (City of Dallas, 2020a). For each watershed, the total available "space" was then translated into capacity in gallons. This was used to estimate the maximum potential capacity for GSI to capture stormwater and reduce system overflows resulting from the storm events considered.

These spatial rules are based on logic and assumptions grounded in the literature review, as well as considering landscape codes and ordinances, practitioners' experiences, and commonly accepted practices. The spatial rules are further described below and in Figure 13.

Bioretention systems are usually placed in public and commercial areas such as parking lot medians, large sidewalks, parks, and "planting strips" (narrow green areas that separate a sidewalk from a curb in residential neighborhoods). The following rules were used to determine the maximum potential area for bioretention systems. Bioretention candidate areas were assigned as a portion of parking lots, road medians, planting strips, parks, and commercial sidewalks, following guidelines from Section 51A-10.125 of Article X in the City of Dallas' Code of Ordinances (City of Dallas, 2018a). As a result, bioretention areas were placed as 10% of parking lots, 35% of vegetated road medians, 35% of nonresidential sidewalks that are greater than 8 ft wide, 35% of the planting strip in residential neighborhoods, and 10% of parks.

Rain gardens are commonly designed for residential or commercial sites, with residential rain gardens typically range in size from 100-400ft2 (Groundwater Foundation, 2020). For this project, the midrange of 200 ft2 was applied to all residential and commercial structures (City of Dallas, 2020a) identified in a challenged subwatershed while estimating the potential area for rain garden installations.

Rainwater harvesting cisterns are used to collect runoff from residential and commercial rooftops structures for storage and later use, or to increase infiltration for improved hydrology. For this project, 1,000-gallon cisterns were applied to all residential and commercial structures identified in a challenged subwatershed.

In order to estimate the maximum potential area or sites for each of the GSI practices considered, ArcGIS layers were obtained from various sources, including the U.S. Census, the City of Dallas and TPL. The ArcGIS data included the total number of structures, non-residential sidewalks, planting strips, parking lots and medians. Figure 13 summarizes the spatial criteria for each system type that were applied to the appropriate GIS layers to estimate the available sites or area for each system. The total number of residential and commercial structures and area of square footage available for bioretention systems were determined for each opportunity subwatershed for each of the scenarios.

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BIORETENTION AREAS	**RAIN GARDEN**	**RAINWATER HARVESTING CISTERN**
Design Criteria: 1 ft^2 = 1.5 ft^3 = 11.2 gal (2.5ft deep x 0.4 porosity=1 ft^3 water) + (0.5ft ponding=0.5 ft^3 water) = 1.5ft^3 water	**Design Criteria:** 1 ft^2 = 0.5ft^3 = 3.7 gal (0.5ft ponding=0.5 ft^3 water)	**Design Criteria:** 1 tank=750 gal (1,000-gal tank; 75% empty)
Spatial Criteria: apply following (%) to available area. • **Parking lots** a (10%) • **Parks and Trails**[a] (10%) • **Planting Strips and Medians**[b] (35%) • **Commercial sidewalks**[b] nonresidential sidewalks, ≥ 8 ft wide. (35%)	**Spatial Criteria:** • **Residential and Commercial structures**:[a] (100%), a 200 ft^2 rain garden, each	**Spatial Criteria:** • **Residential and Commercial structures:** a (100%), a 1,000-gal cistern each

Figure 13. Design and Spatial Criteria for Selected GSI Practices

[a] GIS data provided by The Trust for Public Land
[b] GIS data from City of Dallas GIS Services, 2020 (City of Dallas, 2020a)

2.4.3. Maximum Potential for Stormwater Management Using GSI Practices

Once the maximum potential area or sites for GSI were determined for each watershed, the system design capacity (Figure 13) was used to estimate maximum storage capacity in volume by system type, for each opportunity subwatershed. Capacity totals were estimated per watershed and citywide. For example, for each opportunity subwatershed, the maximum capacity was estimated as follows:

> **bioretention capacity** = (10% of parks and trails area + 35% planting strips and medians area + 10% parking lot area + 35% of commercial sidewalk area) x 11.2 gal
>
> **rain garden capacity**= total number of residential and commercial structures x 200 ft^2 x 3.7 gal
>
> **rainwater harvesting capacity**= total number of structures x 750 gal

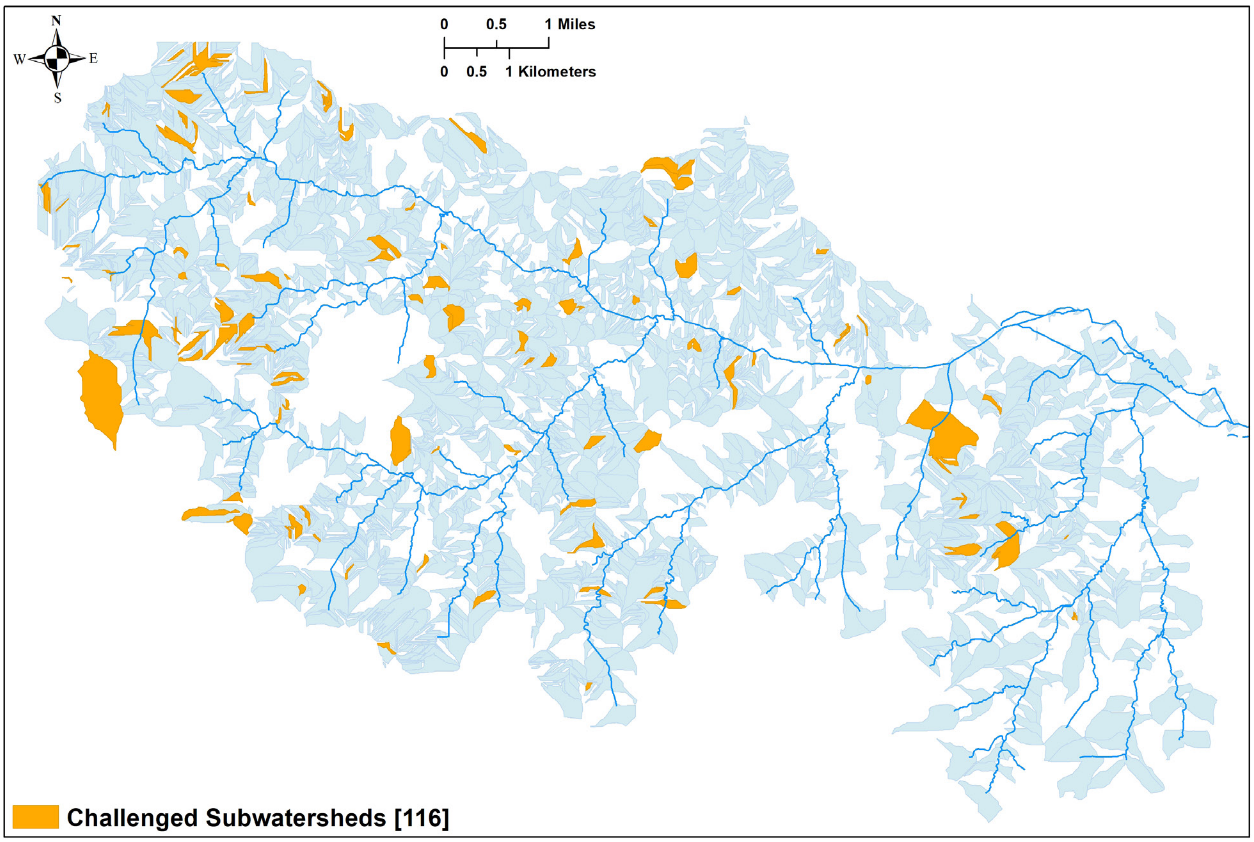


Figure 14. Total Challenged Subwatersheds, All Classes, as Modeled for Five Mile Creek Watershed, 2-year (50%) Storm (4 inches), Current Conditions

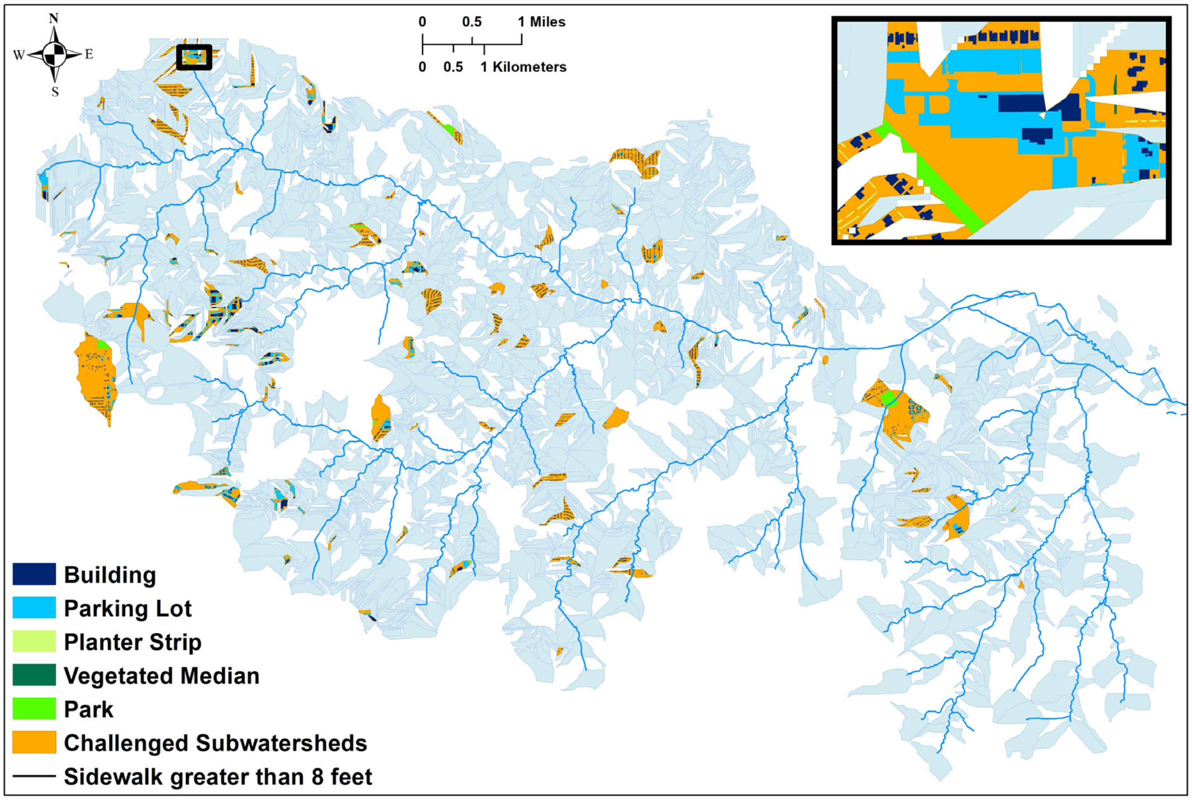


Figure 15. GSI Spatial Opportunity assessment, as Modeled for Five Mile Creek Watershed, 2-year (50%) Storm (4 inches), Current Conditions

2.4.4. Cost per Volume Managed by GSI

The literature was reviewed (see Appendix 4) along with experiences of practitioners working in Texas and in other U.S. locations, to evaluate typical construction and maintenance cost ranges for each GSI system considered, including engineering costs. Land costs were not included in this analysis. These costs were translated into costs per gallon managed, based on the standard designs (section 2.4.2) and the assumption that each system would capture its full capacity in each storm event.[20] Table 1 summarizes the literature and cost analyses. Midrange values were selected and used as summarized below. Maintenance costs are an important part of discussions about the costs of GSI and are therefore included below; however, equivalent costs for gray infrastructure maintenance were not available and are therefore not included.

[20] Cost per gallon of GSI can vary based on several factors that can vary regionally and from project to project- including construction, land and permitting costs, scale of the project and design volume. Further, cost per gallon can be estimated based on volume captured during the design storm event or based on volume captured on an annualized basis. This study uses midrange construction cost figures, including engineering and maintenance costs, from literature representative of several U.S. regional contexts, and assumes full volume capture by standard designs for each storm event.

Table 1. Estimated Costs per Gallon Managed per Storm Event[a] by GSI

	BIORETENTION AREA	RAIN GARDEN	RAINWATER HARVESTING CISTERN
System capacity	1 ft^2 = 1.5ft^3 = 11.2 gal	1 ft^2 = 0.5ft^3 = 3.7 gal	750 Gallon
Construction cost (Pre-engineering)	$14.74/$ft^2$	$10.6/$ft^2$	$1.75/gal
Construction costs (including 20% engineering)	$17.70/$ft^2$	$12.72/$ft^2$	$2.09/gal
Estimated cost per volume managed ($/gallon)	$1.58/gal	$3.44/gal	$2.09/gal
Average maintenance costs	$0.18/gal	$1.34/gal	$0.54/gal

[a] See Appendix 4 for literature review and cost analysis. Cost/gallon is based on the standard designs (described in section 2.4.2) and the assumption that each system would capture its full capacity in each storm event.

2.4.5. Comparing Green and Gray Infrastructure Capacity and Costs per Gallon

Overflow volumes were estimated for each overflowing inlet identified in Part 1, based on hydrographs[21] created in SWMM. These overflow volumes were then compared to the maximum potential stormwater volumes that could be managed by GSI for each challenged watershed and each storm, and the cost per gallon captured was estimated.

Additionally, the capacity and cost for reducing the modeled overflow volumes was compared with gray infrastructure for the 100-year (1%) current return period storm—the required design storm for all upgrades to the stormwater drainage system (City of Dallas, 2019b). The following steps were taken to estimate the capacity of and costs for undertaking gray stormwater improvements to manage overflow volumes within each watershed:

- Locate and determine size of existing pipes.
- Calculate increased pipe size required to address modeled overflow volume for the 100-year (1%) storm.
- In SWMM, model incremental increases in pipe sizes (up to the maximum diameter size of 96 in) until no overflow occurs, or maximum flow reduction is achieved (if 100% not achievable with the maximum pipe size).
- Determine capital cost of improvement with gray infrastructure.

The capital costs of improvement with gray infrastructure were determined by averaging material and engineering fees provided by the City of Dallas (DWU staff, email to author, July 20, 2020). The cost was then normalized as $/gal and compared to the $/gal figures for the studied GSI.

[21] Hydrographs show the rate of flow or depth versus time at a specific point. The area between the curve and the inlet capacity represents the total overflow volume at that node.

2.5. Part III Methods: Pre- and Post-GSI Analysis

2.5.1. Citywide Assessment

In order to evaluate the potential impact of GSI on system hotspots, a desktop pre- and post-assessment was conducted for the current conditions storms (section 2.3.4). For each challenged subwatershed, the pre-GSI overflow volumes (section 2.3.7) were reduced by the estimated GSI capacity (section 2.4.3.) to estimate post-GSI volumes. These results were classified using the same ranges for pre-GSI installation overflow volumes. The post-GSI conditions were then mapped citywide and the percentage change in each category was calculated.

2.5.2. Neighborhood Sub-study

While impractical at the citywide scale, GSI can be modeled within SWMM to assess neighborhood-scale impacts. Accordingly, a small neighborhood within Five Mile Creek Watershed was modeled in more detail. The neighborhood was selected based on the following criteria: incudes several challenged subwatersheds; has opportunity to implement the three GSI types; includes different land uses (residential, parks, commercial, and school); includes proximity to planned City bond projects; and scores high for equity challenges in TPL's Smart Growth for Dallas Decision-Support tool.

The stormwater drainage network for the neighborhood-scale study area was extracted from the citywide model and a separate SWMM model was constructed for each challenged subwatershed with boundaries entirely within the study area. The GSI candidate locations within the challenged subwatersheds were analyzed, and two scenarios were created in the SWMM models:

> Scenario 1: 100% implementation: GSI is implemented in 100% of the total opportunity area identified within the challenged subwatersheds.
>
> Scenario 2: 50-25-25% implementation: GSI is implemented at the following percentages of the total opportunity area identified within the challenged watersheds: 50% of potential bioretention areas, 25% of potential rain garden sites, and 25% of potential rainwater harvesting cisterns sites.

After execution of each scenario, the depth hydrographs and associated overflow volumes were determined for their respective outlets as described in section4.5. The calculated overflow volumes were then compared to the pre-GSI installment scenarios.

3. Results

3.1. Summary

This study utilized hydrologic modeling and spatial analysis to assess the potential for cost-effective integration of green stormwater infrastructure for urban flood management in Dallas, Texas. SWMM modeling helped to identify challenged subwatersheds—as indicated by overflowing inlets in simulations for the 2-year (50%), 10-year (10%), and 100-year (1%), 24-hour storms under current and forecasted future conditions. Each subwatershed is associated with one overflowing inlet. These subwatersheds were classified by severity of inlet overflows—which indicate potential network limitations. Finally, challenged subwatersheds were evaluated for the opportunity and costs to reduce stormwater flooding with GSI, for each current condition simulated storm.

After data-related exclusions, approximately 118,418 acres, or 53% of the City's land cover, were included in the analysis. Within the area modeled, substantial opportunities were identified for high-impact and cost-effective implementation of GSI for stormwater flood management, particularly within the Joes' Creek, Cedar Creek, and Five Mile Creek watersheds, and portions of the White Rock watershed. Results from Part I and Part II of the analysis are described below and summarized in Figure 17 and Figure 18.

3.2. Part I Results: Identify System Hotspots and Challenged Subwatersheds

To identify those areas of Dallas where GSI will most effectively enhance flood management, EPA SWMM v. 5.1 was used to identify system hotspots—specific locations where the modeled network is undersized and likely to contribute to inlet overflows and areal flooding under a variety of precipitation events. These locations were indicated by stormwater inlets that overflowed during simulations for the three selected storm events for current and forecasted future climate change (RCP 8.5) scenarios. Challenged subwatersheds, which contribute to inlet overflows, were identified to further evaluate opportunities for green stormwater infrastructure (Part II).

Table 2 summarizes current and future forecasted precipitation levels for the 2-year (50%), 10-year (10%) and 100-year (1%), 24-hour storms, in Dallas. Data shows that climate change will substantially impact extreme storm events (the 10- and 100-year storms). The 10-year (10%) and 100-year (1%), 24-hour storms, show an increase in precipitation of 52% and 54%, respectively, as compared to a 12% increase for the 2-year (1%) storm event. Precipitation forecasted for the 100-year (1%) storm in 2045, is similar to that for the current 100-year (10%) storm for Dallas.

Challenged subwatersheds were described citywide (Figure 16 and Table 2) and hydrologically classified into five categories ranging from very low to very high, based on the modeled inlet overflow severity (Figure 17, Figure 18, and Table 3, for each scenario). Appendix 2 includes the maps of modeled inlet overflows and challenged subwatersheds for each watershed and scenario.

Table 2. Precipitation Levels for Return Period Storms in Dallas, Current and Forecasted Conditions

Return Period Storm	Current Conditions Precipitation (in)	Forecasted 2045 Precipitation (in)	Percentage Change
2-year (50%)	4	4.5	+12%
10-year (10%)	6	9.1	+52%
100-year (1%)	9.5	14.7	+54%

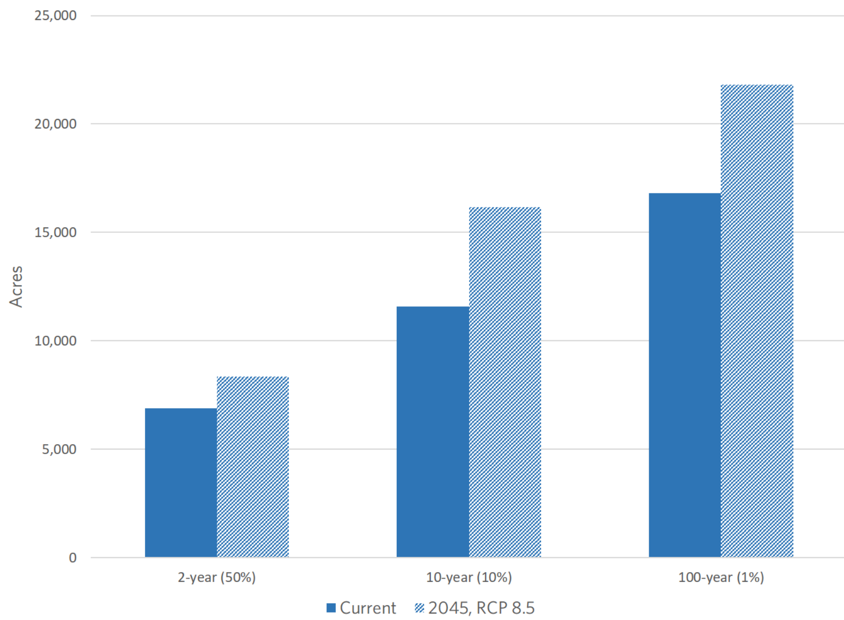
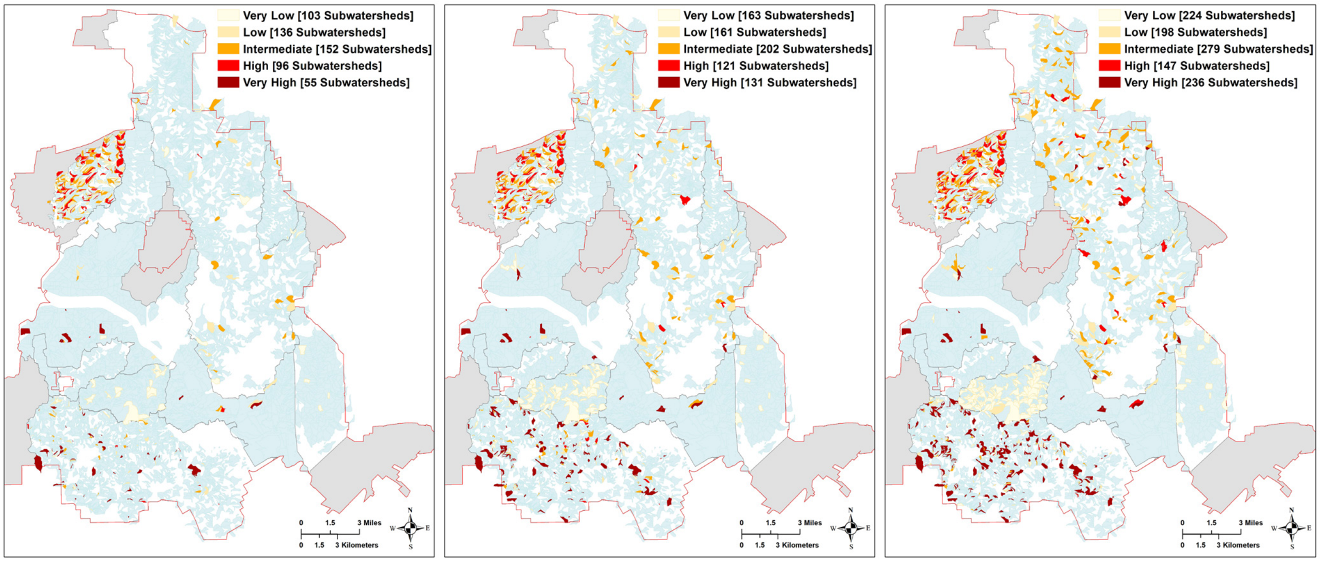


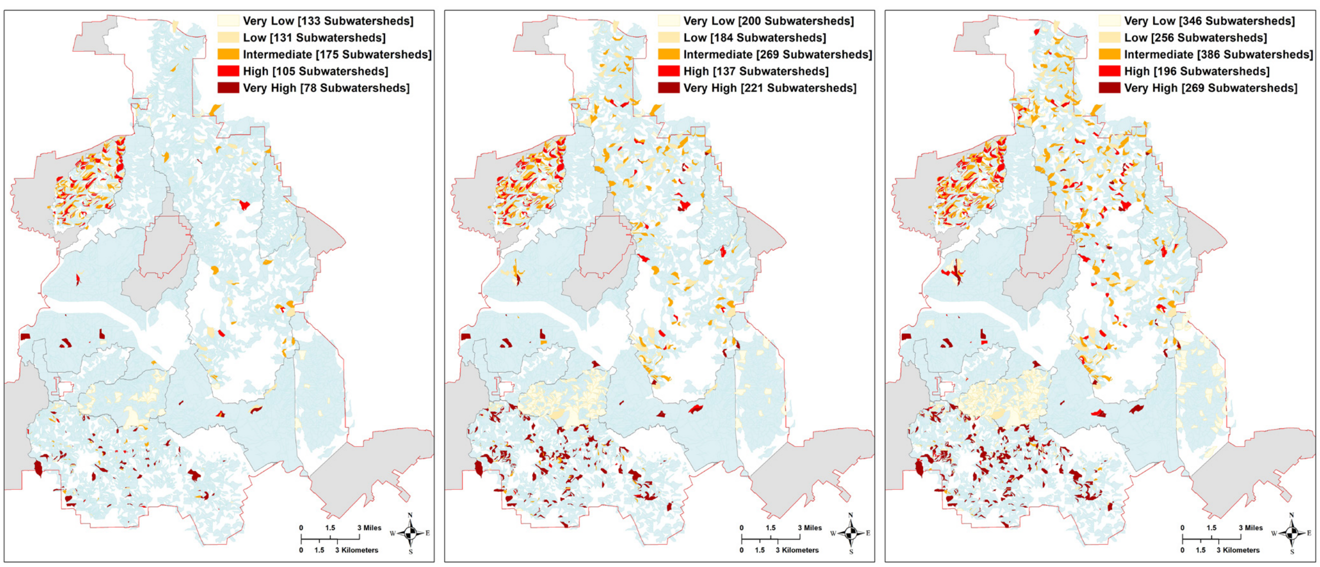
Figure 16. Total Challenged Subwatershed Area for Return Period Storms

ABOVE: Sacred Heart Church Bioretention. © Fauna Creative



2-year (50%) **10-year (10%)** **100-year (1%)**

Figure 17. Challenged Subwatersheds, Classified by Severity of Inlet Overflows, as Modeled for Return Period Storms, Current Conditions



2-year (50%), 2045 **10-year (10%), 2045** **100-year (1%), 2045**

Figure 18. Challenged Subwatersheds, Classified by Severity of Inlet Overflows, as Modeled for Return Period Storms, Forecasted Conditions

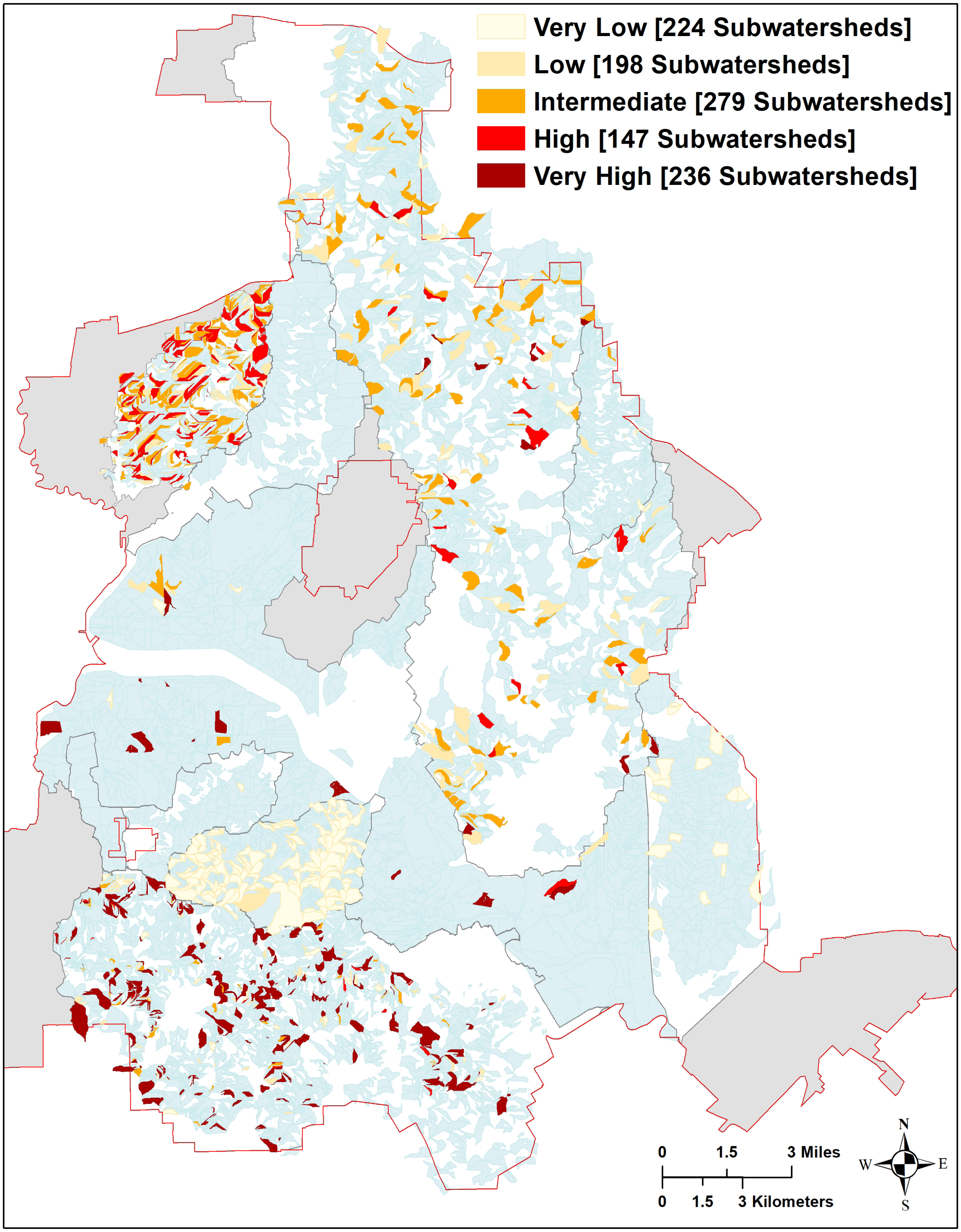


Figure 19. Challenged Subwatersheds, Classified by Severity of Inlet Overflows, as Modeled for 100-Year (1%), 24-Hour Storm, Current Conditions

Table 3. Stormwater Network System Hotspots and Challenged Subwatershed Areas Classified by Severity of Inlet Overflows

RETURN PERIOD STORM	Inlet Overflow Severity	Number of Hotspots	Challenged Sub-watersheds (acres)	FORECAST 2045	Number of Hotspots	Challenged Sub-watersheds (acres)	% Change (acres)
2-year (50%, 4 in)	VERY LOW	103	1,850	**2-year (50%, 4.5 in)**	133	2,477	34%
	LOW	136	1,430		131	1,427	0%
	INTERMEDIATE	152	1,699		175	1,959	15%
	HIGH	96	1,000		105	1,177	18%
	VERY HIGH	55	901		78	1,311	46%
	TOTAL	**542**	**6,880**		**622**	**8,351**	**21%**
10-year (10%, 6 in)	VERY LOW	163	3,298	**10-year (10%, 9.1 in)**	200	4,482	36%
	LOW	161	2,142		184	2,970	39%
	INTERMEDIATE	202	2,665		269	3,963	49%
	HIGH	121	1,362		137	1,688	24%
	VERY HIGH	131	2,115		221	3,059	45%
	TOTAL	**778**	**11,582**		**1,011**	**16,162**	**40%**
100-year (1%, 9.5 in)	VERY LOW	224	4,595	**100-year (1%, 14.7 in)**	346	7,116	55%
	LOW	198	3,040		256	3,475	14%
	INTERMEDIATE	279	4,134		386	5,161	25%
	HIGH	147	1,845		196	2,517	36%
	VERY HIGH	236	3,209		269	3,540	10%
	TOTAL	**1,084**	**16,823**		**14,53**	**21,809**	**30%**

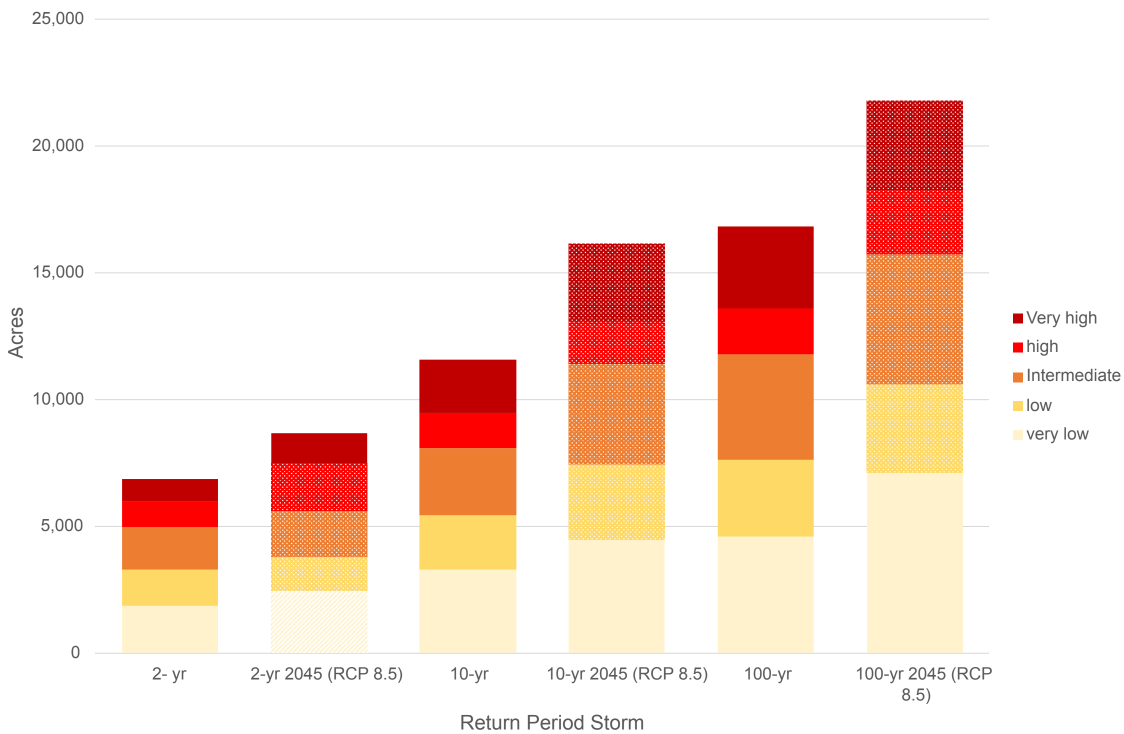


Figure 20. Challenged Subwatershed Area (acres), Classified by Severity of Inlet Overflows, as Modeled for Return Period Storms, Current and Forecasted Conditions

3.2.1. Current Conditions: Trends between Storm Events

In current conditions, data show increasing precipitation between storm events, resulting in increasing system hotspots and challenged watersheds. Trends are described here in terms of percentage change, with associated numbers reported in Table 4. From the 2- to the 10-year, 24-hour storms, data show a 50% increase in precipitation, resulting in an increase in system hotpots (+44%) and in the area of challenged subwatersheds (+68%). Furthermore, we saw a 67% increase in system hotpots and an 83% increase in subwatershed area classified as high or very high in severity between the 2 and 10-year storms.

Between the 10- and 100-year, 24-hour storm events, data showed a 58% increase in precipitation, resulting in an increase in system hotpots (+39%) and area of challenged subwatersheds (+45%). There was a 52% increase in system hotpots, and a 45% increase in subwatershed area classified as high or very high in severity. Compared to the 2-year storm, the 100-year, 24-hour storm brings a 138% increase in precipitation, resulting in a 161% increase in system hotpots and a 145% increase in challenged subwatershed area. Compared to the 2-year storm, there is a 154% increase in system hotpots and a 143% increase in challenged subwatershed area classified as *high* or *very high* in severity.

In current conditions, 6% of the modeled area is challenged during the 2-year storm, 10% by the 10-year storm and 16% by the 100-year storm. Overall, we see a steady increase in the number of system hotpots (mean increase of 41.4%) and area (mean increase of 56.8 %) of challenged subwatersheds between storms, with a notable increase in the number and area classified in the high and very high severity category between the 2- and 10-year storms.

3.2.2. Forecasted Climate Change Conditions, 2045 (RCP 8.5): Trends between Current and Forecasted Scenarios

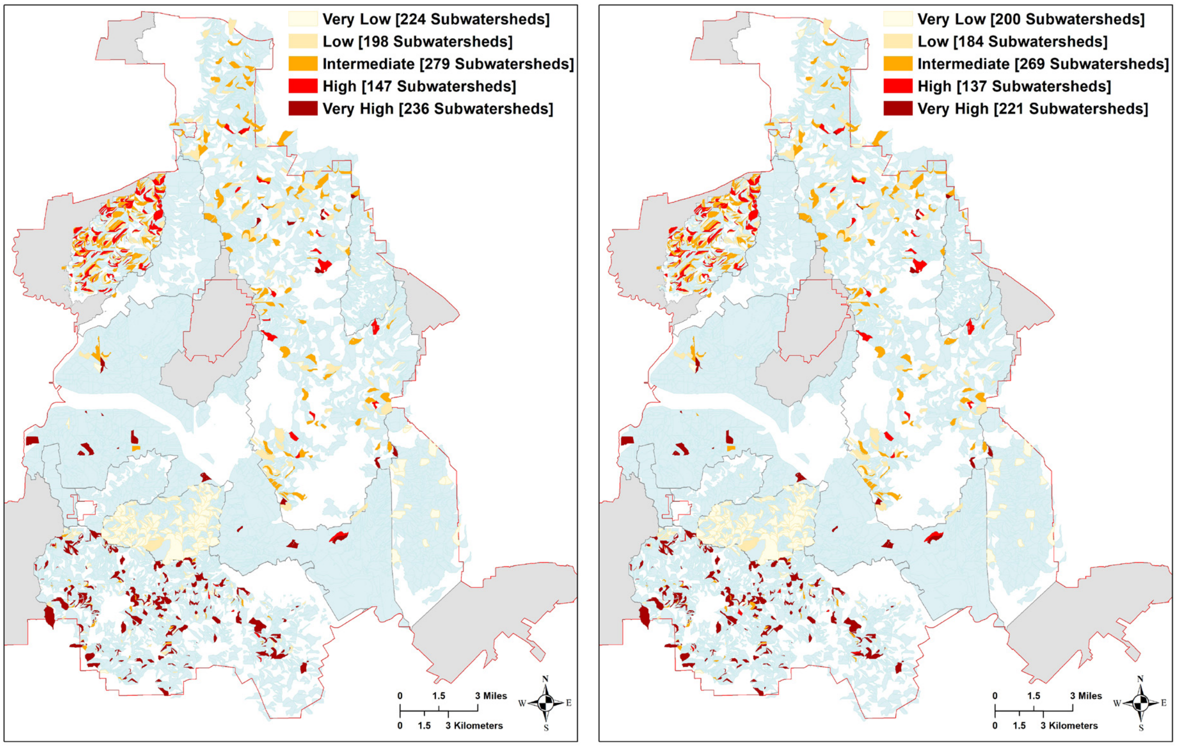
In the forecasted climate change conditions for 2045 (RCP 8.5), we see an average of 39.6% more precipitation than in current conditions for the three return period storms studied, with the greatest increases occurring for the 10-year (+51.7%) and 100-year (+54.7%), 24-hour storms. This reflects a much greater increase in precipitation between storm events (average increase of 83% between storms) in the climate change scenario compared to current conditions (average of 54%). The area of challenged subwatershed increases to 7%, 14%, and 20% of the modeled area, respectively, during the 2-, 10-, and 100-year storms forecasted for 2045.

Additional key impacts from climate change, as modeled, include:

- Overall, models indicate that climate change will result in an average increase in the number of system hotspots (+26%) and area of challenged subwatersheds (+30%), compared to current conditions for the three return period storms studied.
- The greatest increase in hotspots and challenged subwatershed area from climate change were seen for the 10-year (+30% hotspots and +40% acres) and the 100-year (+34% hotspots and +30% acres) storms.
- The number of system hotpots classified as high or very high in severity increased from current conditions by 42% for the 10-year, and 21% for the 2-year and 100-year storms, compared to current conditions. There is a 96% increase in system hotspots and a 91% increase in subwatershed area classified as high or very high in severity, between the 2- and 10-year storm in forecasted climate change conditions.
- Importantly, we find that precipitation amounts and trends for challenged subwatersheds are very similar between current conditions 100-year (1%) and forecasted climate change 10-year (10%), 24-hour storms; therefore, interventions addressing today's 100-year storm apply to the forecasted 10-year storms.

As expected, models indicated that larger amounts of precipitation will lead to more—and more severely—overflowing inlets and challenged subwatersheds, which in turn will lead to additional areas of opportunity for installing GSI (Part II) to enhance stormwater flooding management. This is true for larger return period storms, and also between current and forecasted 2045 (RCP 8.5) conditions.

Furthermore, a regression analysis showed that each additional inch of precipitation results in an increase of 83.8 system hotpots ($r2$=.99) and 1,389 acres ($r2$ =.96) as shown in Figure 22 and Figure 23.



100-year (1%), storm current conditions

10-year (10%) storm, 2045 (RCP 8.5)

Figure 21. Challenged Subwatersheds, Classified by Severity of Inlet Overflows, as Modeled for Current 100-Year and Forecasted 10-Year Storms

Table 4. Precipitation, No. of Hotspots (overflowing inlets), and Challenged Subwatershed Area (acre) for All Simulated Storm Events

Return Period Storm	Precipitation (in)	Number of Hotspots	Subwatershed Area (acres)
2-year (50 %)	4	542	6,880
2-year (50%), 2045 (RCP8.5)	4.5	622	8,351
10-year (10%)	6	778	11,582
10-year (10%), 2045 (RCP8.5)	9.1	1,011	16,823
100-year (1%)	9.5	1,084	16,823
100-year (1%), 2045 (RCP8.5)	14.7	1,453	21,809

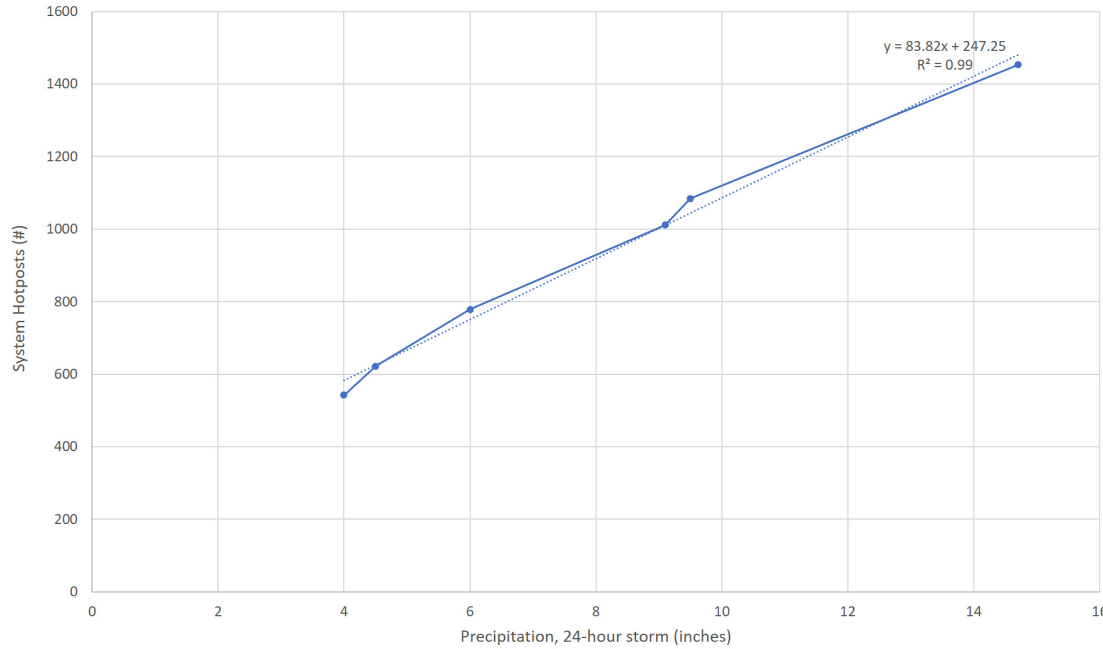


Figure 22. System Hotpots (overflowing inlets) per Inches of Precipitation, based on All Simulated Storm Events

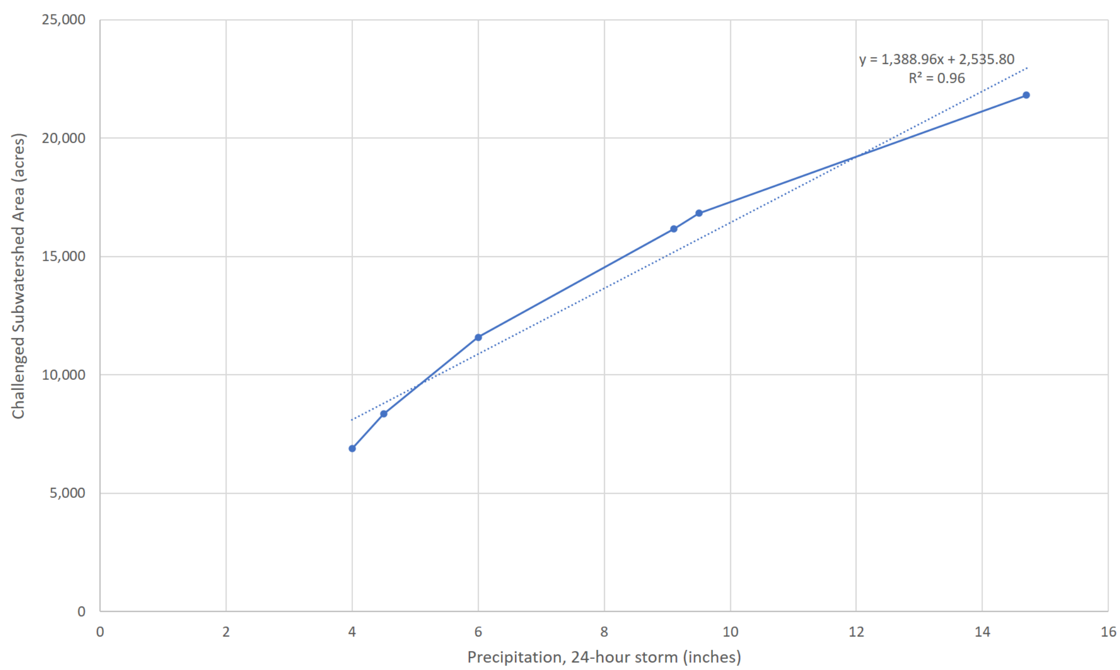


Figure 23. Challenged Subwatershed Area (acres), per Inch of Precipitation, based on All Simulated Storm Events

3.3. Part II Findings: Identify & Quantify Green Stormwater Infrastructure Opportunity

In Part II, the subwatersheds contributing to system hotspots for each of the current conditions storms were spatially evaluated for opportunities to deploy three types of green stormwater infrastructure—bioretention areas, rain gardens, and rainwater harvesting cisterns. Standard designs and spatial criteria—described in the methodology (section 2.4.2)—were applied across challenged subwatersheds to estimate the maximum potential siting availability and capacity for these practices to manage stormwater in each modeled storm condition. Additionally, the costs and overflow reduction capacity for using GSI was estimated for each return period storm and compared to gray infrastructure for the 100-year, (1%) storm.

Climate change conditions were not included in Part II due to uncertainties related to future land use changes and emissions scenarios. Focusing on the potential for GSI in current conditions provides decision makers with actionable near-term options, with higher certainty of impact. Furthermore, alleviating system hotpots as modeled in current conditions appears likely to provide substantial stormwater management benefits for the forecasted scenarios for the 2- and 10-year, 24-hour storm.

As shown in Table 5 and Table 6, substantial cost-effective opportunities have been identified to deploy GSI for improved stormwater management in challenged subwatersheds—particularly within the Joes' Creek, Cedar Creek, and Five Mile Creek Watersheds, and portions of the White Rock Watershed. If GSI were deployed in all opportunity areas within subwatersheds identified as challenged by the 2-year storm, then approximately 111.2 MG per event, or an estimated 31% of the modeled overflow (Part I), could be captured and infiltrated at a cost of approximately $2.40/gal. Approximately 191.6 MG per event, or an estimated 25% of the modeled overflow, could be captured and infiltrated if GSI were deployed in all potential sites within subwatersheds challenged by the 10-year storm. Approximately 284.5 MG per event, or an estimated 17% of the modeled overflow, could be captured and infiltrated if GSI were deployed in all potential sites within subwatersheds challenged by the 100-year storm.

Based on this analysis, GSI is cost effective in each watershed, when compared to upgrading gray infrastructure alone, per gallon managed. Combining green with gray infrastructure will result in the most volume captured and provided an overall lower cost than with gray infrastructure alone.

For each storm, bioretention areas provide the most potential beneficial impact, in terms of the site availability, volume captured, and associated costs, compared to rain gardens and rainwater harvesting cisterns. On average across all storms, bioretention areas provided approximately 71% of the overall stormwater volume managed by GSI. Further, parking lots provide the largest spatial opportunity for bioretention areas within the study area (58-68% of all bioretention volume, and 41-48% of all GSI potential). However, parks, rain gardens, cisterns, and planting strips also offer substantial volume capture.

ABOVE: Sidewalk bioretention areas in Deep Ellum. © Katy Evans/ City of Dallas

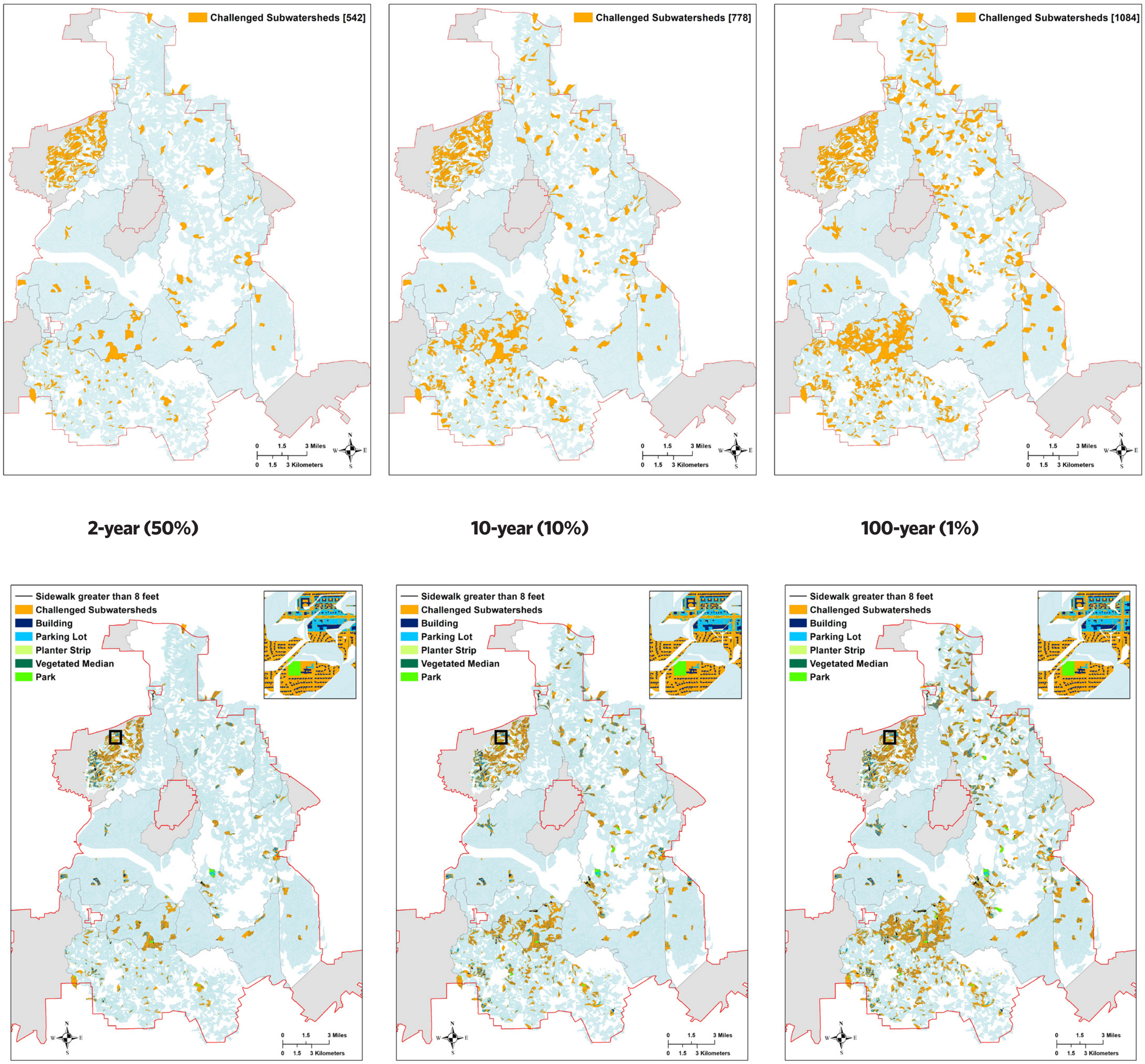


Figure 24. Total Challenged Subwatersheds, All Classes (top) and Spatial Opportunity for Select GSI (bottom), as Modeled for Return Period Storms, Current Conditions

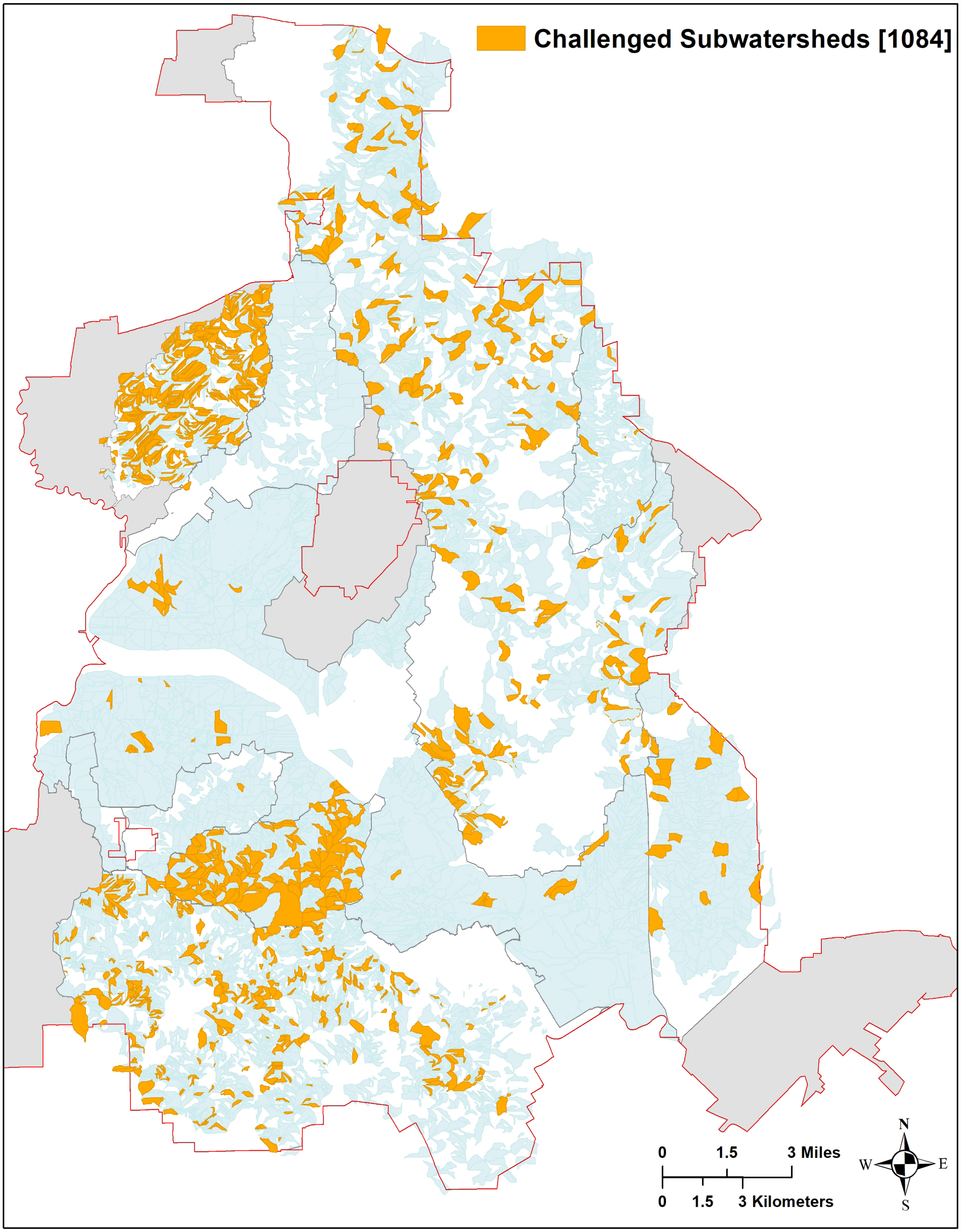


Figure 25. Total Challenged Subwatersheds, All Classes, as Modeled for 100-Year (1%), 24-Hour Storm, Current Conditions

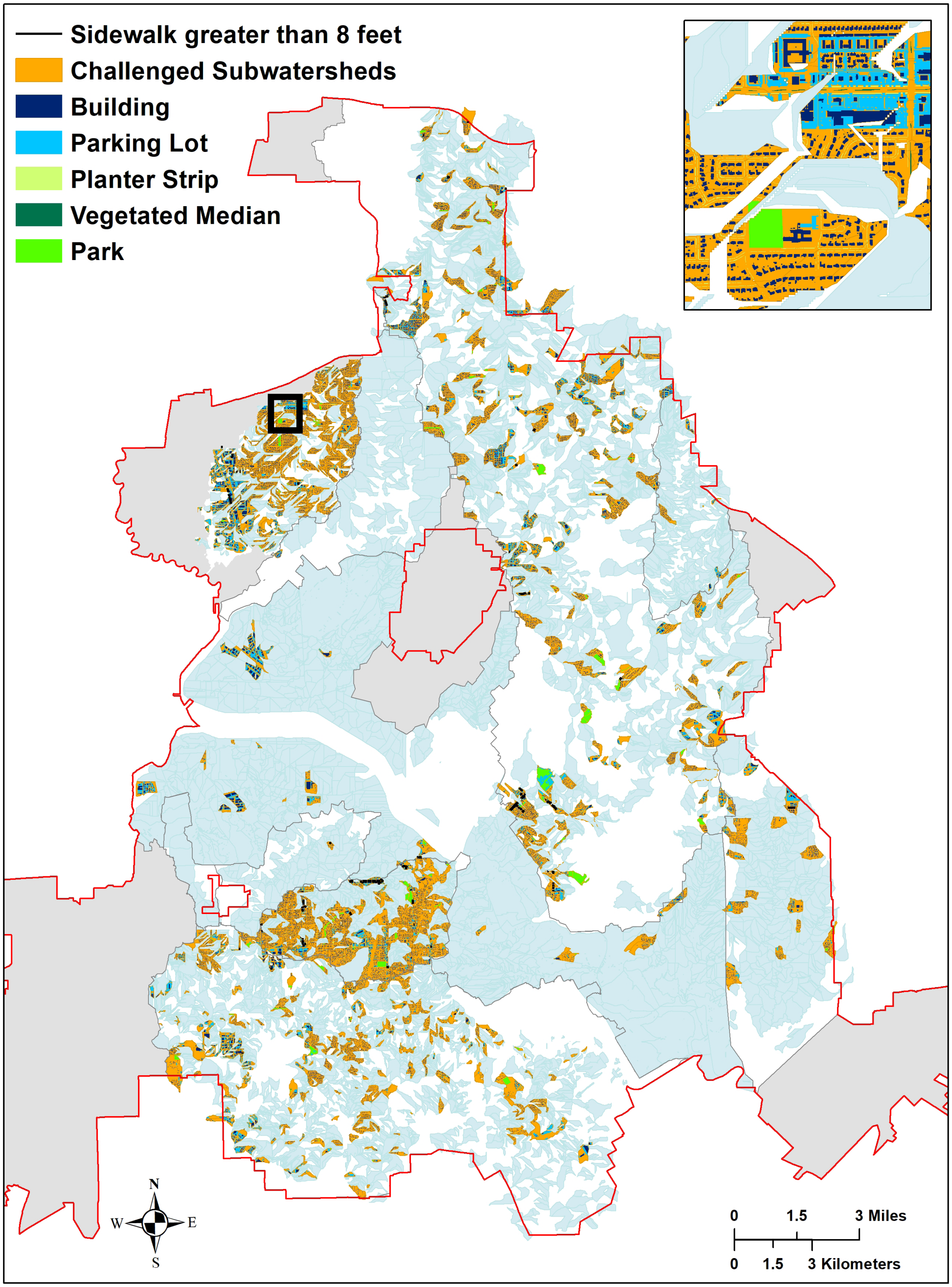


Figure 26. Spatial Opportunity Assessment for Select GSI, 100-Year (1%), 24-Hour Storm, Current Conditions

Table 5. Estimated Maximum Potential Spatial Availability and Stormwater Volume Capture Capacity for GSI, Based on Standard System Designs and Spatial Criteria

RETURN PERIOD STORM	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]	Potential Volume Capture/Event [MG]
2-year (50%)	BIORETENTION	Commercial Sidewalks	0.2 acres	0.5	78.4
		Parking lots	216 acres	53.5	
		Parks	47 acres	10.2	
		Planting strips	10 acres	11.1	
		Vegetated medians	4 acres	3.1	
	RAINGARDEN	Structures	92 acres	16.4	16.4
	RAINWATER CISTERN	Structures	20,217 units	16.4	16.4
				TOTAL	**111.2**
10-year (10%)	BIORETENTION	Commercial Sidewalks	0.4 acres	1.2	135.6
		Parking lots	590 acres	88.1	
		Parks	101 acres	20.0	
		Planting strips	26 acres	20.7	
		Vegetated medians	8 acres	5.6	
	RAINGARDEN	Structures	156 acres	28.1	28.1
	RAINWATER CISTERN	Structures	33,927 units	27.9	27.9
				TOTAL	**191.6**
100-year (1%)	BIORETENTION	Commercial Sidewalks	0.4 acres	1.9	200.9
		Parking lots	696 acres	117.3	
		Parks	136 acres	40.3	
		Planting strips	37 acres	31.9	
		Vegetated medians	11 acres	9.5	
	RAINGARDEN	Structures	219 acres	42.0	42.0
	RAINWATER CISTERN	Structures	47,731 units	41.8	41.8
				TOTAL	**284.7**

Table 6. Estimated Stormwater Management Capacity Potential Reduction of Modeled Overflows, and Costs per Gallon Captured by GSI, per Storm Event

WATERSHED	2-Year (50%)				10-Year (%10)				100-Year (1%)			
	CAPTURE CAPACITY/EVENT (MG)	OVERFLOW REDUCTION (%)	AVERAGE COST ($/GAL)[c]	AVERAGE COST WITH MAINTENANCE ($/GAL)	CAPTURE CAPACITY/EVENT (MG)	OVERFLOW REDUCTION (%)	AVERAGE COST ($/GAL)[c]	AVERAGE COST WITH MAINTENANCE ($/GAL)	CAPTURE CAPACITY/EVENT (MG)	OVERFLOW REDUCTION (%)	AVERAGE COST ($/GAL)[c]	AVERAGE COST WITH MAINTENANCE ($/GAL)
Bachman	No overflow				No overflow				No overflow			
Cedar Creek[b]	11.9	49%	2.3	2.9	27.9	0.4	2.3	2.9	47.1	23%	2.2	2.8
Chalk Hill	No overflow				No overflow				No overflow			
Coombs Creek	No overflow				0.2	33.9%	2.3	2.9	0.2	21.4%	2.3	2.9
Dixon[a]	0.3	58.9%	1.7	2.0	1.1	37.0%	2.0	2.4	1.1	19.5%	2.0	2.4
Five Mile[ab]	15.5	35.9%	1.9	2.2	38.7	29.1%	1.9	2.2	55.5	19.4%	1.9	2.2
Joe's Creek[ab]	51.4	29.1%	1.9	2.3	56.6	19.6%	1.9	2.3	61.7	12.4%	1.9	2.2
Trinity	10.9	25.8%	1.7	1.9	15.0	19.4%	1.7	2.0	18.6	12.8%	1.7	1.9
Upper Prairie	1.7	20.9%	2.1	3.1	5.0	16.2%	2.1	2.6	10.9	10.6%	2.1	2.6
White Rock[b]	19.5	28.7%	2.0	2.4	47.3	28.7%	1.9	2.3	89.6	20.6%	1.9	2.3
City of Dallas TOTAL	**111.2**	**30.6%**	**1.9**	**2.4**	**191.6**	**24.7%**	**2.0**	**2.4**	**284.7**	**16.9%**	**2.0**	**2.4**

[a] Problematic watersheds as identified by the City of Dallas watersheds.
[b] Key Opportunity watersheds identified in the analysis.
[c] Maintenance not included.

Table 7. Estimated Overflow Reduction Potential of GSI Practices and Gray Infrastructure, and Cost per Gallon for the 100-year (1%) storm, Current Conditions

WATERSHED	GSI				Gray (Pipe) Infrastructure			Green and Gray Infrastructure		
	CAPTURE CAPACITY/EVENT (MG)	OVERFLOW REDUCTION (%)	AVERAGE COST ($/GAL)	AVERAGE COST WITH MAINTENANCE ($/GAL)	CAPTURE CAPACITY/EVENT (MG)	OVERFLOW REDUCTION (%)	AVERAGE COST ($/GAL)[c]	CAPTURE CAPACITY/EVENT (MG)	OVERFLOW REDUCTION (%)	AVERAGE COST ($/GAL)[c]
Bachman		No overflow				No overflow			No overflow	
Cedar Creek[b]	47.1	22.7%	2.2	2.8	35.7	17%	10.4	82.7	40.0%	5.7
Chalk Hill		No overflow				No overflow			No overflow	
Coombs Creek	0.2	21.4%	2.3	2.9	0.8	100.0%	10.6	0.97	100.0%	8.8
Dixon[a]	1.1	19.5%	2.0	2.4	2.7	48.5%	10.9	3.77	68.0%	8.4
Five Mile[ab]	55.5	19.4%	1.9	2.2	97.9	34.2%	10.6	152.9	53.6%	7.5
Joe's Creek[ab]	61.7	12.4%	1.9	2.2	89.4	17.9%	11.5	151.1	30.3%	7.6
Trinity	18.6	12.8%	1.7	1.9	8.2	5.7%	10.9	26.8	18.5%	4.5
Upper Prairie	10.9	10.6%	2.1	2.6	13.9	13.4%	10.5	24.9	24.0%	6.8
White Rock[b]	89.6	20.6%	1.9	2.3	165.8	37.8%	10.7	256.1	58.4%	7.6
City of Dallas TOTAL	**284.7**	**16.9%**	**2.0%**	**2.4**	**414.4**	**24.6%**	**10.6**	**699.1**	**41.5%**	**7.1**

[a] Problematic watersheds as identified by the City of Dallas watersheds.
[b] Key Opportunity watersheds identified in the analysis.
[c] Maintenance not included.

3.4. Part III: Pre-Post GSI Modeling

3.4.1. Citywide Modeling

A pre- and post-assessment was conducted for current conditions 2-year (50%), 10-year (10%) and 100-year (1%), 24-hour storms (section 2.5.1), in order to evaluate the potential impact of GSI on system hotspots for current conditions.

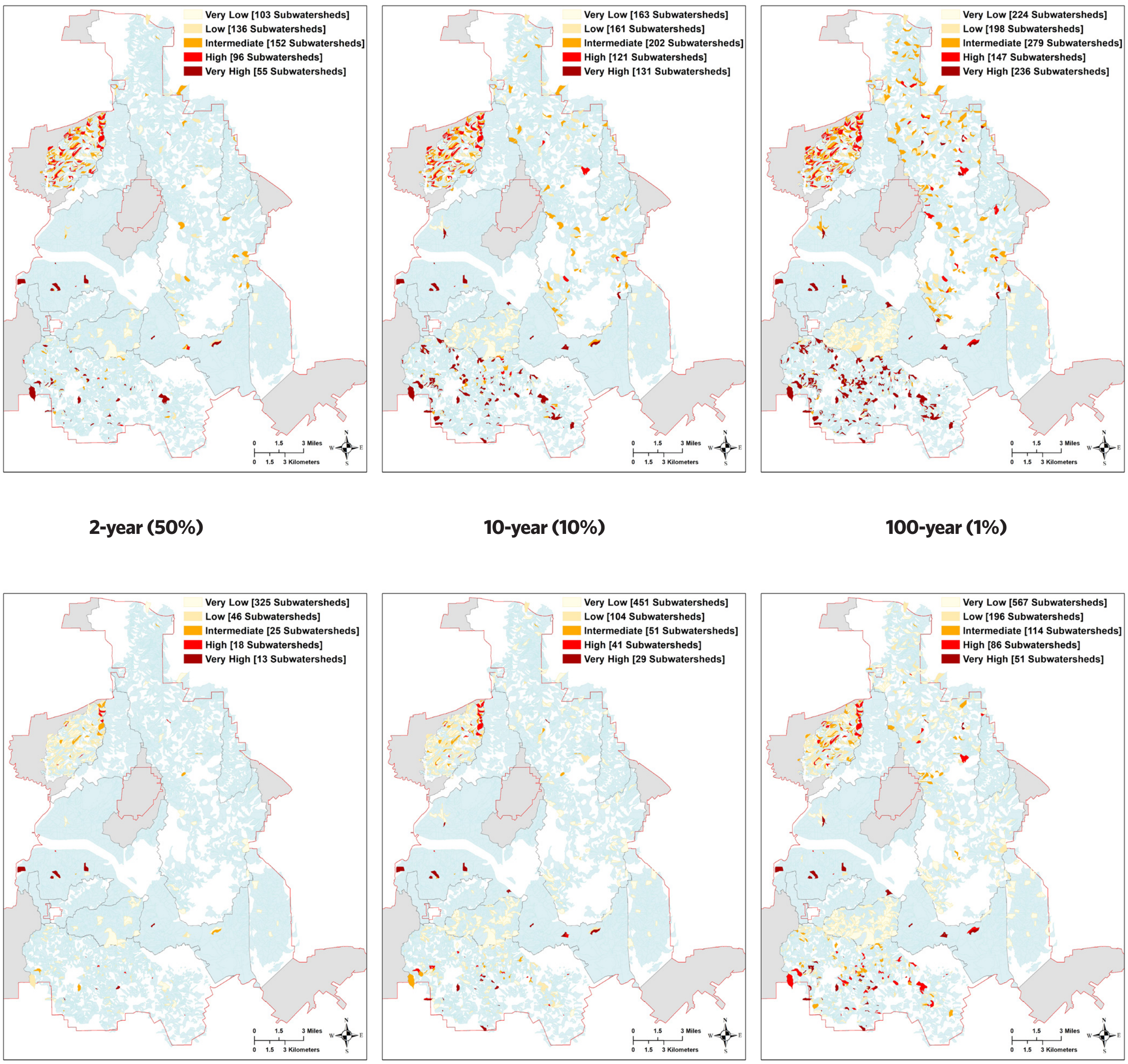


Figure 27. Challenged Subwatersheds Before and After Implementation of GSI, as Modeled for Return Period Storms, Current Conditions

As can be seen in Figure 27 and Table 8, the analysis revealed an overall reduction in hotpots and challenged subwatershed areas, with the maximum implementation of GSI—particularly for the 2-year storm. However, the largest impacts seen across all storm sizes, on average, were the reduction in challenged subwatersheds classified as *very high* (-73%), *high* (-58%), and *intermediate* (70%), and the shifting of those watersheds into less severe classifications (+125%, in subwatersheds classified as *very low*).

Table 8. System Hotpots and Challenged Subwatersheds Before and After Implementation of GSI, for Return Period Storms, Current Conditions

RETURN PERIOD STORM	Inlet Overflow Severity	Number of Hotspots (Pre-GSI)	Number of Hotspots (Post-GSI)	% Change	Acres (Pre-GSI)	Acres (Post-GSI)	% Change
2-year (50%, 4 in)	VERY LOW	103	325	216%	1,850	4,325	134%
	LOW	136	46	-66%	1,430	519	-64%
	INTERMEDIATE	152	25	-84%	1,699	475	-72%
	HIGH	96	18	-81%	1,000	112	-89%
	VERY HIGH	55	13	-76%	901	269	-70%
	TOTAL	**542**	**427**	**-21%**	**6,880**	**5,700**	**-17%**
10-year (10%, 6 in)	VERY LOW	163	451	177%	3,298	7,533	128%
	LOW	161	104	-35%	2,142	1,486	-31%
	INTERMEDIATE	202	51	-75%	2,665	643	-76%
	HIGH	121	41	-66%	1,362	461	-66%
	VERY HIGH	131	29	-78%	2,115	534	-75%
	TOTAL	**778**	**676**	**-13%**	**11,582**	**10,658**	**-8%**
100-year (1%, 9.5 in)	VERY LOW	224	567	153%	4,595	9,713	111%
	LOW	198	196	-1%	3,040	2,767	-9%
	INTERMEDIATE	279	114	-59%	4,134	1,577	-62%
	HIGH	147	86	-41%	1,845	1,473	-20%
	VERY HIGH	236	51	-78%	3,209	824	-74%
	TOTAL	**1,084**	**1,014**	**-6%**	**16,823**	**16,354**	**-3%**

3.4.2. Neighborhood-Scale Sub-study

GSI was modeled within SWMM to assess neighborhood-scale impacts, in a 331-acre area within the Five Mile Creek Watershed. The area falls between W. Kiest Boulevard to the north, W. Redbird Lane to the south, Marvin D. Love Freeway to the east, and Woodhollow Dr. to the west. The area is intersected by W. Ledbetter and S. Hampton Rd. and includes a portion of the Dallas Executive Airport. (see Figure 28and Figure 29). The neighborhood was selected based on the following criteria: incudes several challenged subwatersheds; has opportunity to implement the three GSI types; includes different land uses (residential, parks, commercial, and a school); includes proximity to potential planned City bond projects; and scores high for equity challenges in TPL's Smart Growth for Dallas Decision Support Tool. The model identified 107.4 acres, or 32% of the study area, as challenged by inlet overflows in the 10- and 100-year storms, with 36.4 of these acres also challenged in the 2-year storms.

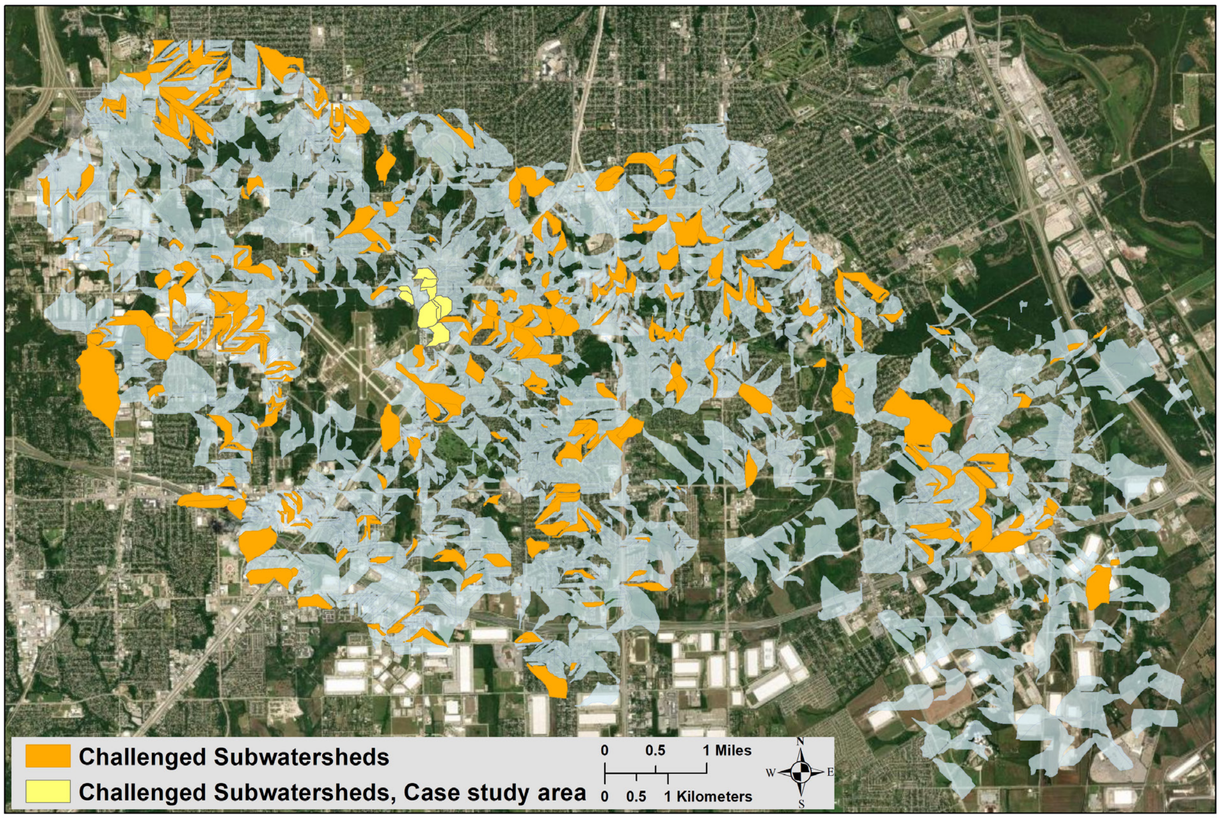


Figure 28. Case Study Area Location within Five Mile Creek Watershed

The challenged subwatersheds include approximately 272 residential units (single and multifamily), 20 commercial structures, 1 school, and the 33.4-acre Thurgood Marshall Park (Figure 29).

Table 9 summarizes the inlet overflow volumes modeled in SWMM, and the estimated reduction and costs after implementing GSI in 100% of the opportunity locations identified (Scenario 1), with 298,105 ft2 of bioretention areas and 292 raingardens (58,400 ft2) and cisterns.

Table 10 summarizes this information for Scenario 2, where bioretention is implemented in 50% of the identified opportunity area (149,052 ft2 of bioretention areas); and rain gardens and cisterns are implemented in 25% of the area identified (73 rain gardens (14,600 ft2) and cisterns).

Figure 29. Challenged Subwatersheds within Neighborhood Study Area

Table 9. Pre- and Post-GSI Model Results for Scenario 1 (100% GSI Implementation), within Case Study Area

Return Period Storms Current Conditions	Challenged Sub-watershed	Overflow Pre-GSI (gal)	Overflow Post-GSI (gal)	Reduction	Cost/Gal ($)
2-year	36.4	1,439,631	178,448	91%	2.13
10-year	107.4	5,347,630	1,753,002	80%	1.47
100-year	107.4	6,787,261	3,506,004	35%	1.95

Table 10. Pre- and Post-GSI Model Results for Scenario 2 (50% bioretention- 25% rain garden-25% cisterns), within Case Study Area

Return Period Storms Current Conditions	Challenged Sub-watershed	Overflow Pre-GSI (gal)	Overflow Post-GSI (gal)	Reduction	Cost/Gal ($)
2-year	36.4	1,439,631	863,169	63%	1.63
10-year	107.4	5,347,630	3,318,480	45%	1.86
100-year	107.4	10,151,165	8,497,131	17%	2.01

The results show that the overflow volumes generally were substantially reduced when using 100% GSI implementation within the challenged subwatersheds. Also, while the reduction percentages decreased with reduced GSI implementation, there were still significant reductions in Scenario 2.

The depth hydrograph[22] at the inlet for Thurgood Marshall Park during modeling of a 10-year storm, before and after GSI installation, further illustrates the impacts of GSI on stormwater capture, as shown in Figure 30.

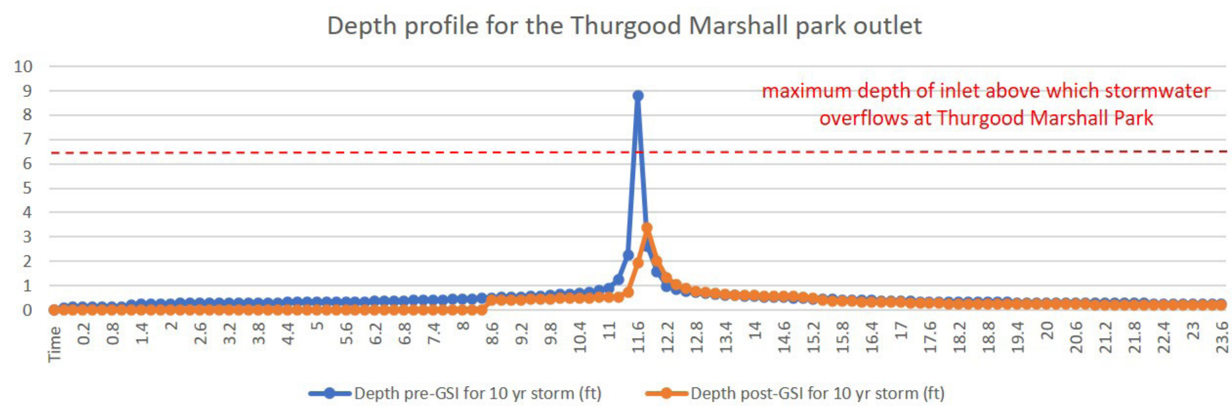


Figure 30. Depth Profile for Thurgood Marshall Park Before and After 100% GSI Installation during the 10-Year Storm

Figure 30 shows that, similar Table 9 to and Table 10, GSI can help avoid potential overflows altogether in some scenarios of challenged subwatersheds during storm events. Furthermore, Figure 30 also illustrates substantial peak flow reduction and delay resulting from GSI, which can reduce areal as well as creek flows and overbank flooding.

[22] "Depth" in the hydrograph does not reflect the depth of areal flooding but is a modeling indicator that is used as a metric to determine overflow and its severity.

Sidewalk bioretention. © Kathy Jack/ TNC

4. Conclusions and Recommendations

This study utilized hydrologic modeling and spatial analysis to help answer the overarching research question: Where can green stormwater infrastructure (GSI) most effectively enhance urban flood management within the City of Dallas, Texas, considering capacity, cost, and future impacts of climate change. The focus was on enhancing flood management where the existing drainage network may be limited. Therefore, the study was limited to areas with complete stormwater drainage system data. After exclusions, a total of 118,418 acres, or 53% of watershed area within the City limits, were included in this analysis.

EPA SWMM v. 5.1 was used to identify and evaluate potential stormwater system hotspots—specific locations where the drainage network is undersized and likely to contribute to inlet overflows and areal flooding under a variety of precipitation events. Models were run for the 2 (50%), 10 (10%), and 100-year (1%) 24-hour storms, for current conditions and forecasted climate change scenarios for 2045 (RCP 8.5).

The challenged subwatersheds contributing to system hotspots were spatially evaluated for opportunities to deploy three types of green stormwater infrastructure—bioretention, rain gardens and rainwater harvesting cisterns. The stormwater management capacity and the associated costs were estimated for the "maximum implementation scenario" of these practices, for each of the selected current conditions storms. These figures were compared between green and grey infrastructure for the 100-year design storm. A desktop pre-post GSI analysis was performed citywide and at the neighborhood level to determine the impact of GSI on challenged subwatersheds from the maximum implementation scenario.

As expected, models indicate that larger amounts of precipitation will lead to more, and more severe, system hotspots and contributing subwatersheds. This is true for larger return period storms, and with the increased precipitation forecasted for 2045 (RCP 8.5) conditions. Our analysis shows that climate change will result in increased precipitation across all storms considered, with much greater increase in precipitation between storm events, compared to current conditions. Overall, models indicate that climate change will result in an average increase in the number of system hotspots (+26%) and area of challenged watersheds (+30%), compared to current conditions for the three return period storms studied. In current conditions, 6 % of the modeled area is challenged during the 2-year storm, 10% by the 10-year storm and 16% by the 100-year storm. The climate change scenario for 2045, indicates that the impacted area increases to 7%, 14%, and 20% of the modeled area, during the 2, 10, and 100-year storms, respectively. Furthermore, precipitation amounts, hotspots, and trends for challenged subwatersheds are very similar between current conditions 100-year (1%) and forecasted climate change 10-year (10%), 24-hour storms; therefore, interventions addressing the current 100-year storm should substantially address the forecasted 10-year storm for 2045.

Substantial cost-effective opportunity has been identified to deploy GSI for improved stormwater management within the study area. If GSI were deployed in all identified opportunity areas—representing the maximum implementation scenario—approximately 31% (111.2 MG), 25% (191.6 MG), and 17% (284.5 MG) of overflows resulting from the simulated 2, 10, and 100-year storms, respectively, could be managed at an average cost of approximately $2.4/gallon. When compared to the capacity and costs for upgrading gray infrastructure for the 100-year design storm, GSI was approximately 77% less costly. However, more stormwater could be managed with a combined implementation of green and gray for a 45.1% reduction in modeled overflows for the 100-year design storm, and at a lower per gallon cost than for gray alone. A regression analysis indicated that additional system hotpots, challenged subwatersheds and GSI opportunity areas will likely be found in those areas excluded from the study due to limited data. Furthermore, alleviating system hotpots as modeled for current conditions appears likely to provide substantial stormwater management benefits for the forecasted climate change scenarios for the 2 and 10 year 24-hour storm.

ABOVE: Sidewalk bioretention areas in Deep Ellum. © Katy Evans/ City of Dallas

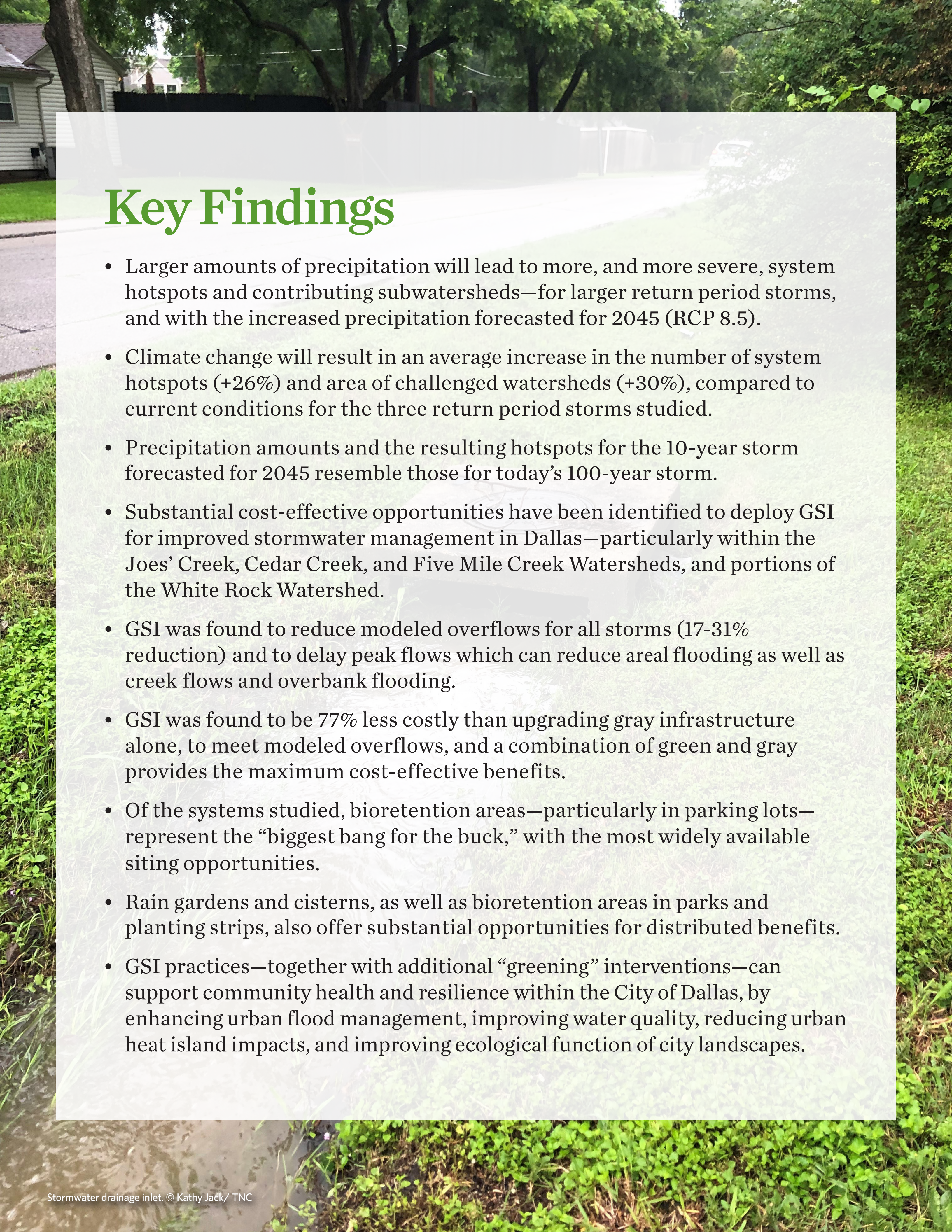
Our findings identify bioretention as the most cost-effective and potentially impactful of the GSI practices considered—in area and volume captured for the study area. Bioretention provides approximately 71% of the overall stormwater volume managed by GSI, in the maximum implementation scenario—ranging from 78.4 MG in the 2-year storm to 200.9 MG in the 100-year storm. Of the potential locations considered for installing bioretention, parking lots provide the largest opportunity (58-68% of all bioretention capacity by volume and 41-48% of all potential GSI capacity). However, rain gardens and cisterns, as well as bioretention areas in parks and planting strips, also offer substantial opportunities for distributed benefits. Additionally, the neighborhood scale sub-study illustrates the important benefit of GSI for peak flow reduction and delay, which can reduce areal as well as creek flows and overbank flooding.

The results of this analysis will be shared with the City of Dallas and integrated into The Trust for Public Land's Smart Growth for Dallas (SGD) decision-support tool for consideration with additional data. Specifically- it is recommended that the outputs from this analysis be considered together with: City data on channel flooding, customer service calls and upcoming streets and parks projects; FEMA flood plain maps and Community Rating System scores; and data on water quality, equity and land use types, available within in TPL's SGD tool. Some GSI practices—and relevant incentives and policy support—will be more appropriate for specific land use types and ownership.

It is our hope that these results will support planners, policymakers, and investors in Dallas to consider GSI as an important—and cost effective—tool for enhancing urban flood management. While this study focused on GSI systems likely to achieve the greatest volumetric capture for the cost, it is important to consider the stormwater management benefits of additional GSI practices and urban "greening" interventions—along with the co-benefits—when planning in the urban landscape. When combined with additional data and planning objectives, the findings may help to prioritize interventions to achieve multiple goals, including community health and resilience, improved water quality, urban heat island mitigation and ecological function within the City of Dallas.

Key Findings

- Larger amounts of precipitation will lead to more, and more severe, system hotspots and contributing subwatersheds—for larger return period storms, and with the increased precipitation forecasted for 2045 (RCP 8.5).
- Climate change will result in an average increase in the number of system hotspots (+26%) and area of challenged watersheds (+30%), compared to current conditions for the three return period storms studied.
- Precipitation amounts and the resulting hotspots for the 10-year storm forecasted for 2045 resemble those for today's 100-year storm.
- Substantial cost-effective opportunities have been identified to deploy GSI for improved stormwater management in Dallas—particularly within the Joes' Creek, Cedar Creek, and Five Mile Creek Watersheds, and portions of the White Rock Watershed.
- GSI was found to reduce modeled overflows for all storms (17-31% reduction) and to delay peak flows which can reduce areal flooding as well as creek flows and overbank flooding.
- GSI was found to be 77% less costly than upgrading gray infrastructure alone, to meet modeled overflows, and a combination of green and gray provides the maximum cost-effective benefits.
- Of the systems studied, bioretention areas—particularly in parking lots—represent the "biggest bang for the buck," with the most widely available siting opportunities.
- Rain gardens and cisterns, as well as bioretention areas in parks and planting strips, also offer substantial opportunities for distributed benefits.
- GSI practices—together with additional "greening" interventions—can support community health and resilience within the City of Dallas, by enhancing urban flood management, improving water quality, reducing urban heat island impacts, and improving ecological function of city landscapes.



Stormwater drainage inlet. © Kathy Jack/ TNC

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Appendices

Appendix 1:
Breakdown of Analyzed Area within All Watersheds in the City of Dallas

Watershed	Total area (ACRES)	Analyzed area (ACRES)	Total analyzed area (%)	Limited/ problematic data (ACRES) (WHITE)[c]	Total excluded area due to lack of data (ACRES)	Total excluded area (%)
Bachman	8,200	5,251	64%	2,949	2,949	36%
Cedar Creek[b]	6,138	6,138	100%	0	0	0%
Chalk Hill Branch	1,328	1,328	100%	0	0	0%
Coombs Creek	3,791	2,416	64%	1,376	1,376	36%
Upper Prairie Creek	11,038	8,391	76%	2,647	2,647	24%
Dixon[a]	4,443	2,885	65%	1,558	1,558	35%
Five Mile Creek[ab]	34,859	17,574	50%	17,285	17,285	50%
Joe's Creek[ab]	7,219	5,101	71%	2,118	2,118	29%
Trinity	40,851	35,957	88%	4,895	4,895	12%
White Rock[b]	57,347	33,378	58%	23,969	23,969	42%
Substantial area falls outside city limit (gray)[d]	47,462	0	0%	NA	47,462	100%
Total	**222,676**	**118,418**	**53%**	**56,796**	**104,258**	**47%**

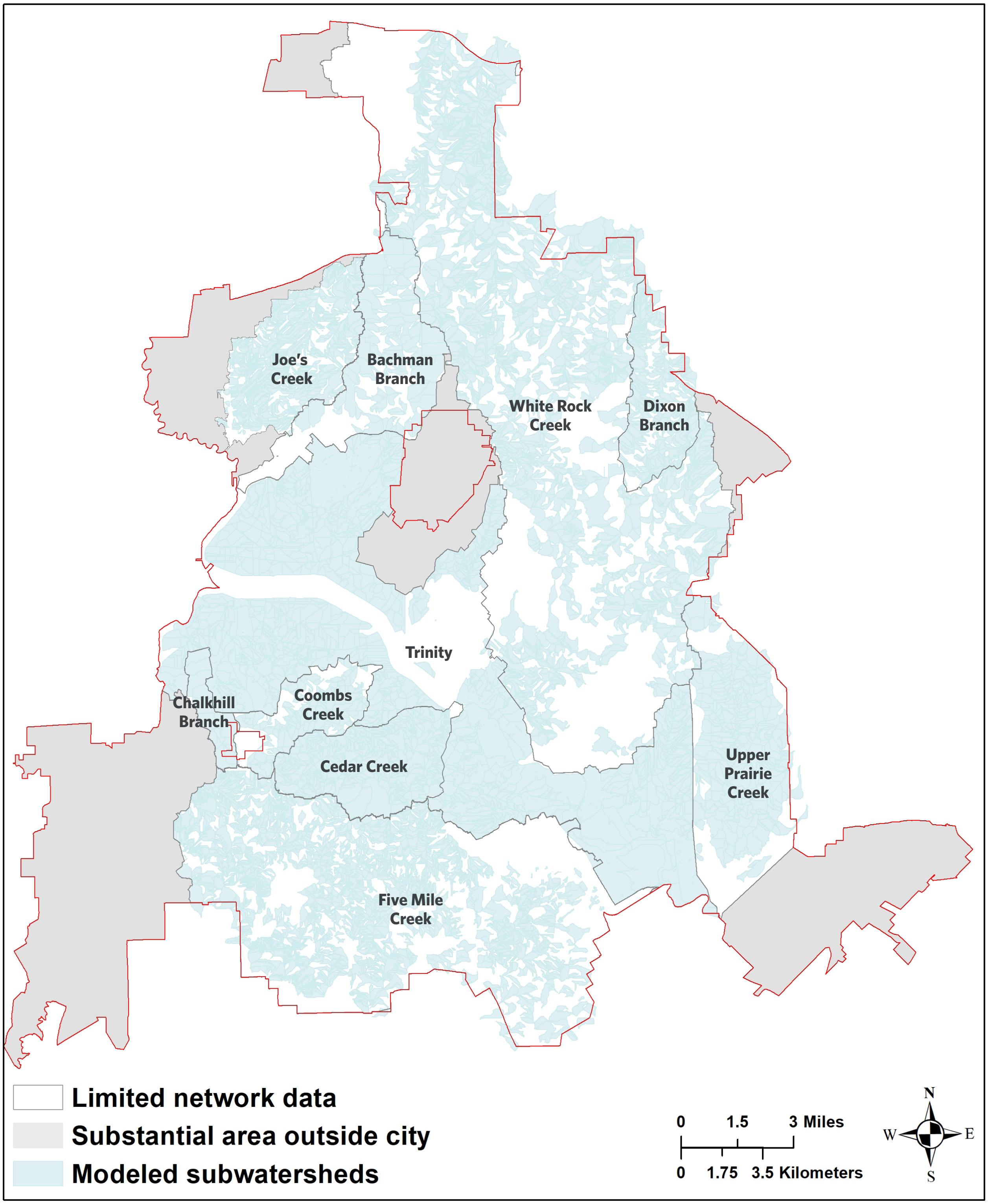
[a] Problematic watershed as identified by the City of Dallas watersheds.

[b] Key Opportunity watersheds identified in the analysis.

[c] The "white" area represents areas with limited or problematic stormwater network data, as shown in Figure 6

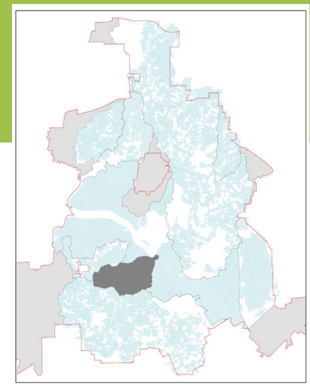
[d] They "gray" area represents those watersheds that had substantial surface area outside the City of Dallas, as shown in Figure 6.

Appendix 2:
System Hotspots, Challenged Subwatersheds, and Spatial Opportunity Assessment for All Watersheds in City of Dallas



City of Dallas Watersheds, Included in Modeling

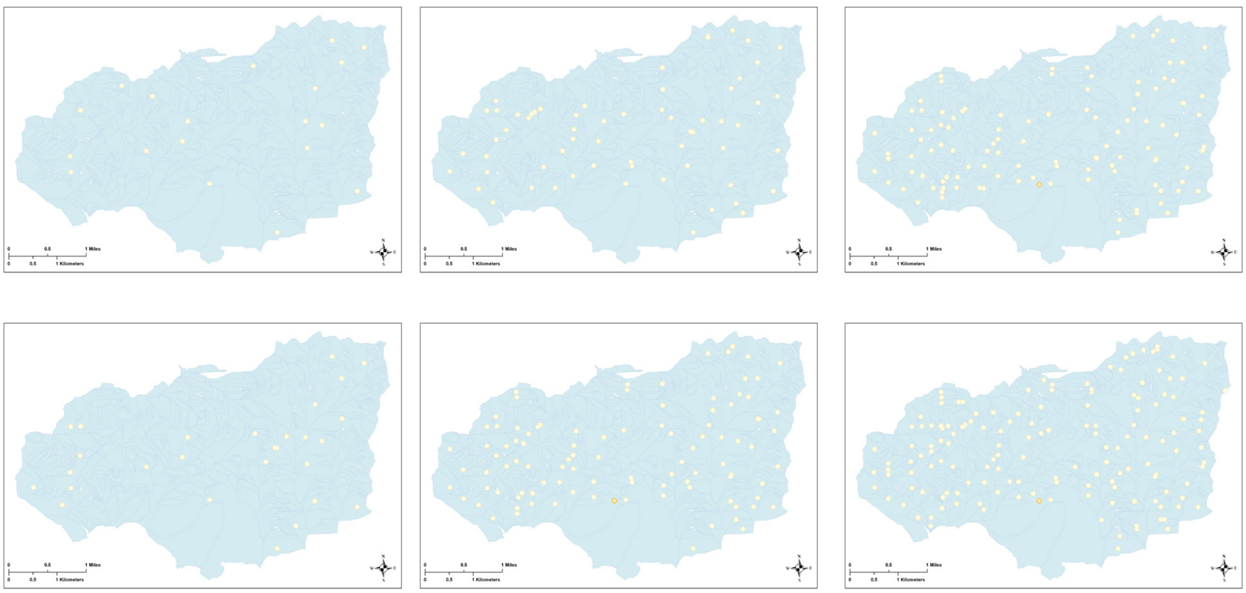
CEDAR CREEK WATERSHED



Very Low Low Intermediate High Very High

System Hotspots by Overflow Severity

2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**

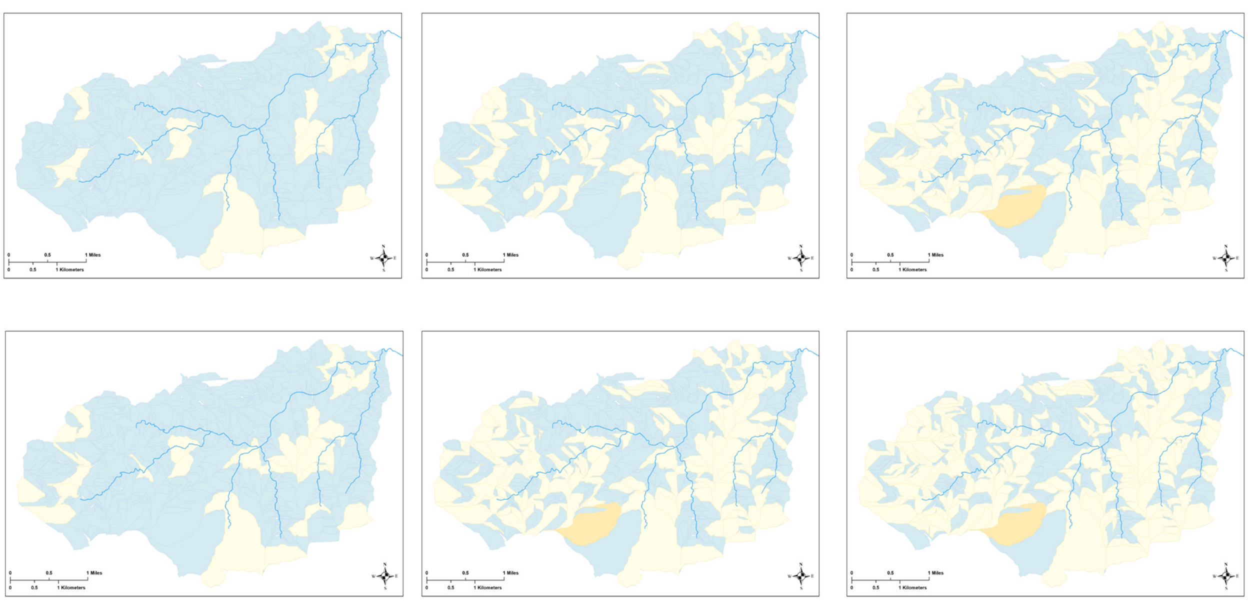


Current Conditions

2045 (RCP 8.5)

Challenged Subwatersheds Classified by Overflow Severity

2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**



Current Conditions

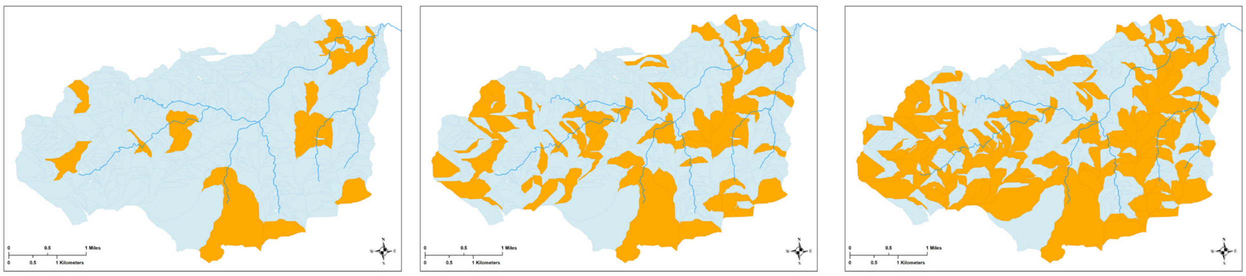
2045 (RCP 8.5)

CEDAR CREEK WATERSHED

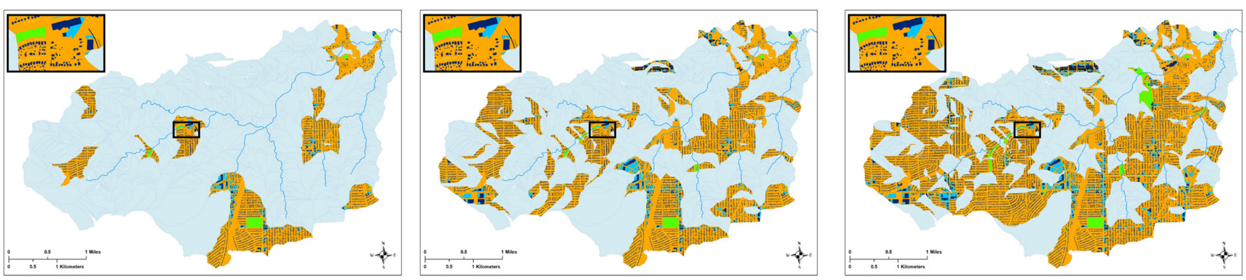
Building | Parking Lot | Planter Strip | Vegetated Median | Park | Challenged Subwatershed

Total Challenged Subwatersheds, All Classes, Current Conditions

2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**



GSI Spatial Opportunity Assessment (Maps and Table)



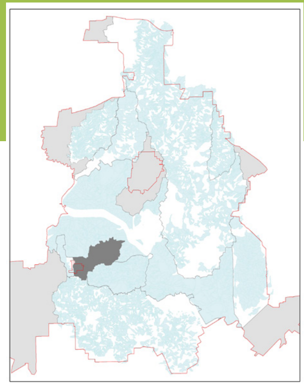
CEDAR CREEK WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	3.4 acres	0.0
		Parking lots	10.7 acres	0.2
		Parks	3.4 acres	1.4
		Planting strips	7.0 acres	2.9
		Vegetated medians	0.7 acres	0.3
		Total bioretention	11.6 acres	4.8
	RAINGARDEN	Structures	4,800 units	3.6
	RAINWATER CISTERN	Structures	4,800 units	3.6
				TOTAL 11.9

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	3.4 acres	0.5
		Parking lots	10.7 acres	0.5
		Parks	3.4 acres	2.8
		Planting strips	7.0 acres	7.1
		Vegetated medians	0.7 acres	1.1
		Total bioretention	11.6 acres	12.0
	RAINGARDEN	Structures	10,653 units	8.0
	RAINWATER CISTERN	Structures	10,653 units	8.0
				TOTAL 28.0

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	2.0 acres	0.8
		Parking lots	1.7 acres	0.7
		Parks	18.7 acres	7.9
		Planting strips	25.9 acres	10.9
		Vegetated medians	5.1 acres	2.1
		Total bioretention	53.4 acres	22.4
	RAINGARDEN	Structures	16,495 units	12.3
	RAINWATER CISTERN	Structures	16,495 units	12.3
				TOTAL 47.1

COOMBS CREEK WATERSHED



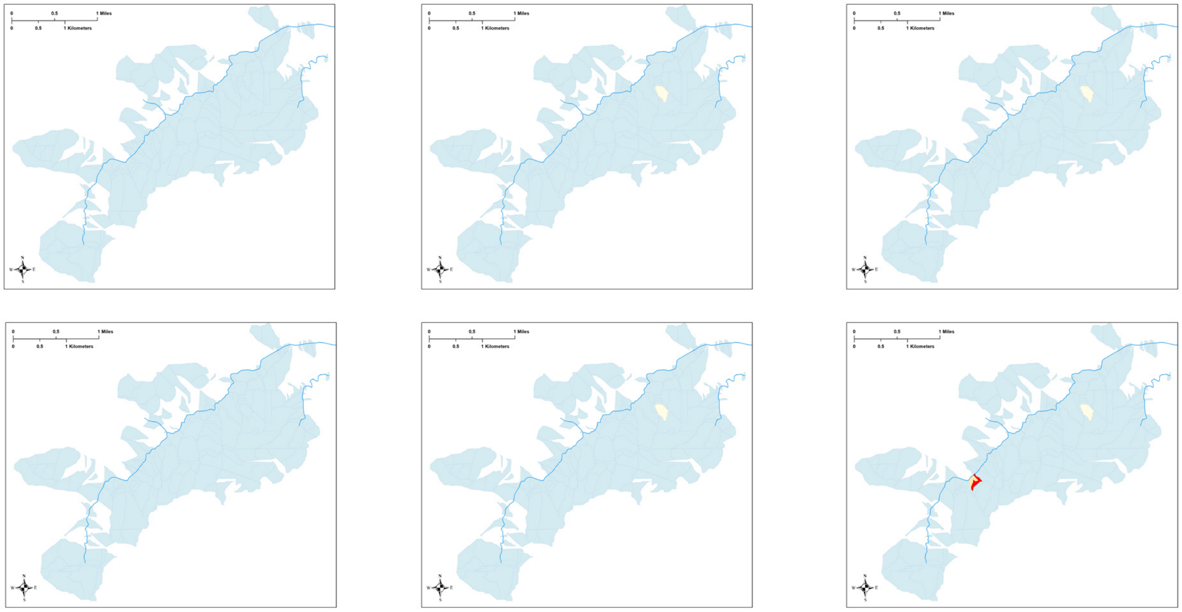
Very Low | Low | Intermediate | High | Very High

System Hotspots by Overflow Severity

	2-Year (50%)	10-Year (10%)	100-Year (1%)
Current Conditions			
2045 (RCP 8.5)			

Challenged Subwatersheds Classified by Overflow Severity

	2-Year (50%)	10-Year (10%)	100-Year (1%)
Current Conditions			
2045 (RCP 8.5)			

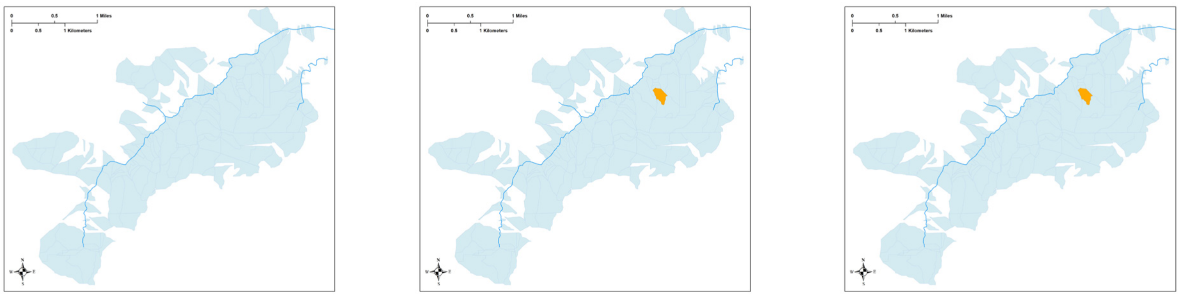


COOMBS CREEK WATERSHED

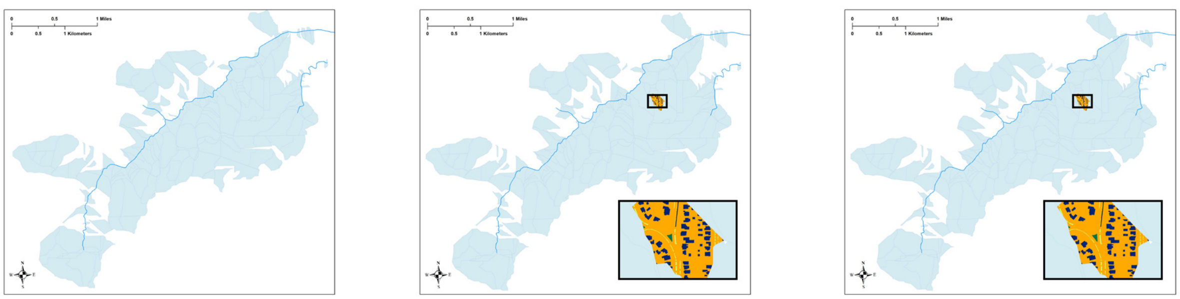
Building | Parking Lot | Planter Strip | Vegetated Median | Park | Challenged Subwatershed

Total Challenged Subwatersheds, All Classes, Current Conditions

2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**



GSI Spatial Opportunity Assessment (Maps and Table)



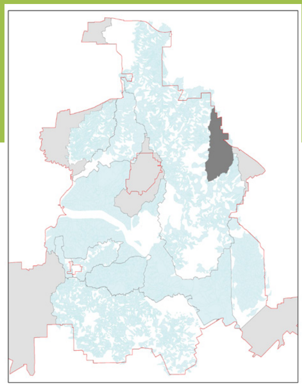
COOMBS CREEK WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks		No modeled Overflow
		Parking lots		
		Parks		
		Planting strips		
		Vegetated medians		
		Total bioretention		
	RAINGARDEN	Structures		
	RAINWATER CISTERN	Structures		

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	0.018 acres	0.01
		Parking lots	0.00 acres	0.00
		Parks	0.00 acres	0.00
		Planting strips	0.095 acres	0.05
		Vegetated medians	0.032 acres	0.02
		Total bioretention	0.15 acres	0.07
	RAINGARDEN	Structures	62 units	0.05
	RAINWATER CISTERN	Structures	62 units	0.05
				TOTAL 0.17

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	0.018 acres	0.1
		Parking lots	0.00 acres	0.00
		Parks	0.00 acres	0.00
		Planting strips	0.095 acres	0.05
		Vegetated medians	0.032 acres	0.02
		Total bioretention	0.15 acres	0.07
	RAINGARDEN	Structures	47,731 units	0.05
	RAINWATER CISTERN	Structures	47,731 units	0.05
				TOTAL 0.17

DIXON WATERSHED



Very Low   Low   Intermediate   High   Very High

System Hotspots by Overflow Severity

2-Year (50%) | 10-Year (10%) | 100-Year (1%)

Current Conditions

2045 (RCP 8.5)

Challenged Subwatersheds Classified by Overflow Severity

2-Year (50%) | 10-Year (10%) | 100-Year (1%)

Current Conditions

2045 (RCP 8.5)

DIXON WATERSHED

Building **Parking Lot** **Planter Strip** **Vegetated Median** **Park** **Challenged Subwatershed**

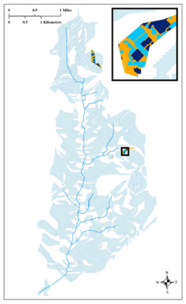
Total Challenged Subwatersheds, All Classes, Current Conditions

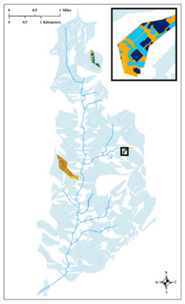
2-Year (50%)

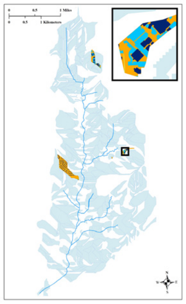
10-Year (10%)

100-Year (1%)

GSI Spatial Opportunity Assessment (Maps and Table)





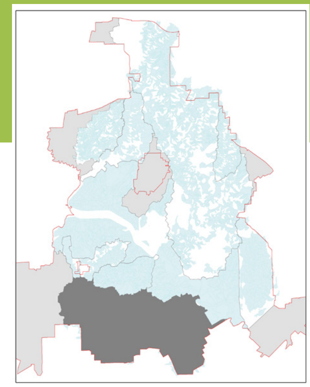


DIXON WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	0 acres	0
		Parking lots	1.03 acres	0.3
		Parks	0 acres	0
		Planting strips	0.02 acres	0
		Vegetated medians	0 acres	0
		Total bioretention	1.05 acres	0.3
	RAINGARDEN	Structures	26 units	0.02
	RAINWATER CISTERN	Structures	26 units	0.02
				TOTAL 0.34

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	0 acres	0
		Parking lots	1.1 acres	0.5
		Parks	0 acres	0
		Planting strips	0.4 acres	0.2
		Vegetated medians	0 acres	0.0
		Total bioretention	1.5 acres	0.7
	RAINGARDEN	Structures	222 units	0.2
	RAINWATER CISTERN	Structures	222 units	0.2
				TOTAL 1.1

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	0 acres	0
		Parking lots	1.1 acres	0.5
		Parks	0 acres	0
		Planting strips	0.4 acres	0.2
		Vegetated medians	0 acres	0.0
		Total bioretention	1.5 acres	0.7
	RAINGARDEN	Structures	222 units	0.2
	RAINWATER CISTERN	Structures	222 units	0.2
				TOTAL 1.1



FIVE MILE CREEK WATERSHED

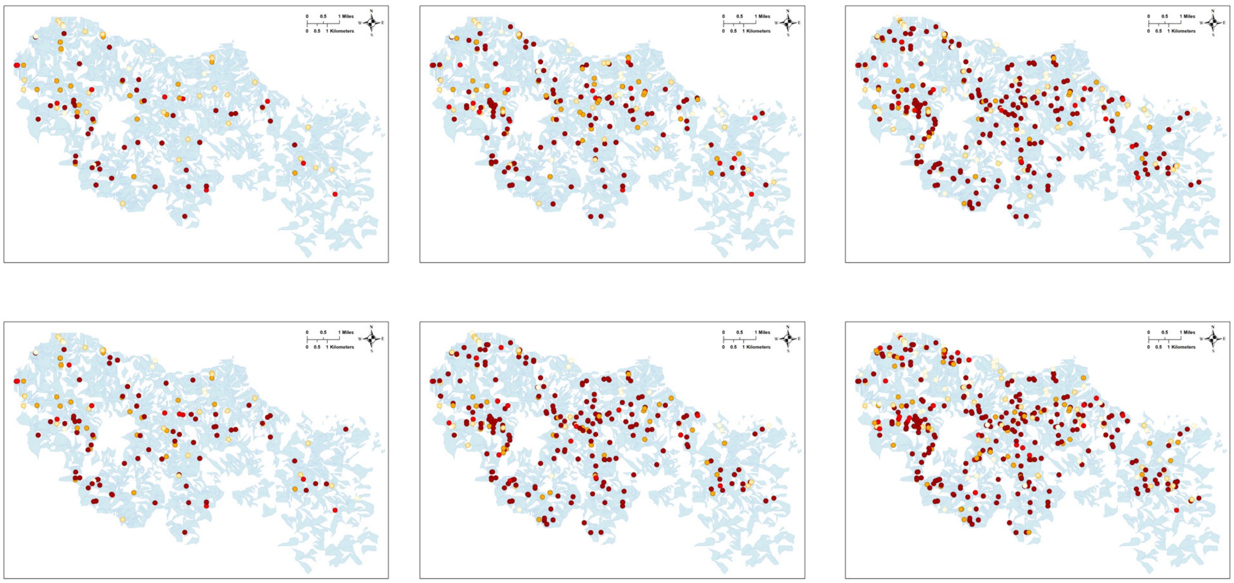
Very Low | Low | Intermediate | High | Very High

System Hotspots by Overflow Severity

	2-Year (50%)	10-Year (10%)	100-Year (1%)

Current Conditions

2045 (RCP 8.5)

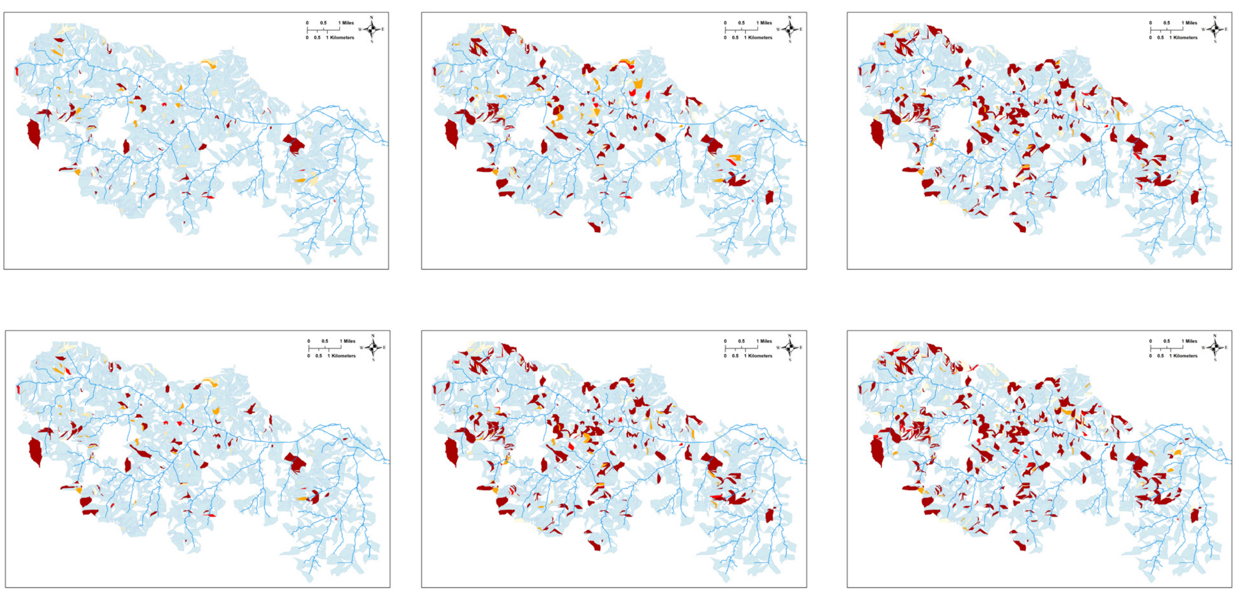


Challenged Subwatersheds Classified by Overflow Severity

	2-Year (50%)	10-Year (10%)	100-Year (1%)

Current Conditions

2045 (RCP 8.5)

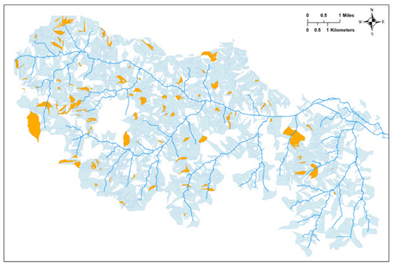


FIVE MILE CREEK WATERSHED

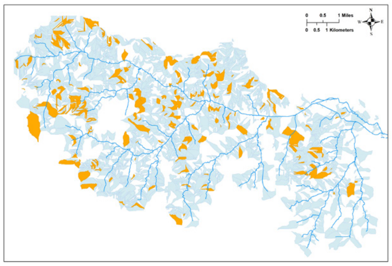
Building Parking Lot Planter Strip Vegetated Median Park Challenged Subwatershed

Total Challenged Subwatersheds, All Classes, Current Conditions

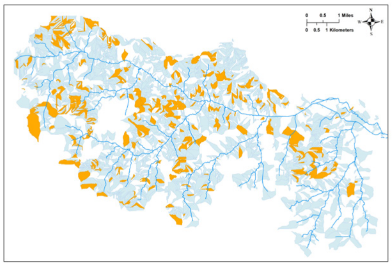
2-Year (50%)



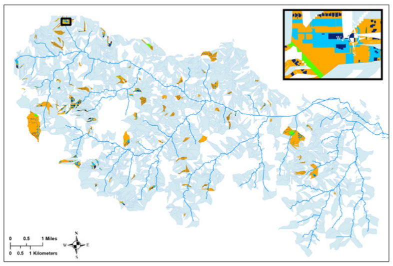
10-Year (10%)

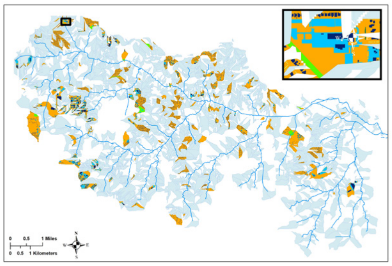


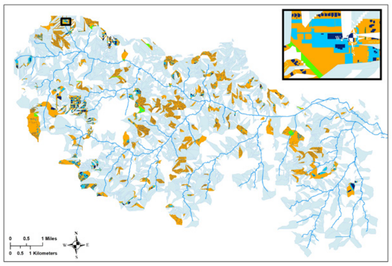
100-Year (1%)



GSI Spatial Opportunity Assessment (Maps and Table)





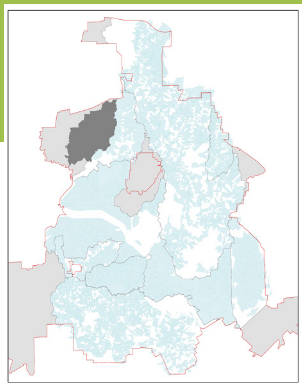


FIVE MILE CREEK WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	0.1 acres	0.0
		Parking lots	21.6 acres	8.2
		Parks	4.7 acres	1.8
		Planting strips	3.5 acres	1.3
		Vegetated medians	1.5 acres	0.6
		Total bioretention	31.4 acres	11.9
	RAINGARDEN	Structures	2,416 units	1.8
	RAINWATER CISTERN	Structures	2,416 units	1.8
				TOTAL 15.5

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	0.1 acres	0.0
		Parking lots	59.0 acres	21.4
		Parks	10.1 acres	3.7
		Planting strips	9.1 acres	3.3
		Vegetated medians	2.9 acres	1.1
		Total bioretention	81.3 acres	29.5
	RAINGARDEN	Structures	6,182 units	4.6
	RAINWATER CISTERN	Structures	6,182 units	4.6
				TOTAL 38.7

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	0.1 acres	0.1
		Parking lots	69.6 acres	29.4
		Parks	13.6 acres	5.7
		Planting strips	12.9 acres	5.4
		Vegetated medians	3.9 acres	1.7
		Total bioretention	100.1 acres	42.3
	RAINGARDEN	Structures	8,952 units	6.7
	RAINWATER CISTERN	Structures	8,952 units	6.5
				TOTAL 55.5

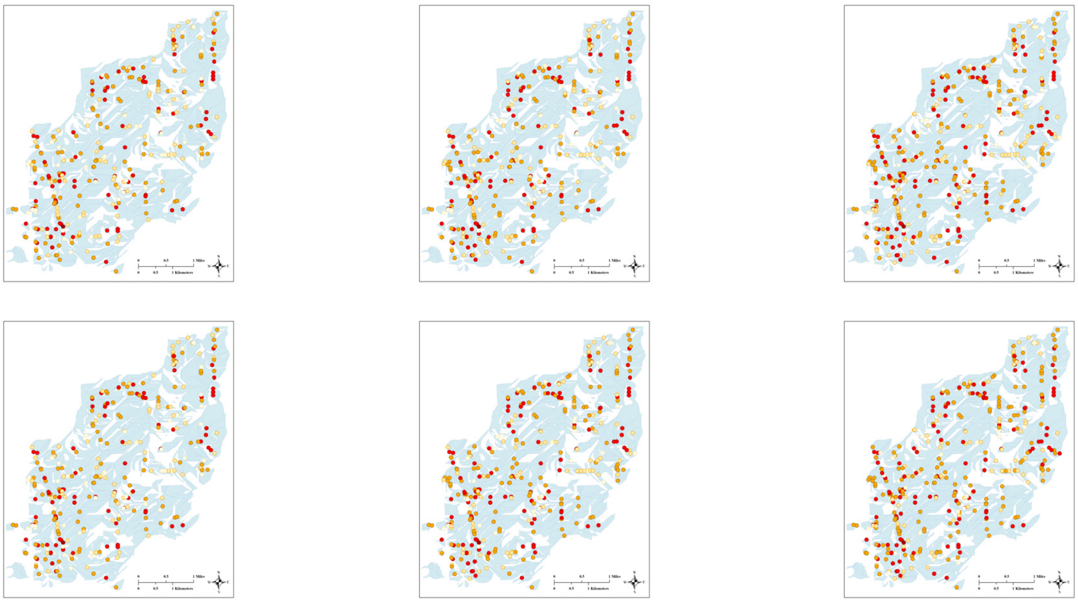


JOE'S CREEK WATERSHED

Very Low Low Intermediate High Very High

System Hotspots by Overflow Severity

2-Year (50%) | 10-Year (10%) | 100-Year (1%)

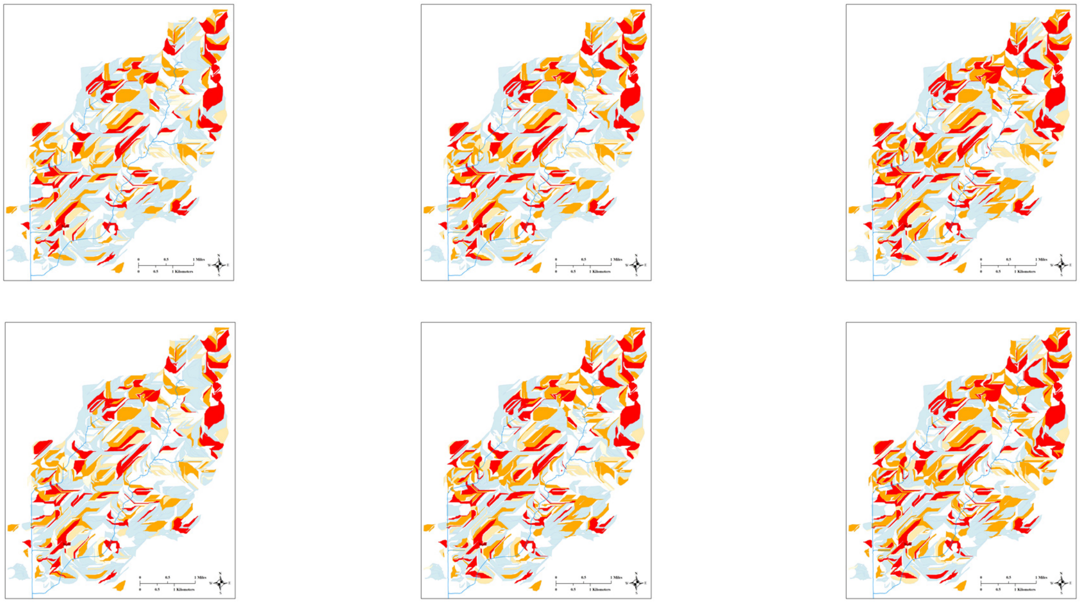


Current Conditions

2045 (RCP 8.5)

Challenged Subwatersheds Classified by Overflow Severity

2-Year (50%) | 10-Year (10%) | 100-Year (1%)



Current Conditions

2045 (RCP 8.5)

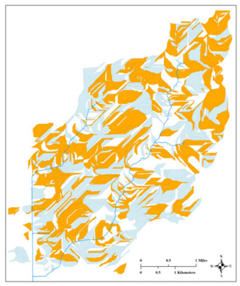
JOE'S CREEK WATERSHED

Building **Parking Lot** **Planter Strip** **Vegetated Median** **Park** **Challenged Subwatershed**

Total Challenged Subwatersheds, All Classes, Current Conditions

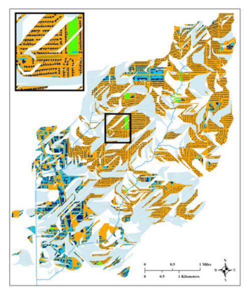
2-Year (50%)

10-Year (10%)



100-Year (1%)

GSI Spatial Opportunity Assessment (Maps and Table)



JOE'S CREEK WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	0.4 acres	0.2
		Parking lots	65.3 acres	28.7
		Parks	4.3 acres	1.9
		Planting strips	13.0 acres	5.7
		Vegetated medians	4.0 acres	1.8
		Total bioretention	87.1 acres	38.3
	RAINGARDEN	Structures	8,654 units	6.5
	RAINWATER CISTERN	Structures	8,654 units	6.6
				TOTAL 51.4

Current Conditions

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	0.5 acres	0.2
		Parking lots	69.5 acres	32.2
		Parks	4.3 acres	2.0
		Planting strips	14.0 acres	6.5
		Vegetated medians	4.1 acres	1.9
		Total bioretention	92.3 acres	42.8
	RAINGARDEN	Structures	9,184 units	6.9
	RAINWATER CISTERN	Structures	9,184 units	6.9
				TOTAL 56.5

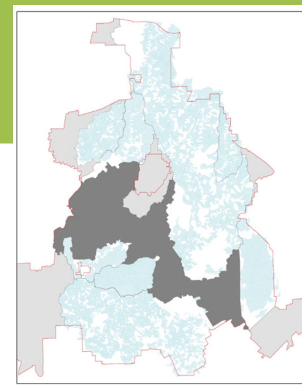
2045 (RCP 8.5)

Current Conditions

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	0.5 acres	0.2
		Parking lots	74.5 acres	35.3
		Parks	4.3 acres	2.0
		Planting strips	15.2 acres	7.2
		Vegetated medians	4.5 acres	2.1
		Total bioretention	99.0 acres	46.9
	RAINGARDEN	Structures	9,925 units	7.4
	RAINWATER CISTERN	Structures	9,925 units	7.4
				TOTAL 61.7

2045 (RCP 8.5)

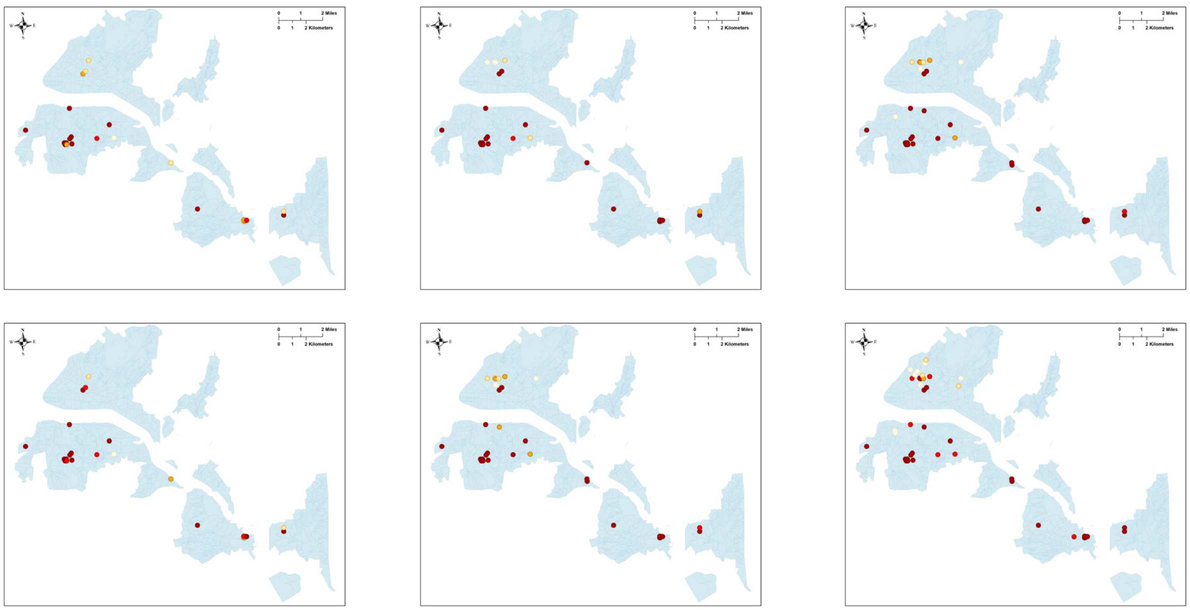
TRINITY WATERSHED



Very Low | Low | Intermediate | High | Very High

System Hotspots by Overflow Severity

2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**



Challenged Subwatersheds Classified by Overflow Severity

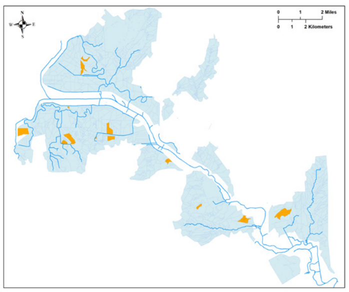
2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**

TRINITY WATERSHED

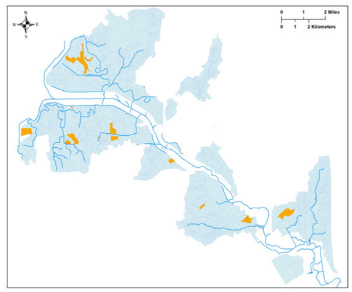
Building **Parking Lot** **Planter Strip** **Vegetated Median** **Park** **Challenged Subwatershed**

Total Challenged Subwatersheds, All Classes, Current Conditions

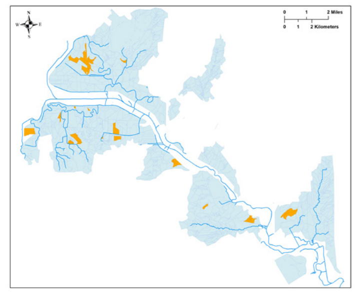
2-Year (50%)



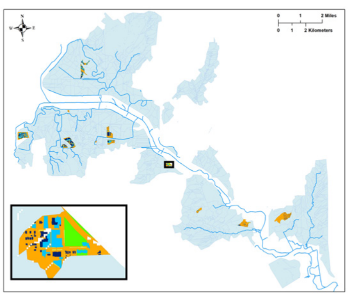
10-Year (10%)

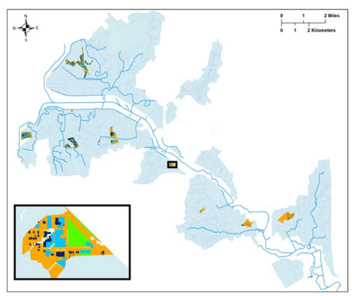


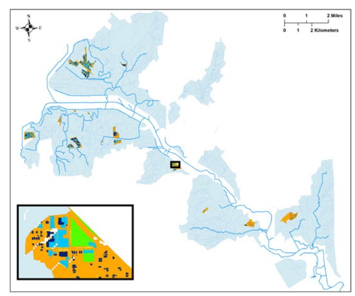
100-Year (1%)



GSI Spatial Opportunity Assessment (Maps and Table)







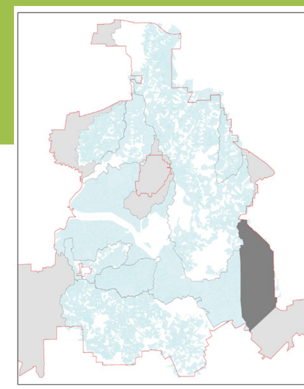
TRINITY WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	0.0 acres	0.0
		Parking lots	17.5 acres	8.4
		Parks	1.1 acres	0.5
		Planting strips	0.8 acres	0.4
		Vegetated medians	0.2 acres	0.1
		Total bioretention	19.6 acres	9.4
	RAINGARDEN	Structures	812 units	0.6
	RAINWATER CISTERN	Structures	812 units	0.6
				TOTAL 10.6

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	0.0 acres	0.0
		Parking lots	25.7 acres	12.6
		Parks	1.1 acres	0.5
		Planting strips	0.8 acres	0.4
		Vegetated medians	0.5 acres	0.2
		Total bioretention	28.1 acres	13.7
	RAINGARDEN	Structures	874 units	0.65
	RAINWATER CISTERN	Structures	874 units	0.65
				TOTAL 15.0

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	0.0 acres	0.0
		Parking lots	32.2 acres	15.8
		Parks	1.2 acres	0.6
		Planting strips	1.0 acres	0.5
		Vegetated medians	0.5 acres	0.2
		Total bioretention	34.9 acres	17.0
	RAINGARDEN	Structures	1,053 units	0.8
	RAINWATER CISTERN	Structures	1,053 units	0.8
				TOTAL 18.6

UPPER PRAIRIE WATERSHED



Very Low   Low   Intermediate   High   Very High

System Hotspots by Overflow Severity

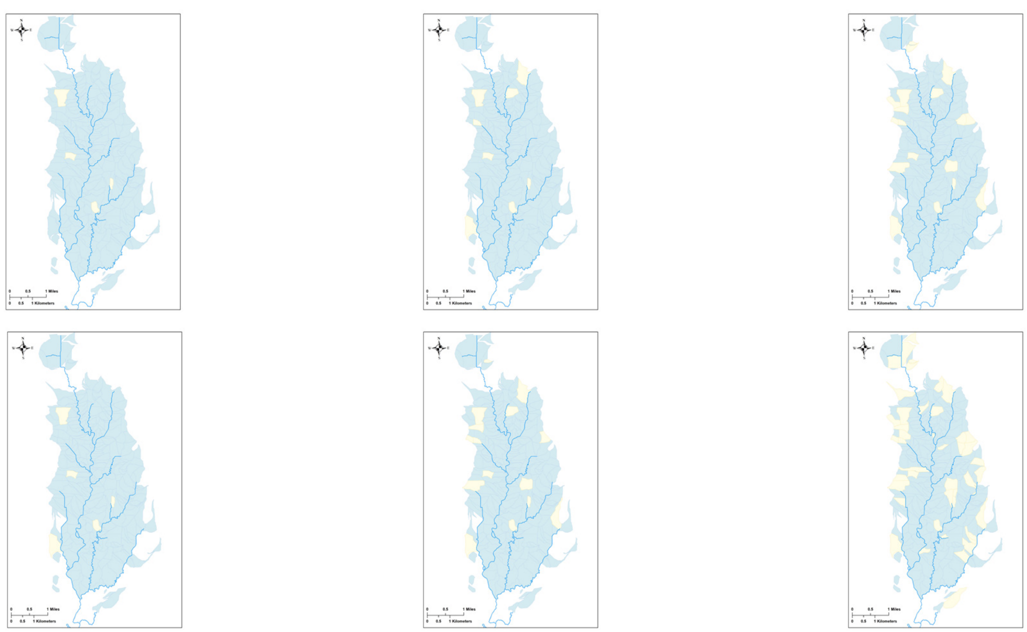
2-Year (50%)   10-Year (10%)   100-Year (1%)

Current Conditions

2045 (RCP 8.5)

Challenged Subwatersheds Classified by Overflow Severity

2-Year (50%)   10-Year (10%)   100-Year (1%)



Current Conditions

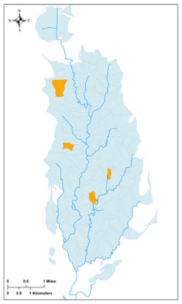
2045 (RCP 8.5)

UPPER PRAIRIE WATERSHED

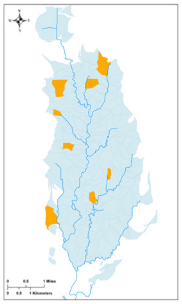
Building | Parking Lot | Planter Strip | Vegetated Median | Park | Challenged Subwatershed

Total Challenged Subwatersheds, All Classes, Current Conditions

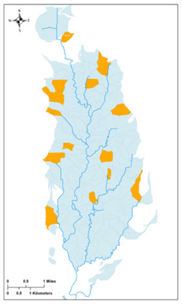
2-Year (50%)



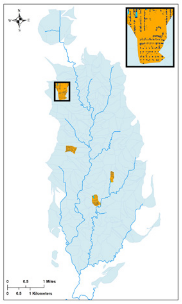
10-Year (10%)

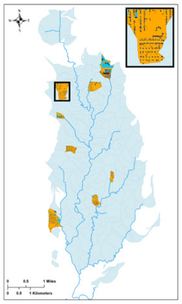


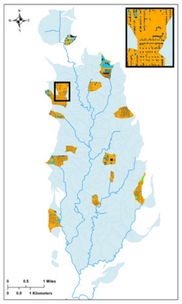
100-Year (1%)



GSI Spatial Opportunity Assessment (Maps and Table)







UPPER PRAIRIE WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	0.00 acres	0.00
		Parking lots	0.03 acres	0.01
		Parks	0.18 acres	0.09
		Planting strips	0.87 acres	0.42
		Vegetated medians	0.04 acres	0.02
		Total bioretention	1.1 acres	0.5
	RAINGARDEN	Structures	759 units	0.6
	RAINWATER CISTERN	Structures	759 units	0.6
				TOTAL 1.7

Current Conditions

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	0.1 acres	0.0
		Parking lots	0.0 acres	0.0
		Parks	4.3 acres	2.1
		Planting strips	1.3 acres	0.6
		Vegetated medians	0.2 acres	0.1
		Total bioretention	5.9 acres	2.9
	RAINGARDEN	Structures	1,405 units	1.1
	RAINWATER CISTERN	Structures	1,405 units	1.0
				TOTAL 5.0

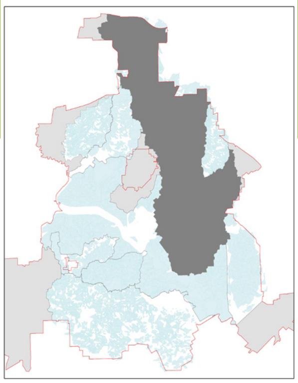
2045 (RCP 8.5)

Current Conditions

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	0.1 acres	0.0
		Parking lots	0.6 acres	0.3
		Parks	8.3 acres	4.1
		Planting strips	3.0 acres	1.5
		Vegetated medians	0.6 acres	0.3
		Total bioretention	12.6 acres	6.2
	RAINGARDEN	Structures	3,163 units	2.4
	RAINWATER CISTERN	Structures	3,163 units	2.4
				TOTAL 10.9

2045 (RCP 8.5)

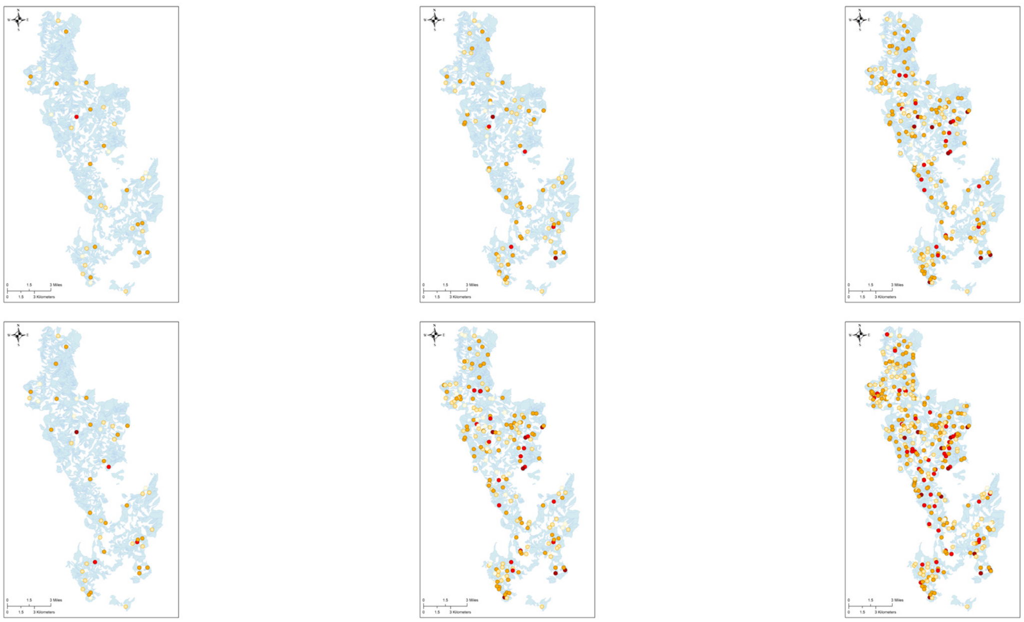
WHITE ROCK WATERSHED



Very Low   Low   Intermediate   High   Very High

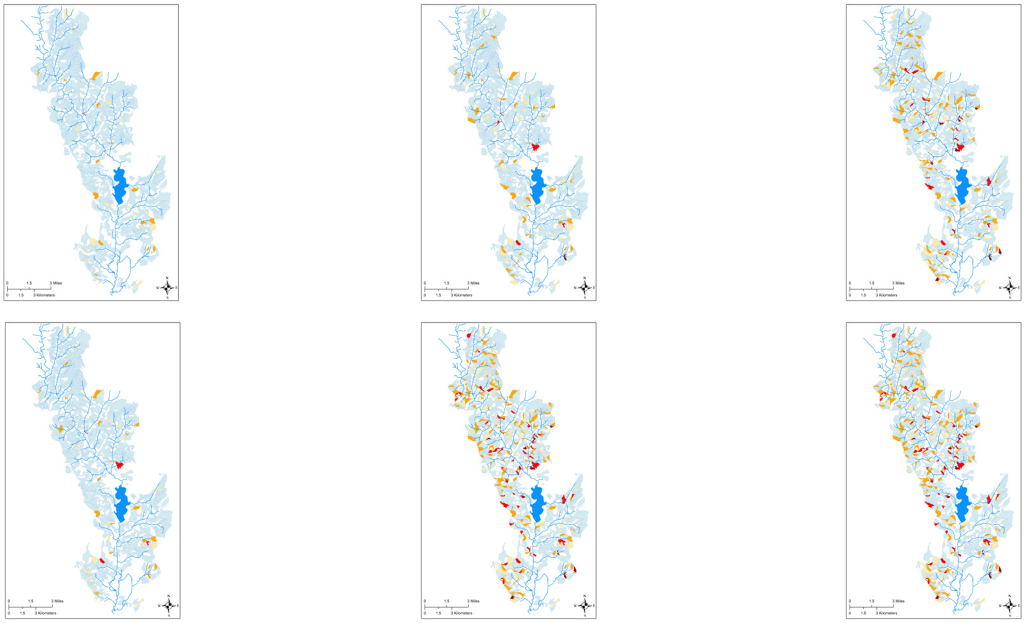
System Hotspots by Overflow Severity

2-Year (50%) | 10-Year (10%) | 100-Year (1%)



Challenged Subwatersheds Classified by Overflow Severity

2-Year (50%) | 10-Year (10%) | 100-Year (1%)

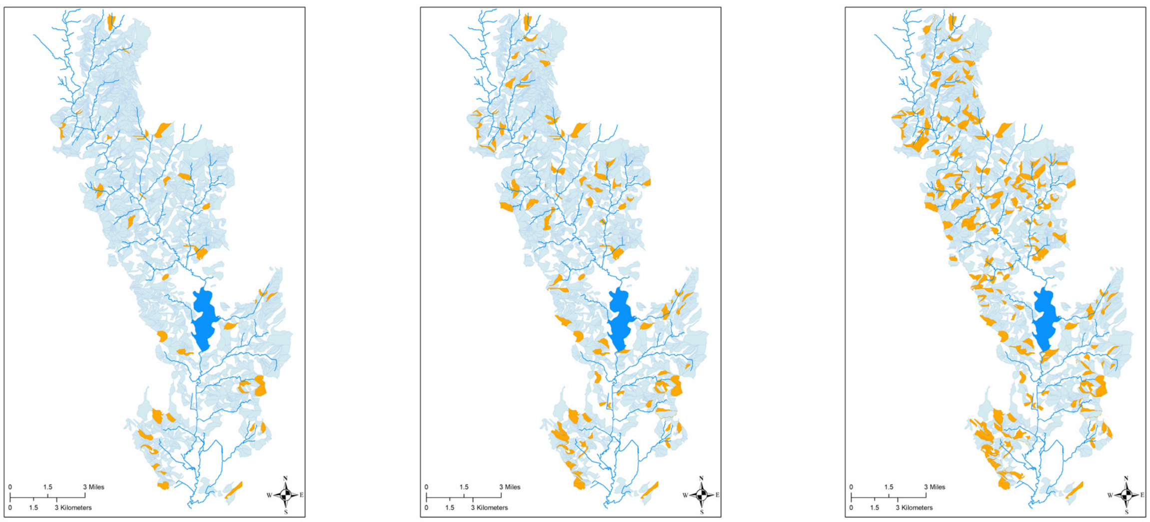


WHITE ROCK WATERSHED

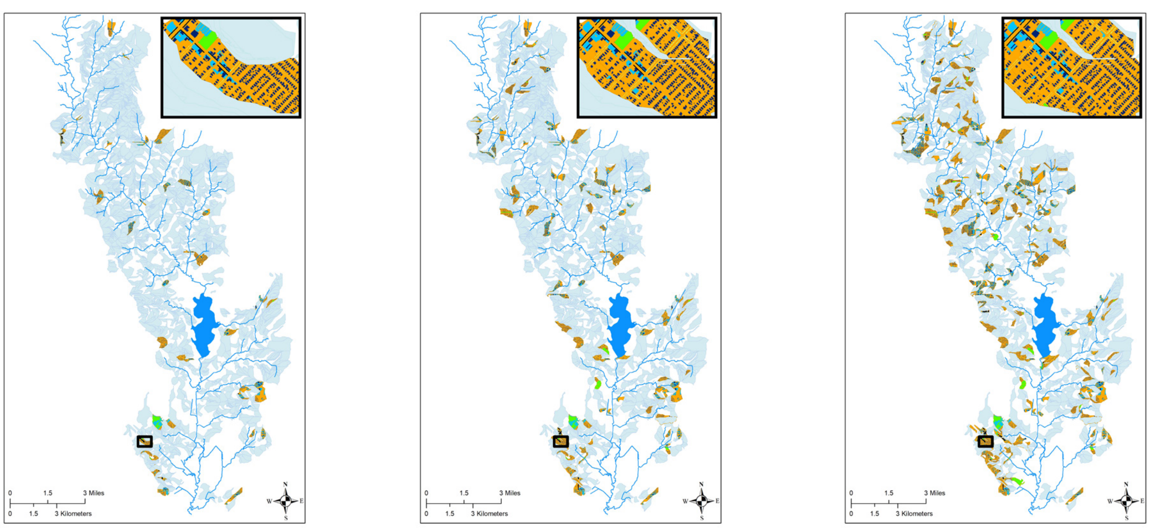
Building | Parking Lot | Planter Strip | Vegetated Median | Park | Challenged Subwatershed

Total Challenged Subwatersheds, All Classes, Current Conditions

2-Year (50%) | **10-Year (10%)** | **100-Year (1%)**



GSI Spatial Opportunity Assessment (Maps and Table)



WHITE ROCK WATERSHED

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
2-year	BIORETENTION	Commercial sidewalks	0.6 acres	0.1
		Parking lots	32.8 acres	8.2
		Parks	12.6 acres	3.5
		Planting strips	3.6 acres	0.88
		Vegetated medians	1.4 acres	0.3
		Total bioretention	51.1 acres	12.98
	RAINGARDEN	Structures	4422 units	3.26
	RAINWATER CISTERN	Structures	4422 units	3.26
				TOTAL 19.5

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
10-year	BIORETENTION	Commercial sidewalks	1.1 acres	0.5
		Parking lots	59.9 acres	20.1
		Parks	23.1 acres	8.6
		Planting strips	9.7 acres	3.4
		Vegetated medians	3.7 acres	1.2
		Total bioretention	97.5 acres	33.8
	RAINGARDEN	Structures	8962 units	6.75
	RAINWATER CISTERN	Structures	8962 units	6.75
				TOTAL 47.3

	GSI Type	Spatial Category	Available Sites	Potential Volume Capture/Event [MG]
100-year	BIORETENTION	Commercial sidewalks	1.9 acres	0.7
		Parking lots	98.1 acres	35.1
		Parks	49.4 acres	19.8
		Planting strips	17.2 acres	6.7
		Vegetated medians	8 acres	2.9
		Total bioretention	174.6 acres	65.2
	RAINGARDEN	Structures	15918 units	12.2
	RAINWATER CISTERN	Structures	15918 units	12.2
				TOTAL 89.6

Appendix 3: GSI Additional Resources

- U.S. Environmental Protection Agency. (2020). What is Green Infrastructure? Retrieved from https://www.epa.gov/green-infrastructure/what-green-infrastructure
- Naturally Resilient Communities. (n.d.). Using Nature to Address Flooding. Retrieved from http://nrcsolutions.org/
- Tarrant Regional Water District. (2018). *Planning and Implementing Stormwater Quality Practices*. Retrieved from https://www.trwd.com/wp-content/uploads/2019/04/TRWD-WQ-Guidance-Manual_June-2018-Updated-Sept.-2018-Compressed.pdf

Rainwater harvesting cistern. © Kathy Jack/ TNC

Appendix 4: GSI Costs

Bioretention Area

	Cost Cited	Cost Includes Engineering (Y/N)	Cost Includes Maintenance (Y/N)	Cost with Engineering (+20% if not included)[1]		Maintenance Annual Value	Life Cycle Maintenance Present Value (2.7% interest and 20-year life span)[2]		Annual Maintenance/ Capital Cost	Full Cost (with engineering +maintenance)		Source
LOW COST	$5.50/FT^2	N	N	$6.60/FT^2	$0.59/GAL	$0.06/FT^2	$0.92/FT^2	$0.08/GAL	0.91%	$7.52/FT^2	$0.67/GAL	(Center for Neighborhood Technology, 2021)
MEDIUM COST	$15.00/FT^2	N	N	$18.00/FT^2	$1.61/GAL	$0.12/FT^2	$1.84/FT^2	$0.16/GAL	0.67%	$19.84/FT^2	$1.77/GAL	(Center for Neighborhood Technology, 2021)
HIGH COST	$24.00/FT^2	N	N	$28.80/FT^2	$2.57/GAL	$0.21/FT^2	$3.21/FT^2	$0.29/GAL	0.73%	$32.01/FT^2	$2.86/GAL	(Center for Neighborhood Technology, 2021)
	$16.95/FT^2	Y	N	$16.95/FT^2	$1.51/GAL	$0.60/FT^2	$9.18/FT^2	$0.82/GAL	3.54%			(The Water Research Foundation, 2021)
LOW COST	$3.00/FT^2	N	N	$3.60/FT^2	$0.32/GAL							(Lake Superior Duluth Streams, n.d.)
HIGH COST	$15.00/FT^2	N	N	$18.00/FT^2	$1.61/GAL							(Lake Superior Duluth Streams, n.d.)
AVERAGE COST (SOURCES REVIEWED)				$15.33/FT^2	$1.37/GAL	$0.25/FT^2	$3.79/FT^2	$0.34/GAL		$19.1/FT^2	$1.71/GAL	
FINAL COSTS USED IN THE ANALYSIS[3]	$14.70/FT^2			$17.70/FT^2	**$1.58/GAL**	$0.14/FT^2	$2.07/FT^2	$0.18/GAL		$19.77/FT^2	**$1.76/GAL**	(Center for Neighborhood Technology, 2021)

Rainwater Harvesting Cistern

	Cost Cited	Cost Includes Engineering (Y/N)	Cost Includes Maintenance (Y/N)	Cost with Engineering (+20% if not included)[1]		Maintenance Annual Value	Life Cycle Maintenance Present Value (2.7% interest and 20-year life span)[2]		Annual Maintenance/ Capital Cost	Full Cost (with engineering +maintenance)		Source
LOW COST	$5.15/FT^2	N	N	$6.18/FT^2	$0.67/GAL	$0.31/FT^2	$4.74/FT^2	$1.28/GAL	5.02%	$10.92/FT^2	$ 3.12/GAL	(Center for Neighborhood Technology, 2021)
MEDIUM COST	$7.00/FT^2	N	N	$ 8.40/FT^2	$2.27/GAL	$0.34/FT^2	$5.20/FT^2	$1.41/GAL	4.05%	$13.60/FT^2	$3.89/GAL	(Center for Neighborhood Technology, 2021)
HIGH COST	$16.05/FT^2	N	N	$19.26/FT^2	$5.21/GAL	$0.34/FT^2	$ 5.20/FT^2	$1.41/GAL	1.77%	$24.46/FT^2	$ 6.99/GAL	(Center for Neighborhood Technology, 2021)
LOW COST	$3.00/FT^2	N	N	$3.60/FT^2	$0.97/GAL							(Raingarden Alliance, 2009)
HIGH COST	$15.00/FT^2	Y	N	$15/FT^2	$4.05/GAL							(Raingarden Alliance, 2009)
		Y	N	$18.91/FT^2	$5.11/GAL	$1.12/FT^2	$17.13/FT^2	$4.63/GAL	5.92%			(The Water Research Foundation (WRF), 2021)
AVERAGE COST (SOURCES REVIEWED)	$18.91/FT^2			$11.89/FT^2	$3.21/GAL	$0.53/FT^2	$8.07/FT^2	$2.18/GAL		$19.96/FT^2	$ 5.70/GAL	
FINAL COSTS USED IN THE ANALYSIS[3]	**$10.60/FT^2**			$12.72/FT^2	**$3.44/GAL**	$0.33/FT^2	$4.97/FT^2	**$1.34/GAL**		$17.69/FT^2	**$4.78/GAL**	(Center for Neighborhood Technology, 2021)

Rain Garden

	Cost Cited	Cost Includes Engineering (Y/N)	Cost Includes Maintenance (Y/N)	Cost with Engineering (+20% if not included)[1]		Maintenance Annual Value	Life Cycle Maintenance Present Value (2.7% interest and 20-year life span)[2]		Annual Maintenance/ Capital Cost	Full Cost (with engineering +maintenance)		Source
LOW COST	$0.61/GAL	N	N		$ 0.73/GAL	$0/GAL		$0/GAL	0.00%		$0.73/GAL	(Center for Neighborhood Technology, 2021)
MEDIUM COST	$1.45/GAL	N	N		$ 1.74/GAL	$0.07/GAL		$1.07/GAL	4.02%		$2.81/GAL	(Center for Neighborhood Technology, 2021)
HIGH COST	$2.88/GAL	N	N		$3.46/GAL	$0.07/GAL		$1.07/GAL	2.03%		$4.53/GAL	(Center for Neighborhood Technology, 2021)
	$2.97/GAL	Y	N		$2.97/GAL	$0.21/GAL		$3.21/GAL	7.07%			(The Water Research Foundation (WRF), 2021)
AVERAGE COST (SOURCES REVIEWED)					$2.22/GAL	$ 0.09/GAL		$1.34/GAL			$3.56/GAL	
FINAL COSTS USED IN THE ANALYSIS[3]	**$1.70/GAL**				**$2.09/GAL**	$ 0.04/GAL		**$0.54/GAL**			**$2.63 /GAL**	(Center for Neighborhood Technology, 2021)

[1] 20 % engineering costs are based on The Water Research Foundation (2021), and experience of consulted project developers.

[2] Life cycle maintenance costs were calculated by applying an interest rate of 2.7% (BankRate, 2021) to estimated average life cycle time of 20 years (Center for Neighborhood Technology, 2021).

[3] Final costs used were based on high and low cost ranges provided in (Center for Neighborhood Technology, 2021), and excluded the maintenance values estimated by WERF, which were substantially higher than for all other sources reviewed.

Appendix 5: Subwatersheds from the Neighborhood-Scale Sub-study, Pre- and Post GSI Analysis

Rainwater Harvesting Cistern

			Overflow volume (gal) Pre-GSI			GSI Implemented			Overflow Volume (gal) Post-GSI			Overflow Reduction (%)			Cost/gallon captured ($)		
SUB-WATERSHED	Acres	Land Use	2-year (50%)	10-year (%10)	100-year (1%)	Bioretention (ft²)	Rain gardens (ft²)	Cisterns (#)	2-year (50%)	10-year (%10)	100-year (1%)	2-year (50%)	10-year (%10)	100-year (1%)	2-year (50%)	10-year (%10)	100-year (1%)
1	15.5	RESIDENTIAL	638,582	1,109,760	1,977,669	7,569	16,800	84	0	743,617	1,739,033	100%	33%	12%	$0.57	$1.00	$1.53
2	12.1	RES/COM	497,142	861,748	1,537,860	43,597	3,800	19	178,448	421,448	1,336,513	64%	51%	13%	$2.58	$1.87	$4.09
3	4.8	RESIDENTIAL	168,984	303,407	565,389	3,488	5,200	26	0	101,734	442,005	100%	66%	22%	$0.79	$0.66	$1.08
4	21.7	PARK	NA	374,550	867,600	13,845	8,400	42	NA	0	583,380	NA	100%	33%	NA	$0.96	$1.27
5	8.0	RESIDENTIAL	NA	547,184	994,234	28,689	4,600	23	NA	0	703,102	NA	100%	29%	NA	$1.04	$1.96
6	7.4	RESIDENTIAL	NA	505,304	921,427	31,819	3,800	19	NA	170,065	482,228	NA	66%	48%	NA	$1.84	$1.40
7	26.0	RESIDENTIAL	NA	874,948	1,856,918	106,229	13,800	69	NA	0	633,799	NA	100%	66%	NA	$2.37	$1.69
8	8.0	SCHOOL	NA	524,954	966,825	28,487	1,400	7	NA	0	767,735	NA	100%	21%	NA	$1.00	$2.63
9	4.1	SCHOOL	134923	245,775	463,243	34,382	600	3	0	0	133,422	100%	100%	71%	$4.57	$2.51	$1.87
TOTAL	107.4		1,439,631	5,347,630	10,151,165	298,105	58,400	292	178,448	1,436,864	6,821,217	91%	80%	35%	$2.13	$1.47	$1.95

Scenario 2 - 50% Bioretention Areas, 25% Rainwater Cisterns, 25% Rain Gardens

			Overflow volume (gal) Pre-GSI			GSI Implemented			Overflow Volume (gal) Post-GSI			Overflow Reduction (%)			Cost/gallon captured ($)		
SUB-WATERSHED	Acres	Land Use	2-year (50%)	10-year (%10)	100-year (1%)	Bioretention (ft²)	Rain gardens (ft²)	Cisterns (#)	2-year (50%)	10-year (%10)	100-year (1%)	2-year (50%)	10-year (%10)	100-year (1%)	2-year (50%)	10-year (%10)	100-year (1%)
1	15.5	RESIDENTIAL	638,582	1,109,760	1,977,669	3,785	4,200	21	579,524	893,488	1,923,321	9%	19%	3%	$2.11	$0.58	$2.29
2	12.1	RES/COM	497,142	861,748	1,537,860	21,799	950	5	283,645	706,372	1,385,883	43%	18%	10%	$1.87	$2.57	$2.62
3	4.8	RESIDENTIAL	168,984	303,407	565,389	1,744	1,300	7	0	206,360	545,487	100%	32%	4%	$0.29	$0.50	$2.45
4	21.7	PARK	NA	374,550	867,600	6,923	2,100	11	NA	0	762,189	NA	100%	12%	NA	$0.40	$1.44
5	8.0	RESIDENTIAL	NA	547,184	994,234	14,345	1,150	6	NA	478688.56	882,065	NA	13%	11%	NA	$3.94	$2.40
6	7.4	RESIDENTIAL	NA	505,304	921,427	15,909	950	5	NA	250227.72	615,823	NA	50%	33%	NA	$1.16	$0.96
7	26.0	RESIDENTIAL	NA	874,948	1,856,918	53,114	3,450	17	NA	667413.53	1,223,743	NA	24%	34%	NA	$4.76	$1.56
8	8.0	SCHOOL	NA	524,954	966,825	14,244	350	2	NA	0	867,523	NA	100%	10%	NA	$0.49	$2.59
9	4.1	SCHOOL	134923	245,775	463,243	17,191	150	1	0	115930.55	291,096	100%	53%	37%	$2.27	$2.36	$1.78
TOTAL	107.4		1,439,631	5,347,630	10,151,165	149,052	14,600	73	863,169	3,318,480	8,497,131	63%	45%	17%	$1.63	$1.86	$2.01

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