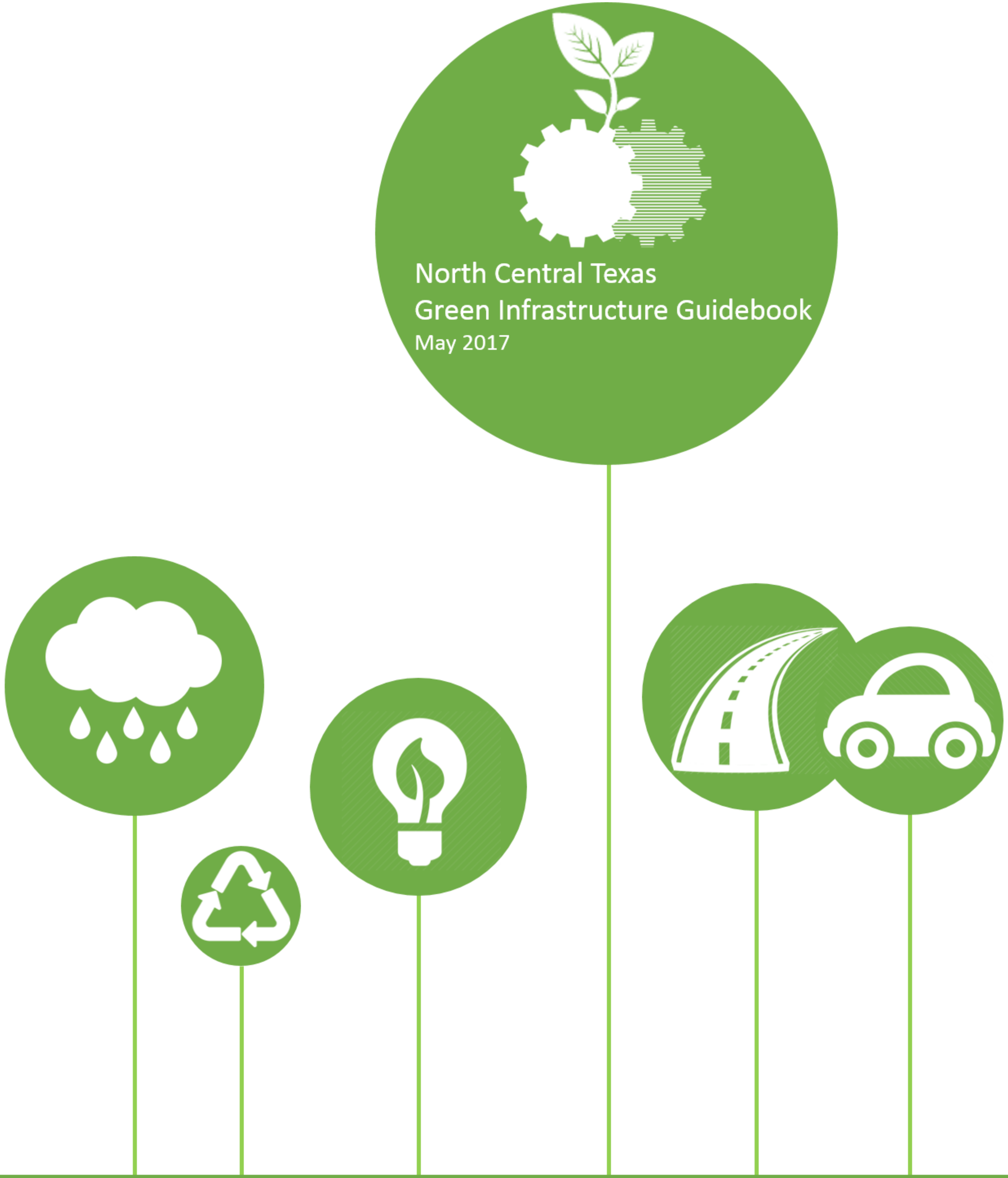

North Central Texas Green Infrastructure Guidebook

May 2017

North Central Texas
Council of Governments

What is NCTCOG?
The North Central Texas Council of Governments is a voluntary association of cities, counties, school districts, and special districts which was established in January 1966 to assist local governments in **planning** for common needs, **cooperating** for mutual benefit, and **coordinating** for sound regional development.

It serves a 16-county metropolitan region centered around the two urban centers of Dallas and Fort Worth. Currently the Council has **238 members**, including 16 counties, 169 cities, 22 independent school districts, and 31 special districts. The area of the region is approximately **12,800 square miles**, which is larger than nine states, and the population of the region is over **6.5 million**, which is larger than 38 states.

NCTCOG's structure is relatively simple; each member government appoints a voting representative from the governing body. These voting representatives make up the **General Assembly** which annually elects a 15-member Executive Board. The **Executive Board** is supported by policy development, technical advisory, and study committees, as well as a professional staff of 324.

NCTCOG's offices are located in Arlington in the Centerpoint Two Building at 616 Six Flags Drive (approximately one-half mile south of the main entrance to Six Flags Over Texas).

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North Central Texas Green Infrastructure Guidebook, May 2017

Abstract: The North Central Texas Council of Governments (NCTCOG) created this guide to aid city engineers, planners, developers, decision-makers, and other transportation and development professionals in assessing their choices when integrating green infrastructure practices into roadway, sidewalk, parking lot, and trail projects. The guide focuses on green infrastructure techniques relevant to the transportation industry. These include permeable pavement and bioretention as well as sustainable choices such as the use of recycled materials and energy-efficient lighting. As a foundation for this guide, NCTCOG examined both in-region and out-of-region case studies to provide real-world costs, maintenance requirements, lessons learned, and the project's economic, environmental, and social benefits.

This guide supports the work that NCTCOG and its regional partners undertake in existing programs such as the Sustainable Development Funding Program, which addresses air quality, congestion, and quality-of-life issues; the Green Initiatives Program, which promotes the use of green or sustainable infrastructure to aid in the reduction of carbon emissions, urban heat islands, and stormwater runoff; the Regional Stormwater Management Program, which aims to manage stormwater quality issues affecting the region; the *integrated* Stormwater Management (iSWM™) and Transportation *integrated* Stormwater Management (TriSWM™), which assist cities and counties in achieving their goals of water quality protection, streambank protection, and flood control; and Texas SmartScape, an educational program with the goal of conserving local water supplies and improving stormwater runoff quality .

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INTRODUCTION

Why This Guide Was Developed

The North Central Texas Council of Governments (NCTCOG) created this guide to aid city engineers, planners, developers, decision-makers, and other transportation and development professionals in assessing their choices when integrating green infrastructure practices into roadway, sidewalk, parking lot, and trail projects. The information in this guide may complement Complete Streets policies and practices, which aim to enable safe access for all users, regardless of age, ability, or transportation mode.

This guide focuses on the following transportation-relevant green infrastructure elements:

- Energy-efficient light-emitting diode (LED) and renewable-energy lighting
- Recycled construction materials in roadways and trails
- Cool pavements
- Green trail materials
- Green stormwater infrastructure (GSI) techniques such as permeable pavement and bioretention, and structural support for trees

By examining the costs and benefits of green infrastructure practices, the guide aims to provide key information for making sound decisions related to the following factors:

- Long-term cost effectiveness
- Community improvement
- Environmental impacts

While this guide will help provide a foundation for assessing these green techniques and practices, professionals will still need to evaluate their particular developments and infrastructure requirements to determine the most effective approach.

Guidance and technologies may evolve over time. This guide is not meant to be a how-to manual. It does not prescribe one method or proprietary brand over another. It neither ventures into design (such as road-width requirements or clustering development) nor attempts to include every best practice.

How This Guide Was Developed

In the development of this guide, NCTCOG reviewed current research and literature related to the topics in the guide. To present a more comprehensive picture of real-world costs and benefits, NCTCOG also gathered and analyzed information from case studies, including projects both in the region and across the nation. The list of case studies along with a map of their locations can be found in Appendix A.

The case study contacts provided information as responses to a questionnaire. A list of the case study contacts and a copy of the questionnaire are available in Appendix A. Some case studies furnished NCTCOG with project literature and articles as additional resources, which are also listed in Appendix A. When necessary, further information was collected by NCTCOG via personal communication. Case studies are denoted in the guide's text with brackets and their case study number, such as "[CS 2]," at their first reference in each section.

The Need for Green Infrastructure

Our region is developing rapidly. According to recent U.S. Census Bureau estimates, the Dallas-Fort Worth-Arlington metropolitan area added more residents than almost anywhere else in the nation (more than 131,000 people from July 1, 2013, to July 1, 2014), behind only Houston-The Woodlands-Sugar Land, as reported by the *Dallas Morning News* April 2015 article "Houston Area and Dallas-Fort Worth Top Nation's Fastest-Growth List." This growth is expected to continue. According to NCTCOG's 2040 Demographic Forecast, the Dallas-Fort Worth Metropolitan Planning Area can expect to almost double its number of residents and jobs from 2010 to 2040.

While this expected growth may be beneficial in many ways, the development required to accommodate this growth will impact the region's already challenged roadways and waterways. Development can deplete natural resources, create urban heat islands (UHIs), decrease air quality, and generate additional stormwater runoff, which leads to an increase in flooding, erosion and sedimentation, and water pollution. For more details on the expected growth and its impacts, see Appendix B.

However, the use of sustainable green elements—either integrated with or in place of gray infrastructure—can help the region cope with some of these challenges. While the expected growth will bring more development, including new and retrofitted transportation infrastructure, it will also bring the opportunity to move toward sustainable green choices.

Potential Benefits of Green Infrastructure

Incorporating green approaches can provide substantial social, economic, and environmental benefits. According to research conducted by the Center for Neighborhood Technology (CNT), the U.S. Environmental Protection Agency, ECONorthwest, and NCTCOG, the use of green features can:

- **Reduce costs.** Green practices are not always more expensive than traditional practices. If initial costs for green practices are higher, these costs may be offset by long-term benefits. For example, the higher construction costs of installing modular structures that reduce soil compaction and support large tree growth may provide for a substantially increased tree lifespan and decreased maintenance costs. Green practices can also cost less than traditional practices initially (for example, when GSI averts the costs of traditional stormwater management), or they may reduce costs in other ways (such as reducing the costs of irrigation with drought-adapted plants). Costs and benefits will depend on unique factors such as soil type, hydrology, availability of items, and so on.

Costs are also affected by circumstances such as the bid environment, and whether the green product is new—and thus perhaps expensive or challenging to find. An overview of challenges related to cost analysis can be found in Appendix C.

- **Reduce urban heat stress.** Green transportation practices such as expanded tree planting and conservation as well as cool and permeable paving applications can help lessen the urban heat island effect by cooling and shading urban neighborhoods.
- **Improve air quality.** Urban vegetation removes pollutants from the air. Green practices that reduce temperatures can mitigate smog and ozone formation.
- **Increase pedestrian safety and improve public health.** GSI techniques such as introducing curves and reducing street widths can slow traffic. Pedestrian-friendly landscapes can promote physical activity. Cooler temperatures and cleaner air can also dramatically improve health for children and the elderly.
- **Reduce consumption of energy resources.** By using precipitation where it falls, the energy required to import, treat, and distribute municipal water could be significantly decreased. The use of cool pavements and increased tree canopy could also decrease energy use. Implementing energy-efficient light fixtures may save money in the long term. With solar panels, the region can harness renewable resources.
- **Reduce erosion and the risk of flash floods.** Increasing infiltration, evapotranspiration, and storage of rainwater close to where it falls will reduce runoff and flooding.
- **Improve water quality.** Vegetation, natural drainage, and other green infrastructure practices can decrease pollutant loads by treating water that would otherwise run off.
- **Increase groundwater recharge.** When transportation projects incorporate GSI such as permeable pavement and rain gardens, impervious cover is reduced. Much of the rainwater that falls on our roadway surfaces and parking lots could infiltrate soil, reducing localized flooding and recharging groundwater. Although many GSI practices were first developed in temperate regions, their potential to help conserve water may be even more relevant in arid and semi-arid climates, according to the 2010 EPA report "Green Infrastructure in Arid and Semi-Arid Climates: Adapting Innovative Stormwater Management Techniques to the Water-Limited West."
- **Reduce waste and reduce consumption of natural resources.** Constructing roadway projects with recycled materials can reduce the amount of construction and industrial waste in landfills and also reduce the region's consumption of natural resources.
- **Improve aesthetics and build communities.** Landscaping can beautify neighborhoods, which can create a unique sense of space and promote neighborhood interaction. It can also provide wildlife habitat.
- **Create the potential for economic development.** Improved aesthetics can potentially increase economic development, and an increase in property values in a floodplain may result from on-site management of stormwater.

GREEN ELEMENTS

Top left: Pervious pavers used at South Main reconstruction parking lot, Carrollton, Texas (source: Studio39). Top right: Biofiltering street at the Dallas Urban Reserve, Dallas, Texas (source: Kevin Sloan Studio). Bottom left: LED streetlight fixture in the Oncor pilot, Dallas-Fort Worth Metroplex, Texas (source: Oncor). Bottom right: Recycled rubber path on the Katy Trail, Dallas, Texas.

Topics	What's Covered
• **Energy-efficient and renewable-energy lighting** • **Recycled construction materials** • **Cool pavements** • **Trail materials** • **Green stormwater infrastructure: permeable pavement, bioretention and infiltration practices, and structural support for trees**	• **Overview** • **Potential benefits** • **Limitations/considerations** • **Costs and life expectancy**

SECTION 1: Energy-Efficient and Renewable-Energy Lighting

1.1 Background

Before discussing energy-efficient and renewable-energy lighting, it is useful to provide some background on energy needs and wastage, or inefficient use of energy.

The Texas Comptroller of Public Accounts' 2008 *Energy Report* states that Texas consumes more energy than any other state due to its heavy industrial base, hot climate, and large population. As Texas's population has increased, so too has its demand for electricity. Both population and energy demand are projected to continue their strong growth in the future.

Doing more with less seems both feasible and affordable as demand for power rapidly increases, energy prices rise, and awareness of environmental and energy security concerns increases, the report continues. According to the U.S. Department of Energy (DOE), much of the energy that the United States currently consumes is wasted through transmission, heat loss, and inefficient technology, resulting in unnecessary energy spending and increased air pollution.

Increasing the use of reliable, energy-efficient technologies and renewable energy provides opportunities for the North Central Texas region to continue to grow and support a robust economy more effectively.

1.2 Energy-Efficient Lighting: Light-Emitting Diodes (LEDs)

1.2.1 Overview

What is energy efficiency? The International Energy Agency (IEA) defines energy efficiency as "a way of managing and restraining the growth in energy consumption." If a product or technology delivers either more service for the same energy input or the same service for less energy input, it is energy efficient.

In recent years, many energy-efficiency lighting programs have moved away from conventional technologies and toward light-emitting diodes (LEDs). The North Central Texas region has shown interest in LEDs for several years. A few examples are included below:

- A decade ago, the region's transportation policy body of the Metropolitan Planning Organization began work on a regional plan to convert existing traffic signals to light-emitting diode (LED) lamps in the North Central Texas Ozone Nonattainment Area. It achieved its goal of 90% deployment by May 2006.
- In 2009, the Town of Fairview joined the Cree LED City® initiative, installing 82 LED streetlights on its Fairview Parkway in an effort to reduce maintenance costs, improve safety, reduce light pollution, and reduce energy consumption.
- In 2010, Oncor's LED Streetlight Pilot and Technical Evaluation program [CS 10] was implemented to assess the ability of various LED streetlights to function in the unique weather conditions of North Central Texas. More than 500 LED streetlights from various

manufacturers were installed in Cedar Hill, Dallas, Grand Prairie (see Figure 1), North Richland Hills, and Plano. The program was then expanded in 2011 to include Colleyville, using LED post tops.

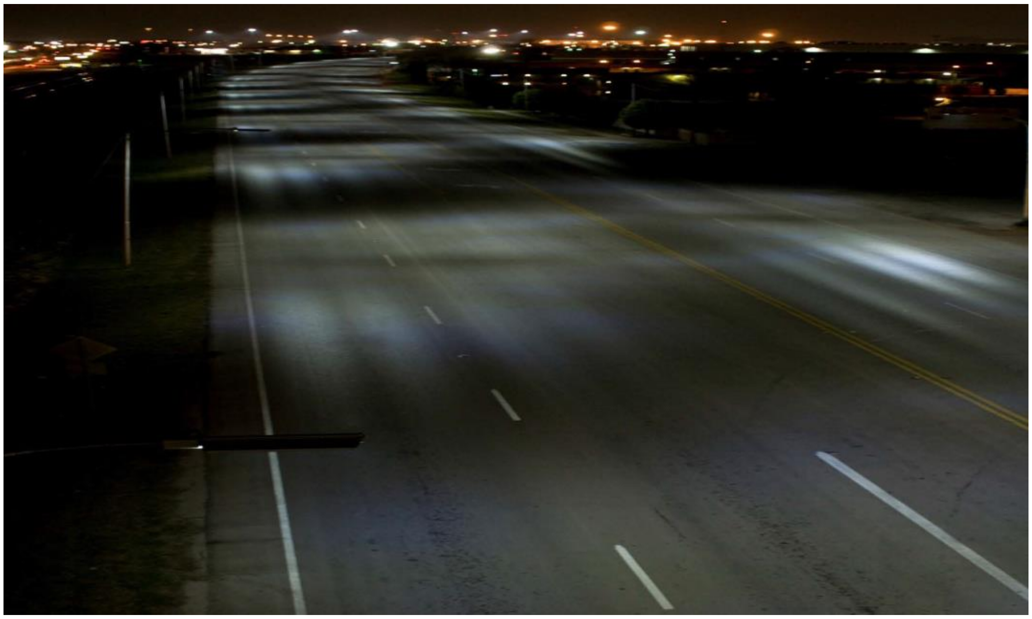


Figure 1. Main Street, Grand Prairie, after LED installation.
Source: Oncor, 2012.

As seen in the below chart (Figure 2), LED technology (bottom blue bar) possesses great efficiency potential.

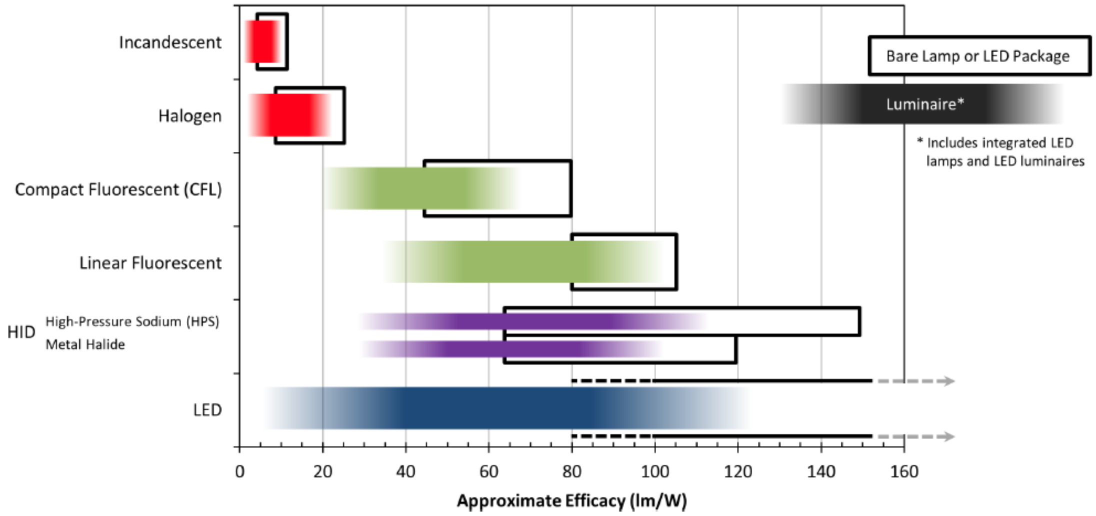


Figure 2. Approximate Range of Efficiency of Common Light Sources.
Source: U.S. Department of Energy, 2013.

The DOE's Office of Energy Efficiency and Renewable Energy reports that while solid-state lighting products such as LEDs cannot yet compete with their conventional counterparts on a first-cost basis, other features including their directional output and long lifetime have proved attractive enough to make them competitive in applications such as streetlights and parking lots.

In recent years, the switch to LED streetlights has become increasingly widespread. With a sizable installation that may have helped reduce costs and improve technology, the City of Los Angeles replaced more than 140,000 streetlight fixtures with LED units and a remote monitoring system over a four-year period that began in February 2009. In July 2009, Fairview became the first town in Texas to have a street lit entirely by LED streetlights, according to a Cree press release. Starting in 2010, several cities in the Dallas-Fort Worth Metroplex area participated in an LED pilot program with Oncor, installing 540 streetlights. That same year in another part of the country, the Mid-America Regional Council (MARC) began the Smart Lights for Smart Cities initiative, installing more than 5,700 streetlights with high-efficiency technologies—mostly LED—in 25 Kansas City area communities, a 2013 MARC report noted. According to a *Forbes* article, the City of Las Vegas outfitted more than 40,000 streetlights with LED fixtures in March 2013, and a month later, the City of Austin announced it would install 35,000 LED streetlights.

1.2.2 Potential Benefits

According to the Environmental Protection Agency (EPA), improving energy efficiency is a prime constructive and cost-effective way to deal with high energy prices, energy security, air pollution, and climate change.

The EPA and IEA report that improving energy efficiency can:

- Improve air quality by reducing greenhouse gas emissions and other pollutants
- Reduce costs, both when compared to investing in new generation and transmission lines as well as when considering products' energy savings compared to conventional products

According to the DOE, LED lighting in parking lots and structures are competitive with their conventional counterparts, even exceeding light output and efficacy levels and displaying more uniform light distribution. They can also be competitive on a lifecycle cost basis.

For streetlight applications, there have been mixed results. The City of Los Angeles's 2013 presentation has "trust but verify" as the first bulleted item in its Lessons Learned slide. However,

Figure 3. Sixth Street Bridge in Los Angeles before (left) and after (right) the LED streetlight installation.
Source: City of Los Angeles's Bureau of Street Lighting, 2013.

despite that warning, Los Angeles has seen electricity savings of over 63% compared to high-pressure sodium (HPS) units—more than its planners had estimated.

The potential benefits of using LEDs in parking lots, parking structures, and streetlight fixtures include:

- **Energy savings and cost effectiveness.** According to a Landscape Architecture case study on Klyde Warren Park in Dallas, Texas, the park's high-efficiency LED lighting system saves approximately 94,000 kilowatts of electricity every year compared to traditional lighting. Projected savings are more than $11,000 each year. Pleasant Hill, Mo., a participant in the Smart Lights initiative, saw average daily energy usage decrease 37.7% from 2012 to 2013, with costs dropping 41.8% over the same period. The City of Los Angeles's August 1, 2014 report on its LED energy efficiency program showed 63% energy savings, saving 91.93 gigawatt hours (GWh) and $8,179,167 annually. This is accompanied by an annual CO_2 reduction of 54,368 metric tons. Las Vegas's city officials also reported exceeding projected savings in its streetlight project. Las Vegas's chief sustainability officer said in a Sustainable City Network article that streetlights are approximately one-third of the city's total energy spending, and that they expect to cut that in half with this project. The city expects to save $2 million in energy and maintenance savings with a return on investment of seven to eight years.
- **Reduction of ozone precursor pollutants**. A reduction of pollutants emitted from the region's electric power generator plants could result in improved public health.
- **Potential reduction in crime.** Los Angeles's Bureau of Street Lighting (BSL) reported a 10.5% reduction of citywide crime from 2009 to 2011 in the hours from 7 p.m. to 7 a.m.
- **Decreased light pollution.** Los Angeles's LED light installation (see Figure 3) received positive comments from the Dark Skies Association for the reduced sky glow and light pollution, according to a statement from the BSL director.
- **Ease of installation and operation.** The City of Los Angeles also found that LED units are smaller and lighter, so they are easy to install and transport; other LED advantages cited are their compatibility with remote monitoring systems, the option of dimmable drivers, and instant on and off operation.

However, buyers must be aware that LEDs are still a relatively new technology. The DOE's Office of Energy Efficiency and Renewable Energy advises potential purchasers to do their homework when comparing LED and conventional lighting. Yet the newness of LED products also means that there is the potential for much more improvement in energy efficiency and savings as well as a decrease in initial cost. See the following sections for more information on known limitations and additional considerations.

1.2.3 Limitations/Considerations

- **The lack of an approved LED streetlight tariff.** The largest regulated electric transmission and distribution service provider for the North Central Texas region is Oncor Electric Delivery. There is currently not an approved LED streetlight tariff that allows Oncor to offer LED streetlights to municipalities within their service territory. Oncor remains committed to testing and evaluating the latest advancements in streetlight technology through their LED Pilot and Technical Evaluation Program while an LED tariff is pursued; however, until a rate is approved by the Public Utility Commission of Texas, cities and municipalities interested in LED streetlights would have to install and maintain the streetlights separate from Oncor.

- **The variance and rapid changes that come with immature technologies.** In a March 2013 fact sheet, the DOE underlined two important issues related to LED products: they vary and change rapidly. LED products are not a mature technology although LED efficiency has improved steadily over time. That improvement is expected to continue based on new materials, new configurations, and better manufacturing processes.

  However, the 2013 *Forbes* article by Justin Gerdes, "Los Angeles Completes World's Largest LED Street Light Retrofit," pointed out that due to its size and influence, Los Angeles and its partners, the Clinton Climate Initiative and C40 Cities Climate Leadership Group, have done much to jump-start the market. This may mean that technology will quickly become more consistent, but this is still to be determined.

- **The many factors that need to be considered, from installation geometry and local ordinances to LED warranties.** Currently, the DOE indicates that LED lighting is competitive in parking lot applications, but it lists several factors that buyers should consider. These include installation geometry, local ordinances, and lighting levels.

  For streetlights, the DOE advises that municipalities keep in mind the technology's wide range in performance; some luminaries do not live up to manufacturer claims. This advice was echoed by the Town of Fairview's Public Works Manager when relaying the Town's experience. Fairview also had issues with the warranty from their LED manufacturer, who went out of business. Furthermore, the DOE mentions difficulties in finding an exact match for existing high-intensity discharge (HID) luminaries.

  In addition, the DOE advises that purchasers should consider not only energy efficiency but also other factors such as operating life and lumen depreciation, expected lifetime, and light output and distribution. Light output might also change over time, especially if light maintenance does not include cleaning. As mentioned in the Oncor LED Streetlight Pilot and Technical Evaluation Program case study, light output can degrade significantly (up to 11.66%) with dirt.

- **The question of how LEDs perform in severe weather.** The Oncor pilot program aimed to answer this question. Looking at six different manufacturers at the first set of pilot locations (excluding Colleyville), the Oncor program assessed the performance of the LED lights by season (see Table 1).

Table 1. Oncor Dallas-Fort Worth Pilot Summary – Number of Failures by Season.

Months/Season	Number of Failures
March-May (Spring)	17
June-August (Summer)	4
September-November (Fall)	15
December-February (Winter)	7
Total	**43**

Source: Oncor LED Streetlight Pilot and Technical Evaluation Case Study, 2012.

The 43 failed fixtures equate to an 8.53% LED failure rate; the HPS failure rate for the same time period was 7.25%. Yet, while the pilot's LED installations were not quite as reliable as HPS lights, the difference is not substantial. In addition, pilot cities responded favorably to the lights and said they would like LEDs as an option once a suitable price point is reached, according to Oncor's pilot survey.

- **The learning curve.** For example, some LEDs may fail because their heat tolerance is less than traditional lighting. This may have been the case with an LED installation at the Green at College Park (University of Texas – Arlington) [CS 1], according to the project case study contact. While the LED lights on poles have not had any issues, the LEDs in ballast boxes were burning out. Improving the ventilation appeared to have resolved the issue.

  To accelerate the learning curve, the DOE created the DOE Municipal Solid-State Lighting Consortium, where members can share technical information and experience related to LED street and area lighting demonstrations. The goal is to build a repository of valuable field knowledge and data so that the consortium can serve as an objective resource. (For more information on the consortium, visit www1.eere.energy.gov/buildings/ssl/consortium.html.)

1.2.4 Costs and Life Expectancy

The following table (Table 2) from the DOE is not transportation-specific, but it serves to show that prices for LED lamps are significantly higher than conventional lighting sources.

Table 2. Prices of Lighting Sources, 2014.

Lighting Source	Price ($/klm)
Halogen Lamp (A19 43W; 750 lumens)	$2.50
CFL (13W; 800 lumens)	$2
CFL (13W; 800 lumens, dimmable)	$10
Fluorescent Lamp and Ballast System (F32T8)	$4
LED Lamp (A19 12W; 800 lumens, dimmable)	$16
CFL 6” Downlight (13W; T4; ~500 lumens)	$10
LED 6” Downlight (11.5W; 625 lumens)	$43
OLED Panel	$500
OLED Luminaire	$1,400

Source: U.S. Department of Energy, Solid-State Lighting Research and Development: Multi-Year Program Plan. 2014.

However, Table 2 shows only initial cost. The DOE analysis revealed that an LED lamp reaches cost parity with a halogen lamp after only 1,700 hours and that utility rebates lowered LED lamp costs even further.

In addition, increased deployment has improved the product while driving down costs. The Los Angeles BSL found that an LED street fixture installed in 2009 cost $432 on average, illuminated at 42 lumens/watt, was expected to last 80,000 hours, and had a 5-year warranty. In 2012, that same fixture cost $245 on average, illuminated at 81 Lm/W, was expected to last at least 150,000 hours, and came with a 7-year warranty.

The BSL estimates that the switch to LED streetlights has provided the City with energy savings of 63% as of October 1, 2014. Demonstrating that efficiency improvements can be considered investments, the June 2013 presentation reported that the program has saved approximately $7 million per year in energy savings and $2.5 million per year in maintenance savings.

While utilization of LED streetlights in the North Central Texas region may be limited for now due to the lack of an approved tariff for LED streetlights from Oncor, LEDs are a technology to watch. According to the 2014 DOE Solid-State Lighting Research and Development report, “LEDs have not even begun to scratch the surface of their potential [in energy savings and annual energy cost savings].”

Another lighting option is LEDs paired with solar panels. See the following Renewable-Energy Lighting section for more information.

1.3 Renewable-Energy Lighting: Solar

1.3.1 Overview

Another emerging interest in North Central Texas is solar power, a renewable energy. The sun produces immense amounts of energy that can be converted into heat and electricity. According to the Texas Comptroller of Public Accounts' 2008 *Energy Report,* Texas possesses the largest solar energy resources among the states due to its large geographic area and abundant sunshine. When renewables are used in place of fossil fuels, they have great potential in reducing greenhouse gas emissions, the EPA reports.

Solar energy technology is used on both large and small scales, from solar farms to road maintenance signs. One potential advantage of a small-scale solar energy system is that it may eliminate the need to connect to the electric grid if it includes storage such as a battery system, which provides additional benefits in emergency preparedness and natural disaster response.

For streetlights, solar energy technologies can be paired with LEDs because LEDs draw a fraction of the energy required by traditional lights. As noted in *LEDs Magazine*'s article "The Case for Solar-Powered LED Lighting," the technology of solar cells, LED lighting, and energy storage is rapidly developing, creating great potential for solar LED lighting.

One early adopter was Lockheed Martin in 2009. After an assessment of its Orlando, Fla., facility revealed that its 25-year-old streetlights and their underground wiring needed replacement, the company chose the stand-alone solar LED lighting as the cost-effective—as well as environmentally friendly and practical—choice to light its entrance roadway and the facility's main loop road.

Another entity that saw the potential of solar LED streetlights years ago was the City of Irving, Texas (Figure 4). In 2011, it completed its installation of 170 solar-powered LED streetlights along a 5.5-mile stretch of Irving Boulevard from State Highway 183 to Loop 12, replacing 266 grid-connected streetlights.

Figure 4. The City of Irving's solar streetlight.
Source: City of Irving.

Because solar energy does not require tie-in to the electric grid and solar panels can be quite small, solar LED lighting can also be used to light trails and bike paths as seen in demonstration projects in Pflugerville, Texas; Philadelphia, Pa. (Figure 5) [CS 35]; Santa Barbara, Calif. (Figure 6) [CS 24]; and Portland, Ore. (Figure 7) [CS 26].

Figure 5. Solar lighting installation on Penn Street Trail, Philadelphia, Pa.
Source: Delaware River Waterfront Corporation.

Figure 7. LED-Mark Light Demonstration Project, Portland, Ore.
Source: Saris Cycling Group.

Figure 6. Solar lighting used in the Obern Trail Retrofit Project, Santa Barbara, Calif.
Source: County of Santa Barbara.

1.3.2 Potential Benefits

- **Cost savings.** According to the IC² Institute, a research unit of The University of Texas at Austin that works to advance the theory and practice of entrepreneurial wealth creation, the cost savings of solar LED lighting can be substantial. These savings come from the value of fossil fuel price hedging as well as avoided generation capacity capital costs, fuel costs, and distribution costs. As seen in a case study of the Lockheed Martin facility, the lack of required underground wiring can save substantial capital cost. Using an energy management system and 35 systems with solar LED streetlights that each illuminated a 125-foot stretch of roadway, the projected initial cost and maintenance savings of solar versus hard wire was $221,000 over 20 years.
- **Energy savings.** The City of Irving expects to save an estimated $1 million in energy costs over the next 10 years.
- **Improved air quality**. Fossil fuel power generation is decreased, reducing emissions that contribute to the region's air pollution and ozone nonattainment status.
- **Increased public safety for areas where solar lights may be the most feasible protective measure.** For example, the LED-Mark Light Demonstration Project in Portland, Ore., an in-road solar LED lighting installation on a curved road visible from a distance of 1,000 meters is intended to steer drivers away from the bike lane. The case study reported that non-solar-powered in-road lights were unfeasible due to installation cost. The Santa Barbara, Calif., installation on a bike path also highlighted improved safety as a benefit due to bright lights and high visibility.
- **Installation flexibility.** The small size of panels and lack of required underground wiring may offer installation flexibility. According the City of Pflugerville, the panels' small size made relocation easy when necessary. The *Forbes* article "When (and Where) Solar LED Lighting Makes Sense" highlights several projects that used solar lighting where there was little or no existing lighting infrastructure: a residential development that added 21 lighting poles after the other utilities had already been buried; an arboretum that could not install grid-tied lights due to concerns over root systems; and a business that wanted to add nighttime events quickly while avoiding major construction.
- **Autonomy from an electric company.** The Santa Barbara, Calif., case study highlighted the autonomy that a standalone solar installation gives to the local agency, with no need to rely on an electric company for maintenance.
- **Resiliency in emergency situations.** Solar streetlights can operate during power outages and can be valuable additions to hazard mitigation action plans and other emergency response plans.
- **Continued innovation and improvements.** According to the *LEDs Magazine* article, companies in this industry are just scratching the surface of opportunities. The article's author sees quantum leaps in the development of LED lighting, solar cells, and energy storage already underway, and says that with every advancement, benefits multiply through the system.

1.3.3 Limitations/Considerations

- **The intermittent source of energy (the sun), which may lead to a need for batteries or grid connection.** The *LEDs Magazine* article "The Case for Solar-Powered LED Lighting" stated that solar LED lighting installations will need batteries unless connected to the grid. The article advised that solar panels and batteries be adequately sized for the period of longest nights, shortest days, and cloudiest weather. The City of Irving's solar fixtures were expected to retain about four to five days of power so they can produce light even on cloudy days, reported *Dallas Morning News*.

- **The importance of the surroundings, both present and future.** Solar panels need the sun's energy to work. If the lights are placed in the shade of a tree or tall building, they could produce inadequate light. Another consideration is the future environment because trees grow and building heights change. This concern may be mitigated by the ability to move the light if it is a standalone installation.

- **The need for caution and research with emerging technologies.** The DOE's advice to be cautious about LEDs also applies to solar and LED lighting. The Santa Barbara, Calif., case study highlighted the need to do research and to procure materials from reputable companies likely to exist for the product's expected lifetime because much of this lighting is proprietary. The project owner also noted the importance of procuring a contractor with experience with the technology.

- **Environmental concerns related to the PV cell, which—similar to e-waste—contains a number of hazardous materials.** According to the Union of Concerned Scientists (UCS), if these toxic materials are not handled or disposed of properly, they could pose serious environmental or public health threats. The Texas Solar Energy Society relays this concern on its webpage "Solar Photovoltaic End-of-Life: Silicon Valley Toxics Coalition Stopping the Solar Photovoltaic Waste Stream Before It Starts." More information is available at www.txses.org/solar/content/solar-photovoltaic-end-life.

1.3.4 Costs and Life Expectancy

Street Lighting

The City of Irving used a $2 million grant from the Department of Energy to fund an installation of 170 solar-powered LED lights along a 5.5-mile stretch of Irving Boulevard from State Highway 183 to Loop 12, replacing 266 grid-connected streetlights. The installation was completed in January 2011. The batteries are expected to last 10 years, and the city expects to save an estimated $1 million in energy costs over the next 10 years. It foresees a payback period of 16 years.

In the Lockheed Martin case study published in *Alternative Energy eMagazine*, a comparison of price between solar and AC-powered fixtures over a period of 20 years found that 35 solar LED streetlights would cost $342,000 (including purchase price and maintenance) versus $563,000 for conventional AC-powered streetlights (including new wiring and electricity costs).

In Richmond, Va., the 21 solar streetlights used by a 40-home residential development cut installation costs in half, saving the developer nearly $600,000 on the installation, according to the *Forbes* article. The installation survived two hurricanes with no issue.

Trail

The Santa Barbara, Calif., project installed 77 solar-powered LED lights on a bike path. Each unit costs $3,890, including the light, pole, battery, solar panel, and all associated hardware. The warranty for the electronics, wiring, and luminaire is 10 years, and the warranty for the mounting hardware and solar panel is 20 years. The installation was completed in October 2013. The maintenance is expected to be minimal.

On Penn Street Trail in Philadelphia, Pa., the cost of material and construction for 15 solar light poles and luminaires provided by HEI Solar Light was

WALKABLE SOLAR-PANELED PATHWAY

GEORGE WASHINGTON UNIVERSITY, VIRGINIA

Solar panels are not installed only on light poles. In the fall of 2013, the first walkable solar-paneled pathway in the world was installed on George Washington University's Virginia Science and Technology Campus [CS 39].

The sidewalk boasts a solar-powered trellis and 27 slip-resistant semi-transparent walkable panels. The trellis creates energy that feeds back to one of the education buildings. The 100 square feet of walkable panels have a combined average of 400-watt peak capacity (Wp)—enough energy to power 450 LED pathway lights below the panels. As mentioned in a May 2014 CityLab article by Nate Berg, it is "not exactly a power plant, but a scalable idea that takes advantage of huge amounts of power-creating potential on the ground."

Figure 8. Walkable solar-powered pathway. George Washington University, Virginia. Source: Studio39.

approximately $202,500. The pole includes the battery and solar panel. The installation was completed in 2013 and is the first phase of a multi-mile trail. The project manager reports being very happy with their performance, low level of maintenance, and aesthetics. While a cost analysis for the solar lighting versus traditional lighting was not performed, the case study notes that installation of the solar lights was cheaper because they did not have to be tied into the grid at all. Without electricity costs, a long-term cost savings is also expected. The batteries are estimated to last about five years. While this project is the first U.S. installation of the HEI Solar Light product, it has been on the ground in Europe and the Middle East since June 2008 when the first project to install the lights was completed in Vienna, Austria.

In-Road Lighting

Saris Racks donated 20 lights to the Portland Bureau of Transportation for the pilot project in 2013. The cost of each light was $120-$145. The cost of the epoxy was $7-$10. The installation cost (including mobilization, traffic control, grinding to countersink in the roadway surface, and additional epoxy) was $1,189. According to Saris, the lights have a battery life of five to seven years.

SECTION 2: Recycled Construction Materials

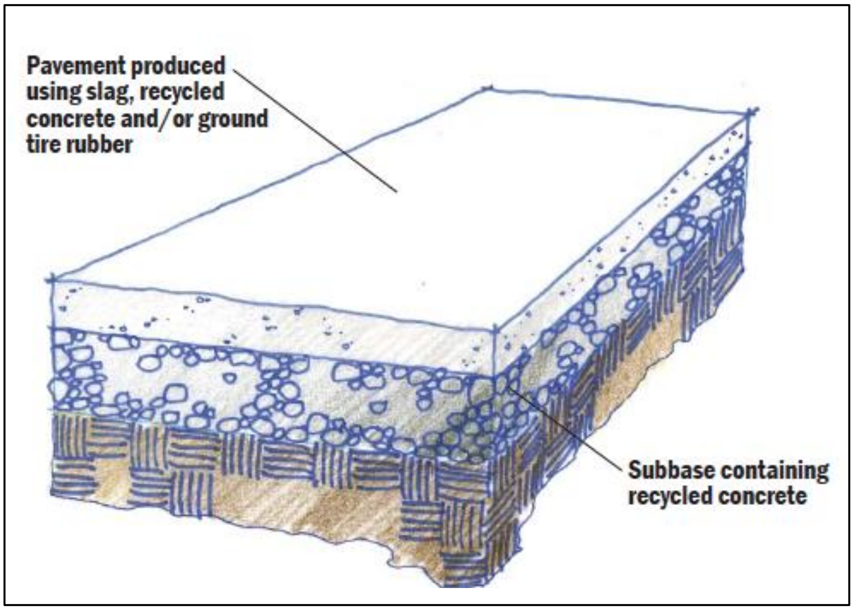


Figure 9. An illustration of recycled construction material.
Source: The City of Chicago's *Chicago Green Alley Handbook*. 2010.

2.1 Overview

Recycling is not a new concept for the transportation industry. The Texas Department of Transportation (TxDOT) has approved specifications that specifically call for the use of recycled materials and assembled information on promising and readily available materials.

As part of the TxDOT's Road to Recycling initiative, an industry panel identified the following recycled materials as offering engineering benefits and cost-effective pricing, having no known environmental risks, and being readily available in large volumes:

- Asphalt shingles
- Coal combustion byproducts, including fly ash, bottom ash, and hydrated fly ash
- Compost and mulch
- Glass
- Industrial sands
- Metals, primarily steel and aluminum
- Plastics
- Reclaimed asphalt pavement
- Recycled concrete aggregate
- Slags, including ground granulated blast furnace slag
- Soils, including petroleum-containing soils
- Tires and tire rubber

TxDOT has assembled information packets on the above materials, including research summaries, specifications, and sources. Visit the Roadway Recycled Materials Summaries section of TxDOT’s website (https://tinyurl.com/haznkvx).


Figure 10. Top image: The Fort Worth Nature Center and Refuge (source: City of Fort Worth). Bottom image: Katy Trail, Dallas, Texas.

Recycled materials offer design versatility, often have a long lifespan, and can require less long-term maintenance than similar products constructed from natural materials, according to the Hill Country Conservancy’s trail design guidelines. (For more detail on recycled materials in trail applications, see Section 4).

Some projects that utilized recycled materials in the North Texas region include the Fort Worth Nature Center and Refuge [CS 12], which incorporated recycled crushed concrete in its permeable parking lot (see Figure 10); Merritt Road in Rowlett, Texas, [CS 17] which used recycled materials in the pavement section and the trench backfill; and the Green at College Park (University of Texas – Arlington) [CS 1], which used concrete amended with fly ash and crushed concrete for a base material. The Green at College Park also incorporated recycled glass pervious paving as a trail surface. The Katy Trail in Dallas, Texas, [CS 7] has a recycled rubber surface for soft, pedestrian-friendly path sections (see Figure 10); Grand Prairie’s Mountain Creek Lake Park Trail [CS 14] uses recycled crushed concrete; and Trinity River Audubon Center [CS 9] has trail sections of boardwalk made from recycled bottles and sawdust.

One easy way to use “recycled” material is to simply reuse material already on site rather than take it to a landfill. At the Dallas Urban Reserve [CS 5], debris left on site was reused as raw material for flagstones, retaining walls along the roadway excavation, and an entrance sign. At Timber Creek High School in Fort Worth [CS 15], the excavated rocks were repurposed in the green stormwater infrastructure. In Wimberley, Texas, the Blue Hole Regional Park project [CS 22] reused the material from demolished roads for gravel. In addition, it reused invasive tree material for items such as fencing, light poles, and play structures and shredded the remainder for mulch, soft-surface trails, and play areas.

2.2 Potential Benefits

- **Waste diverted from landfills.** When products are made of recycled materials, those materials do not end up wasting valuable landfill space.

- **Reduced need to extract or produce resources.** Products can use recycled material rather than virgin material.

- **Reduced CO_2 emissions.**

- **Can help develop technologies and may provide superior engineering performance.** Recycled materials can offer great promise and solve problems. The Katy Trail's pedestrian path used recycled rubber because it was softer than traditional surfaces. A *Public Roads* article by Rebecca Davio titled "Lessons Learned: TxDOT's Efforts to Increase the Use of Recycled Materials," provided recycled-plastic manhole-adjusting rings as an example of a recycled product with superior engineering performance, a lifecycle cost advantage, and environmental benefits. Davio noted that the recycled rings are lighter in weight and less fragile than their traditional counterparts while maintaining their strength. In Alexandria, Va., the Department of Recreation, Parks and Cultural Activities installed the pervious Flexi-Pave surface throughout Dora Kelley Park [CS 38] (see Figure 11). The park suffered from flooding issues, and the department was limited in the surfacing type that could be put in a national resource protection area. According to the department, the surface needed to be pervious, but gravel or mulch would have washed out. Instead, it chose Flexi-Pave, a hard surface that was still pervious. As the material installed was made from recycled rubber passenger tires (in this installation alone, 1,597 tires were used), Flexi-Pave had the additional benefit of diverting waste from landfills.

- **Cost savings.** Repurposed items can also save the project owner money, not only on the cost of the item, but also on the costs to transport that item from where it was sourced. The engineer/landscape architect for Timber Creek High School in Fort Worth repurposed the excavated rocks and reduced transportation costs with the added benefit of reducing associated emissions.

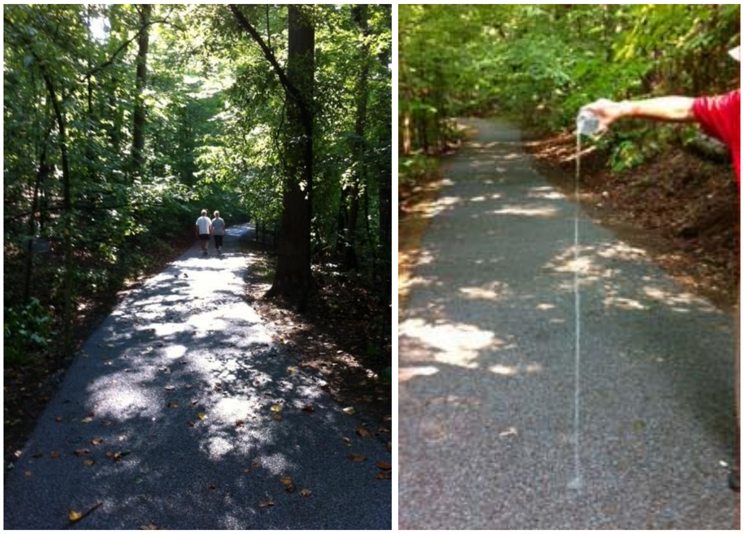


Figure 11. Flexi-Pave at Dora Kelley Park, Alexandria, Va.
Source: City of Alexandria.

The Blue Hole Regional Park project (see Figure 12) found substantial cost savings in reusing gravel from the site's demolished roads. Reusing excavated boulders and limestone saved an additional $40,000. In addition, the design team saved approximately $230,000 by reusing tree material removed during construction for fencing, light poles, wheel stops, and nature-based play structures. Leftover wood was double-shredded for mulch, soft-surface trails, and play areas.

Figure 12. Invasive ashe junipers were repurposed, and remaining cedars were shredded for mulch, soft-surface trails, and play areas at Blue Hole Wimberley Park.
Source: Design Workshop.

2.3 Limitations/Considerations

- **Verification of performance, environmental effects, and long-term costs of new, innovative recycled material.** Recycled materials can offer performance advantages unattainable with virgin materials, and a wide array of recycled materials exceeds standards. However, a product made from recycled material is not necessarily a better choice. An innovative recycled material's engineering properties need to be verified. The environmental quality and effects of the material also need analysis. Research and demonstration projects may be necessary to determine effectiveness and long-term costs.

  One example of this experimentation is provided by the City of Santa Monica, Calif. [CS 25]. Facing an escalating number of sidewalk repairs and maturing trees with invasive root systems, the City chose a recycled-rubber-and-plastic sidewalk in an attempt to both reduce escalating numbers of tear-outs and concrete re-pours and save its urban canopy. The first concept was to use brick pavers (see Figure 13, top left), but the pavers created an uneven surface area when roots encroached from underneath, increasing the potential for trip-and-fall hazards. The city has tried several iterations of rubber sidewalks (see Figure 13) and now has a "wait-and-see" attitude. The experiment did not pan out as the City's cost-benefit analysis forecasted, and the City saw issues with warping and expansion. Many rubberized panels lasted only two years rather than the projected seven to 10. However, the City's streets supervisor reported that the last iteration (TerreCool) has been working well, and the manufacturer claims that the product will stay 10% cooler than regular concrete sidewalks on hot days.

Figure 13. Santa Monica. Top left: brick pavers. Top right: rubber pavers. Bottom left: second-generation TerreWalks. Bottom right: third-generation TerreWalks.
Source: City of Santa Monica, Calif.

2.4 Costs and Life Expectancy

Recycled materials may be less expensive than new materials; however, even if the initial capital costs are higher, recycled materials could be deemed reasonable if they supply superior performance compared to new materials. The College Green case study noted that the use of concrete amended with fly ash does not add any cost compared to traditional concrete. According to Davio's article in *Public Roads*, transportation/delivery costs and disposal costs for job-site materials may also be less. (The product may be lighter, easily manufactured in multiple places rather than purchased from one source far from the project site, or easily recycled itself.) In addition, project savings can also be found in the reuse of site material rather than the purchase of virgin materials.

At the Dora Kelley trail resurfacing project, the Flexi-Pave surface was installed in August 2012. It is too soon to know if it will last the expected 15-20 years, but they had not experienced any issues with it as of 2014. At the Katy Trail project, the recycled rubber surface was expected to last seven years; it has already surpassed that, and a recent inspection showed mostly minor wear and tear. While the City of Santa Monica's recycled rubber sidewalk panels have not yet fulfilled their projected life expectancy, the manufacturer is continuing to work on the product, so it is possible the life expectancy will improve.

For information specific to asphalt and recycling, see Appendix E.

SECTION 3: Cool Pavements

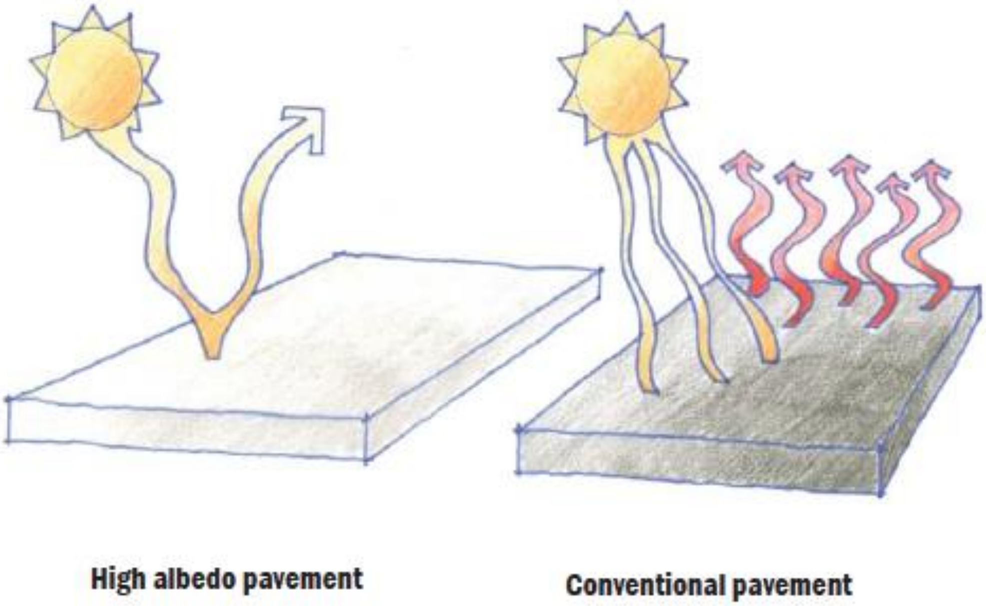


Figure 14. A simple illustration of high-albedo pavement versus conventional pavement.
Source: The City of Chicago's *Chicago Green Alley Handbook*, 2010.

3.1 Overview

Cool pavement technology is one key strategy in *Reducing Urban Heat Islands: Compendium of Strategies,* a publication from the U.S. Environmental Protection Agency (EPA). Pavement comprises the largest percentage of land cover—from 30% to 45%—in many U.S. cities, according to the EPA's Urban Heat Island Project. While many people think of pavement as limited to streets and highways, pavement is also used for road shoulders, driveways, parking, patios, sidewalks, and ancillary surfaces. These surfaces contribute to the urban heat island effect by absorbing and storing solar energy. Conventional pavements are impervious concrete and asphalt that may reach 150°F in summer. The impact of this heat is felt not only during the day; these surfaces can transfer heat down into the subsurface, which then re-releases the heat at night.

While the EPA notes that cool pavement technologies are not as advanced as other heat island mitigation strategies and that there is no official standard or labeling program to designate cool paving materials, it is a green practice worth considering, given how much pavement a city contains.

3.1.1 High-Albedo/Reflective Pavement

One type of cool pavement is high-albedo pavement that reflects sunlight from the surface rather than absorbing it. Because it absorbs less heat from sunlight, the pavement radiates less heat, reducing the urban heat island effect and conserving energy through reduced cooling needs and improved air quality. A composite index called the solar reflectance index (SRI) estimates how hot a surface will become when exposed to full sun. It varies from 100 for a standard white surface (coolest) to zero for a standard black surface (hottest). Table 3 provides a few examples.

Table 3. Solar reflectance (albedo) and solar reflectance index (SRI) of select surfaces.

Material Surface	Solar Reflectance	SRI
New asphalt	0.05	0
Aged asphalt	0.1	6
Aged concrete	0.2-0.3	19-32
New concrete (ordinary)	0.35-0.45	38-52
New white Portland cement concrete	0.7-0.8	86-100

Modified from a table from Concrete Thinker, “Benefits: Heat Island Reduction,” 2008.

High-albedo pavement can be used under a wide variety of site conditions. It includes conventional asphalt pavements modified with high-albedo materials or treated after installation to raise reflection, conventional concrete pavements, other reflective pavements such as resin-based pavements, chip seals, whitetopping, and microsurfacing.

3.1.2 Permeable Pavements

The definition of cool pavements has been extended to include permeable pavements that allow air, water, and water vapor into the voids of a pavement, keeping the material cool when moist. Moisture evaporates as the surface heats, drawing out heat from the pavement. Permeable pavement systems containing grass or low-lying vegetation can stay particularly cool, according to the EPA.

3.1.3 Alternatives

Alternatives to cool pavements include reducing the amount of paved surfaces (for example, narrowing street widths) or shading the pavement with trees. Solar panels can also shade pavements while simultaneously generating electricity.

3.2 Potential Benefits

- **A more comfortable environment.** Cool pavements in areas where people congregate may provide a more comfortable environment during hot weather. The Green at College Park (University of Texas – Arlington) project [CS 1] expects to mitigate the urban heat island by utilizing shade and paving materials with an SRI value of 29 or greater. The Chicago Green Alley program [CS 29] employs high-albedo concrete, pervious concrete, and brick pavers with a high SRI. Its monitoring data shows that a high-albedo green alley’s pavement surface temperature can be more than 23˚F cooler than traditional asphalt.

- **A reduction of urban heat island effects, which in turn helps conserve energy, provides cost savings, and improves air quality**. The South Grand Boulevard Great Streets Initiative, a Landscape Architecture Foundation case study for a six-block corridor redevelopment in St. Louis, Mo., projected that in areas where asphalt was replaced with high-albedo pervious concrete, the peak ground-level temperature could decrease by 7.8˚F. The project is also estimated to save electric consumption in cooling (7.8% to 15.6%).
- **Enhanced nighttime visibility of reflective pavements, which could save both money and energy.** This assumes that reflective pavements may decrease lighting requirements.
- **Lowered stormwater runoff temperatures.** Cool pavements can result in lowered stormwater runoff temperatures, so aquatic life experiences less thermal stress. According to the Dallas Sustainable Skylines Initiative (DSSI) report, cool pavements can contribute to meeting stormwater quality standards, potentially reducing runoff temperatures by 2-4˚C.

Other benefits associated with permeable pavements, such as improved water quality, are found in the Permeable Pavements section (see Section 5.1.2).

3.3 Limitations/Considerations

- **Unintentional consequences of reflection.** For high-albedo materials, reflected heat may be absorbed by surrounding buildings, warming them and contributing to the nighttime urban heat island effect. Certain high-albedo materials may also have high glare.
- **Unknown effects for dry permeable pavements.** The EPA notes that more research is needed to better understand the effect of dry permeable pavements on ambient air temperature.

3.4 Costs and Life Expectancy

The EPA's *Reducing Urban Heat Islands: Compendium of Strategies* report emphasizes the challenges in comparing the costs of conventional paving materials with those of cool pavements. It points out that "the cost of any pavement application varies by region, the contractor, the time of year, materials chosen, accessibility of the site, local availability of materials, underlying soils, size of the project, expected traffic, and the desired life of the pavement."

Thus, the comparative costs table included in the report (see Table 4) is to be used with caution, especially because the numbers come from a 2008 document.

Table 4. Comparative Costs of Various Pavements.

Basic Pavement Types	Examples of Cool Approaches	Approximate Installed Cost, $/square foot*	Estimated Service Life, Years
	New Construction		
Asphalt (conventional)	Hot mix asphalt with light aggregate, if locally available	$0.10-$1.50	7-20
Concrete (conventional)	Portland cement, plain-jointed	$0.30-$4.50	15-35
Nonvegetated permeable pavement	Porous asphalt	$2.00-$2.50	7-10
	Pervious concrete	$5.00-$6.25	15-20
	Paving blocks	$5.00-$10.00	> 20
Vegetated permeable pavement	Grass/gravel pavers	$1.50-$5.75	> 10
	Maintenance		
Surface applications	Chip seals with light aggregate, if locally available	$0.10-$0.15	2-8
	Microsurfacing	$0.35-$0.65	7-10
	Ultra-thin whitetopping	$1.50-$6.50	10-15

*Some technologies, such as permeable options, may reduce the need for other infrastructure, such as stormwater drains, thus lowering a project's overall expenses. Those savings, however, are not reflected in this table. (1 square foot = 0.09 m^2)

Source: EPA, *Reducing Urban Heat Islands: Compendium of Strategies.* 2008.

For more information, see EPA's *Reducing Urban Heat Islands: Compendium of Strategies* chapter on cool pavements, available online at www2.epa.gov/heat-islands/heat-island-compendium.

SECTION 4: Trail Materials


Figure 15. Left: Mountain Creek Lake Park Trail, Grand Prairie, Texas (source: Grand Prairie Parks, Arts & Recreation Department). Right: the College Green at University of Texas, Arlington (source: Gus Chavarria).

4.1 Overview

This section provides information on a wide range of available green trail surface options. These include:

- Permeable concrete pavement and pavers
- Permeable asphalt, recycled asphalt, and recycled glassphalt
- Native soils
- Alternative surfacing products that are derived from industrial processes or that use recycled materials or natural by-products
- Crushed aggregates
- Solid materials such as wood, rock, and recycled rubber and plastic

However, surface material is only one of many decisions to be made in trail design and construction. Anasazi Trails’ 2008 Rio Grande Trail Surfacing report notes that a properly designed trail is critical for water management and drainage as is awareness of critical or sensitive habitats. While the trail width will necessarily depend on anticipated use, a smaller corridor and trail tread will disturb less area. Smaller trails also expose less soil to erosion and invasive plants and are less disruptive to sensitive habitat areas.

The myriad topography, soils, hydrology, and vegetation on each trail is often as diverse as its users. The needs and wants of joggers, horseback riders, bicyclists, and those walking with strollers will differ. The American Association of State Highway and Transportation Officials (AASHTO) "Guide for the Development of Bicycle Facilities" provide guidance on a range of design components. This guide and other appropriate resources should be consulted when designing a trail and selecting a surface. In addition, the Americans with Disabilities Act (ADA) accessibility guidelines call for surfaces that are "firm, stable, and slip-resistant."

Figure 16. One traditional trail surface and one recycled surface at the Katy Trail, Dallas, Texas.

The importance of both design and maintenance are shown by the Trinity River Audubon Center (TRAC) case study [CS 9]. TRAC's operations director reported that the steepness of many slopes has resulted in rapid erosion. The director underscored the importance of understanding the hydrology of a site, suggesting that TRAC's trails would have benefited from the integration of more switchbacks. The City of Dallas's project manager for TRAC noted that trails were laid out with the assumption that daily or weekly maintenance would be performed; however, this has not been possible due to staff and budget constraints which may have affected trail performance.

Some important factors to consider include:

- Existing soil and environmental conditions
- Aesthetic considerations
- Anticipated trail use
- Availability of surfacing materials
- Overall management strategies and maintenance

The following tables summarize information from Anasazi Trails' 2008 Rio Grande Trail Surfacing report, the Texas Department of Health's booklet "How to Build a Walking Trail," the City of Santa Cruz's "Trail Materials Analysis and Comparison Matrix," and Hill Country Conservancy's *2010 Violet Crown Trail Final Master Plan*. When applicable, a reference to the relevant NCTCOG case study is included.

4.2 Potential Benefits

Table 5. Green Trail Surface Descriptions and Potential Benefits.

Trail Type	Descriptions and Potential Benefits
Native soil	Native material. Easiest for volunteers to build and maintain. Somewhat permeable. Lowest cost.
Wood fiber (shredded wood, engineered wood chips) Crushed bark and Barka-Mulch may be used, according to the Texas Dept. of Health.	Some wood fiber is soft, spongy, and good for walking. Permeable. Moderate to low cost. If the fiber is reused from on-site waste, it also may provide additional savings and environmental benefits.
Soil cement/surfacing alternatives Examples and descriptions from the Rio Grande report: Natural Pave XL, a resin pavement binder emulsion that is appropriate for riparian areas; Soiltac, a biodegradable liquid copolymer; Soil-Sement, a polymer emulsion effective for dust control, erosion control, and soil stabilization. Other brands are also mentioned in the Rio Grande report.	Makes use of natural materials. Binders vary. Can produce a firm, stable, slip-resistant surface with proper installation. Accommodates multiple users. Moderate cost.
Granular stone/crushed aggregates/decomposed granite	Soft surface can be compacted to firm. Crushed concrete might make for a softer surface than concrete or asphalt, and be acceptable for cross-country runners. May not float away in runoff, unlike some wood fiber. Natural material. Accessible. Moderate cost.
Permeable asphalt	Hard, flexible pavement. Supports most users. Permeable. Time-tested material. Can be colored to match the environment. Low maintenance.
Permeable concrete	Hard, nonflexible pavement. Best in areas of extreme environment. Can be colored and formed. Supports multiple uses. Accessible. Resists freeze/thaw. Durable. Low maintenance.
Rubber/plastic/glass products (excluding boardwalk) Examples and descriptions from the Rio Grande and Santa Cruz reports: EcoTrack, which may provide years of high-performance outdoor use; Filter-Pave, made from recycled glass held by a flexible elastomeric glue; Geoblock, interlocking blocks made from recycled plastics; and Gravel Pave 2, porous paving with heavy load-bearing support and containment of gravel. Others mentioned: Geoweb, Nike Grind, and Super Deck.	Innovative. Examples include: Katy Trail, Dora Kelley Park Trail, and the Green at College Park. Increased lifespan. Easier to install. Rubber is soft and more suitable for joggers.
Wood boardwalk	Necessary in wet or ecologically sensitive landscapes. Natural looking. Medium maintenance. Can be built by volunteers.
Recycled boardwalk (Trex)	Made from recycled material (recycled milk bottles, water bottles, and sawdust).

This is a modified version of a table in *Violet Crown Trail Final Master Plan*, 2010.

PERMEABLE TRAIL SURFACES

When a trail is located in a more natural area, it may seem unnecessary to increase the permeability of trail surfaces or to incorporate green stormwater infrastructure. But, as seen in the Red Oak Creek Trail case study [CS 3], adding these in key areas may provide great benefits. Red Oak Creek Trail is a mostly concrete trail in Cedar Hill, Texas, but it also includes more than a quarter mile of decomposed granite trails, decomposed granite accents to various amenity areas, and landscaped beds.

A recent trail enhancement was the removal of part of an asphalt street; in place of that street, open channels and landscaping were installed to help filter runoff from an existing neighborhood (see Figure 17). Previously, water would run down the street and discharge into the greenbelt adjacent to Red Oak Creek with little or no filtration or ability to percolate into the soil. The case study reported that the removal of the asphalt road provided a great enhancement to the water runoff quality in that area.

Figure 17. Red Oak Creek Trail, Cedar Hill, Texas.
Source: City of Cedar Hill.

4.3 Limitations/Considerations

Table 6. Trail Surface Limitations and Considerations.

Trail Type	Limitations/Considerations
Native soil	Dusty when used. High clay content soils cause trails to be slick or muddy when wet. Ruts when wet, and difficult to smooth out when ruts dry. High rate of cohesion in clay's extra fine particles means soils take a long time to dry out. Surface may be uneven/not accessible. Produces sediment that may harm streams. May be high maintenance depending on soil and uses.
Wood fiber (shredded wood, engineered wood chips)	Decomposes under exposure to sunlight, moisture, and high temperatures. Limited accessibility. Not appropriate for flood-prone areas. High maintenance. Short life. (Wood bark can be uneven, so it is less desirable.)
Soil cement/surfacing alternatives	Mixed results. May be only considered feasible, economical, and appropriate if the material source is close to the project site and is otherwise suitable. Difficult to achieve uniform surface. May require specific installation procedures and ideal site conditions to perform optimally. May require soil testing and specific soil textures to ensure performance/longevity. Surface erodes and wears unevenly. Not stable in all weather. Difficult to achieve uniform surface. Can be high maintenance if not installed correctly.
Granular stone/crushed aggregates/decomposed granite (DG)	Surface can erode with heavy rainfall, producing unstable tread conditions. Performance depends on diameter. Medium maintenance depending on installation. Refreshing of trail surfacing materials is required on a routine basis. Not for use on steep slopes or in floodplains. According to the City of Santa Cruz report, construction costs for a DG path with steel edging can be the same cost as a concrete path, and a heavily-used DG path will require complete reconstruction every five to seven years. The Trinity River Audubon Center's DG might work well, but the case study reported that birders do not like it because it is noisy.
Permeable asphalt	Can be costly to repair. Not a natural surface. Uncomfortable for walking and running. Hot during summer use.
Permeable concrete	High installation cost. Very urban appearance. Hot during summer use.
Rubber/plastic/glass products (excluding boardwalk)	Costly. Some new technologies may not live up to claims. The Flexi-Pave case study mentioned that a proprietary product might make it harder to contact the company immediately. The recycled glass pervious paving at the College Green used a binder that was not as UV stable as it needed to be for this region, so the company found a more suitable UV stabilizer. While the paving is easy to patch, it is not aesthetically pleasing.
Wood boardwalk	Slippery when wet. Easily damaged by use and vandalism. High cost to install. High cost to maintain if damaged.
Recycled boardwalk (Trex)	Have to be aware of importance of deck substructure. Wood that was used under sections of one installation eventually warped, which caused Trex to crack and buckle. (However, Trex now provides dimensional material to replace the treated lumber installed.)

Source: This is a modified version of a table in *Violet Crown Trail Final Master Plan*, 2010.

4.4 Costs

The unit cost estimates are national averages and may cover a wide range. Actual costs will vary. More specific cost analysis will be necessary based on design factors suitable for anticipated use, maintenance, and existing conditions. Use local trail building expertise to help ensure current cost analysis and engineering estimates for variables such as excavation, sub-base preparation, drainage, appropriate materials, transportation costs, material placement, wetting, compaction, and finish work.

Table 7. Trail Surface Costs.

Trail Type	Costs
Native soil, assuming 4–6 ft. wide	$10.00-$12.00/LF*
Wood fiber (shredded wood, engineered wood chips), assuming 6–8 ft. wide	$12.00-$15.00/LF*
Soil cement/surfacing alternatives, assuming 8 ft. wide	$15.00-$20.00/LF*
Granular stone/crushed aggregates/decomposed granite (DG), assuming 10 ft. wide	$12.50-$40.00/LF**
Permeable asphalt	$20.00-$81.30/LF**
Permeable concrete	$55.00-$116.00/LF**
Rubber/plastic/glass products (excluding boardwalk)	$35.60-$96.00/LF**
Wood boardwalk	$280.00-$380.00/LF*
Recycled boardwalk (Trex)	$3.92-$64.00/LF**
* Costs taken from ***Violet Crown Trail Final Master Plan***, 2010.	
** Costs taken from NCTCOG cost research. See Appendix D.	

Source: This is a modified version of a table in *Violet Crown Trail Final Master Plan*, 2010.

SECTION 5: Green Stormwater Infrastructure

The concept behind green stormwater infrastructure (GSI) is summed up by the American Society of Landscape Architects (ASLA): Nature can be harnessed to deliver critical services to communities, protecting them against flooding and excessive heat while helping to improve air and water quality, the foundation of human and environmental health.

Using vegetation, soils, and natural processes, GSI aims to simultaneously manage water and create healthier urban environments. On the broader scale of a city or county, GSI can refer to a network of natural areas that provides flood protection, wildlife habitat, cleaner water, and cleaner air. At a site-specific scale, GSI refers to stormwater management systems that mimic nature's hydrologic processes.

As mentioned in the introduction, this guide is not meant to be a how-to manual, and it does not prescribe one method nor does it venture into design. For guidance on stormwater treatment suitability, water quality performance, site applicability, and implementation considerations, please see the "Transportation *integrated* Stormwater Management (TriSWM) Appendix" (available at http://iswm.nctcog.org/Documents/TriSWM_Appendix_Final_9-18-14.pdf) and the *integrated* Stormwater Management Technical Manual (available at http://iswm.nctcog.org/technical_manual.asp).

The guide's introduction and Appendix C list several challenges related to cost analysis. Costs are an important factor in decisions, so this guide provides cost information when available. These numbers should be used only as a general reference. The cost of a green stormwater element will be site-specific, and the evaluation of benefits will depend on the project's and community's needs.

Tools are being developed to help calculate costs and benefits of a project, such as the set of Green Values calculators provided by the Center for Neighborhood Technology. For example, the National Green Values™ Calculator allows for a quick comparison of GSI to traditional stormwater management practices, looking at performance as well as lifecycle costs and benefits.

Even GSI is not incorporated in the final design, the project could still be designed with its potential inclusion in mind. If funds are then available in the future, the project may easily—and

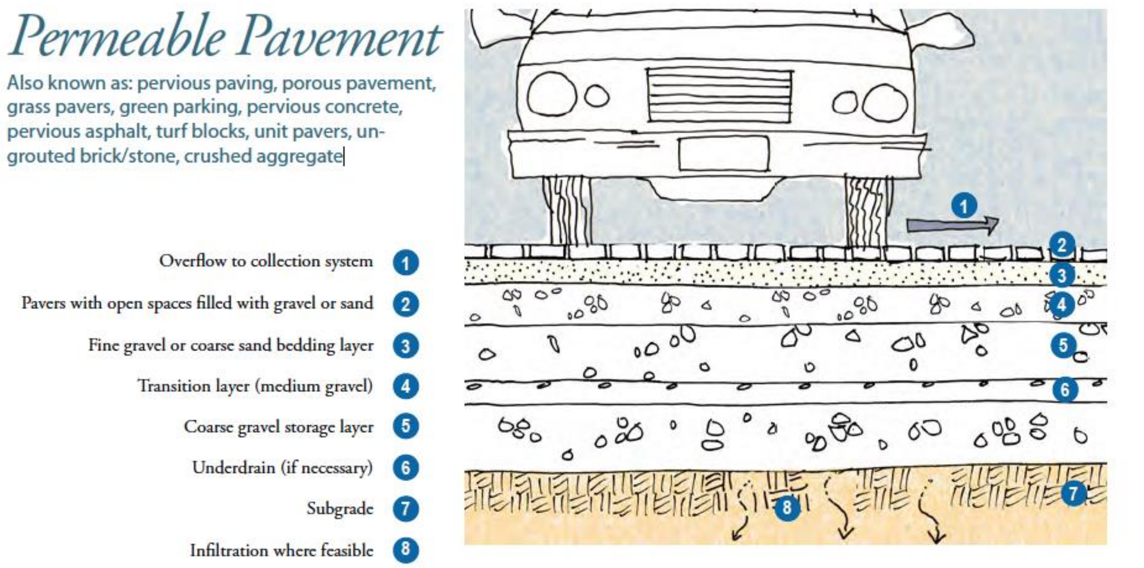
ADDITIONAL RESOURCES

This guide provides a high-level overview for a range of green stormwater infrastructure best management practices (BMPs) that are relevant to transportation projects, but green infrastructure includes much more than what is covered in this document. The American Society of Landscape Architects' online section on green infrastructure (www.asla.org/greeninfrastructure.aspx) has a wealth of information on topics such as forests and nature reserves, wildlife habitat and corridors, constructed wetlands, green streets, and green roofs and walls. The EPA's green infrastructure site (http://water.epa.gov/infrastructure/greeninfrastructure/index.cfm) is another helpful resource.

less expensively—be retrofitted with GSI, reported Verdunity, a Dallas-based consulting firm.

For more information on the impacts of expected growth, including natural resource depletion, urban heat islands, decreased air quality, increased flooding, and decreased water quality as well as a discussion of the potential problems of depending solely on gray infrastructure, see Appendix B.

5.1 Permeable Pavement



Permeable Pavement

Also known as: pervious paving, porous pavement, grass pavers, green parking, pervious concrete, pervious asphalt, turf blocks, unit pavers, un-grouted brick/stone, crushed aggregate

Figure 18: An illustration of permeable pavement.
Source: San Francisco Stormwater Design Guidelines, 2010.

5.1.1 Overview

Several different names refer to permeable pavement types, including porous asphalt, pervious concrete, modular permeable pavers, and crushed aggregate. Permeable pavement is a porous surface that infiltrates, treats, and/or stores rainwater close to where it falls. If native soils have good infiltration rates, the water infiltrates; with poor infiltration rates, the water should be conveyed elsewhere to be stored or discharged. While permeable pavements may not be appropriate in all paved areas, they can be particularly cost-effective where land values are high and where flooding or icing is a problem, the EPA reports.

Due to its specific application for pavements, permeable pavements are discussed separately from other GSI approaches, but they are often used with other bioretention and infiltration features.

One common application for permeable pavements is parking lots.

- At the Fort Worth Nature Center and Refuge [CS 12], issues with continual groundwater seepage from the parking lot were solved with a new parking lot made of compacted gravel and crushed concrete combined with five bioswales.

- As part of the Dallas Arboretum's expansion and improvement program that included additional parking, the design team chose an ADA-compliant permeable surface that would blend into the surrounding area while mitigating stormwater runoff concerns.

- In Carrollton, Texas, a downtown parking lot uses Grasstone pavers for interior parking spaces [CS 2] (see Figure 19). The pavers allow grass to grow on the pavers' interior and permits stormwater to infiltrate into the pavement subsurface.

Figure 19. A parking lot installation of permeable pavers in Carrollton, Texas. Source: City of Carrollton.

- St. Stephen's Pedestrian Green [CS 18] in Austin, Texas, uses pervious pavers in the parking area to collect and store runoff in the paver voids, releasing water slowly to the bioinfiltration planter below.

- At Blue Hole Regional Park [CS 22] in Wimberley, Texas, 90% of gravel from roads that existed prior to restoration was repurposed to provide 280 new parking spaces and create 1.25 miles of roadway. Despite these added amenities, impervious surface coverage was limited to a mere 7.8% of the site.

- An installation at Triangle Parking Lot [CS 41] in Stone Mountain Park, Ga., used porous pavement for the entire parking area and access drives for a 430-car parking lot (see Figure 20).

- In Highland Park, Ill., heavy clay soils eliminated infiltration as a treatment option, so permeable pavers and an underground detention vault were used in the Ravinia Festival South Parking Lot [CS 30] to prevent frequent surface flooding that occurred even after small storm events.

Figure 20. Permeable concrete unit pavers at Triangle Parking Lot in Stone Mountain, Ga.
Source: Robert and Company.

Permeable pavements can also work well for sidewalks and walkways.

- The renovation of Elm Street in Dallas, Texas, [CS 6] included permeable pavers in sidewalk draining toward tree planters. The Green at College Park (University of Texas – Arlington) [CS 1] incorporated pervious recycled glass in the walkway.

- The City of Olympia, Wash., has installed approximately five miles of pervious concrete sidewalk to date [CS 28] (see Figure 21).


Figure 21. Pervious concrete sidewalk in Olympia, Wash. Source: City of Olympia.

5.1.2 Potential Benefits

- **Reduced project costs.** GSI elements may cost less than their traditional infrastructure counterparts, or they may lead to saved costs by reducing or eliminating the need for gray infrastructure.

  In Chicago, the Ravinia Festival South Parking Lot's installation of 27,000 ft^2 of permeable concrete unit pavers instead of traditional poured concrete saved the project over $35,000 in construction costs. Preserving 49 oak trees threatened by root-zone compaction and inundation saved over $25,000 in tree replacement costs.

  For the City of Olympia, Wash., building sidewalks with pervious concrete means the city does not need to construct costly stormwater ponds, which would require the acquisition of additional land or right-of-way. The Dallas Arboretum's choice of permeable paving meant that the project did not need to install a storm drain system. The Triangle Parking Lot and the Ravinia Festival South Parking Lot projects also eliminated the need for large detention ponds; for Ravinia, this saved the project $1.8 million.

- **Reduced stormwater runoff volume and rates, leading to reduced flooding and erosion as well as increased groundwater recharge and improved water quality.** As noted in the Center for Neighborhood Technology's "The Value of Green Infrastructure," studies have shown that as much as 80% to 100% of the rain that falls on a site can infiltrate. This infiltration can lead to increased groundwater recharge and lower water treatment costs. Infiltration and the pollutant filtration can also result in improved water quality.

  The Texas A&M AgriLife project results showed grass pavers and interlocking concrete pavers to have a stormwater volume reduction of approximately 65% with total suspended solids (TSS) reduced 25% for the grass and 56% for the concrete.

  The Triangle Parking Lot project's field observations showed a reduction of over 80% of predevelopment flow rates for more frequent storm events, significantly better than their design calculations of approximately 35%.

Figure 22. Before (left image, source: Ravinia Festival) and after (right image, source: SmithGroupJJR) the installation of permeable pavers and an underground detention vault at the Ravinia Festival South Parking Lot.

The new design of the Ravinia Festival South Parking Lot eliminated surface flooding, which previously occurred an average of 25 days per year (see Figure 22). After receiving more than 8 inches of rain in 48 hours in 2011, the lot remained free from standing water. The project also reduced complaints related to parking lot inaccessibility and nearby flooded yards and basements from several hundred per year to zero.

- **Support of increased development.** The new design for the Fort Worth Nature Center and Refuge parking lot allowed for additional parking spaces. The choice of pavers for the Triangle Parking Lot project led to an increase in available surface area, which equaled 40 additional spaces. Carrollton's permeable parking lot stemmed from the city's desire to add additional parking in a historic downtown area that does not have the capacity to handle a 100-year flood event.

- **Reduced urban heat island (UHI) effect.** Conventional pavements can contribute to the urban heat island effect. They may reach up to 150˚F during the summertime, according to EPA's "Reducing Urban Heat Islands" compendium, and heat stored in the subsurface is re-released at night. Permeable pavements may stay cooler through evaporative cooling.

- **Improved air quality.** By reducing the urban heat island effect, permeable pavement can help decrease ground-level ozone formation. Reduced energy use and water treatment costs can also contribute to decreased CO_2 emissions.

- **Reduced energy use and reduced energy spending.** By lowering air temperatures, permeable pavement can lessen demand for cooling in buildings.

- **Enhanced public safety.** During and after rain events, improved water drainage from permeable pavements can enhance safety by increasing traction and reducing water spray from moving vehicles.

- **Improved community livability.** The open pores of permeable pavements can reduce tire noise by 2 to 8 dB, decreasing local noise pollution, according to the EPA webpage "Cool Pavements." While a parking lot may not be the first thing that comes to mind when beautifying an area, the examples of Carrollton and the Fort Worth Nature Center show improved aesthetics.

5.1.3 Limitations/Considerations

- **Level of traffic, weight of vehicles, and location specifics.** The best locations are often parking and sidewalks in low- or medium-traffic areas in soils with high permeability. Other possibilities include alleys, highway shoulders, emergency vehicle access-ways, road gutters, driveways, parking lots, pedestrian paths, recreational trails, and patios. Underground utilities should be avoided if possible. The surface grade is an important consideration as is vehicle or equipment weight. Permeable pavement may not be a good choice in areas where heavy vehicles or equipment are stored or operated regularly.

- **Special attention to design, with an understanding of the project site's use, and construction.** The Dallas Arboretum permeable paving parking lot has worked well, according to its vice president of property development, because it was designed so that large vehicles such as concrete trucks would be kept off the lot. It is also important to ensure that heavy machinery is not driven over the pavement during construction. If the system is poorly designed, poorly constructed, inadequately maintained, or used in destabilized areas, the system may fail. The St. Stephen's Pedestrian Green case study contact highlighted the importance of covering pervious pavers during construction to avoid having dust and debris from construction fill the pervious joints.

  While clay-rich soils pose a challenge, permeable pavement installations with the appropriate consideration and design can still be successful. As mentioned previously, the Ravinia project used an underground detention vault in the face of low infiltration rates. Another successful system example is one designed for the Wasatch Touring Pervious Pavement project in Salt Lake City, Utah, which won an American Council of Engineering Companies' Engineering Excellence Award in 2010. This system allows water and oxygen to percolate from the concrete surface down through the pavement and soil—with a 15-foot-thick clay soil layer beneath the surface—using a perforated drain pipe, a catch basin, a darcy column, and an impermeable membrane between the system and adjacent buildings. To address freeze/thaw concerns, a rock layer was inserted between the top soil and the pervious pavement to allow water to expand without cracking the pavement.

- **Pollutant removal requirements.** The level of the pollutant removal depends on the system used. Typically, permeable pavement is used as a secondary treatment option. For more information, refer to the Transportation *integrated* Stormwater Management (TriSWM) Appendix (http://iswm.nctcog.org/Documents/TriSWM_Appendix_Final_9-18-14.pdf) and the *integrated* Stormwater Management (iSWM) Technical Manual (http://iswm.nctcog.org/technical_manual.asp).

  While permeable pavements may significantly reduce TSS, they may contribute other pollutants. The Texas A&M AgriLife project found that grass pavers released nitrate while the interlocking concrete pavers released orthophosphate. However, its report did not see this as an area of concern, noting that these concentrations were still low overall.

- **Need for region-specific studies.** The Texas A&M AgriLife report mentions a wide array of studies on permeable pavements showing a reduction in runoff and associated pollutant loads with a few including clay soils, but points out that region-specific studies are required to compare the effectiveness of permeable pavement types to maximize their benefits.

- **The importance of inspection and maintenance.** Infiltration rates could decline over time, depending on design, installation, sediment loads, and consistency of maintenance. Sand spreading should be avoided near permeable surfaces. As mentioned in the Olympia case study, pervious concrete requires a shift in maintenance from traditional stormwater infrastructure to sidewalk cleaning. How the maintenance is funded and equipped should be taken into consideration. Modular porous pavers can fail if they are inadequately maintained or used in unstable areas.

5.1.4 Costs and Life Expectancy

The entire installation cost for permeable pavement ranges from $16.70-$22.69 per square foot according to detailed cost estimates provided in the *San Antonio River Basin Low Impact Development Technical Design Guidance Manual,* which gathered 2013 unit bid costs from TxDOT, the City of Austin, and the City of San Antonio (see Table 13 in Appendix D).

Porous asphalt/concrete are installed in a similar manner to their impervious counterparts, but the initial costs of permeable pavement are often higher than traditional materials. While traditional asphalt/concrete costs range from $0.50 to $1.00 per square foot, porous asphalt can cost $2.00 per square foot; porous concrete, $6.00 per square foot. Pervious pavers may range from $2.50 to $3.00 per square foot. The California Stormwater Management Association estimates that a one-acre permeable pavement surface will incur approximately $10,000 in total construction costs and $4,000 in annual maintenance.

According to the San Francisco Public Utilities Commission's *San Francisco Stormwater Design Guidelines*, construction costs can be comparable to or less than traditional paving. If all construction and drainage costs are included, permeable pavement can be up to 25% cheaper. The Olympia, Wash., case study notes that because pervious concrete sidewalks negate the need to build a stormwater facility, a true cost comparison must add the cost of that facility to traditional bid prices. This cost should include the purchase of required land (which may not even be available for retrofit projects) along with the facility's installation, maintenance, and repair.

The Ravinia Festival South Parking Lot project reported that it saved over $35,000 in construction costs by using permeable pavers and that the use of detention vaults avoided the need to purchase three adjacent lots for aboveground stormwater detention, resulting in savings of $1.8 million. The Triangle Parking Lot project reported that initial capital costs were 5% to 10% higher than traditional gray infrastructure costs, but lifecycle costs and enhanced usability made the green choices a viable economic alternative.

Permeable pavements require regular inspection and maintenance to prevent their void spaces from clogging permanently, so maintenance costs can be greater than those for traditional pavement. Maintenance can include sweeping, blowing, cleaning out debris, and replenishing material. The maintenance for Olympia, Wash., pervious sidewalks varies from year to year; in general, 150 to 300 hours are spent annually on maintenance for approximately 27,000 linear feet of sidewalk. The City sweeps permeable pavement roadways at least four times per year with a regenerative sweeper. The Fort Worth Nature Center and Refuge reported its system as being very low maintenance; it mostly included sweeping material back in place. If the system is planted, the vegetation health needs to be checked and the area reseeded or replanted as necessary.

While the California Stormwater Management Association estimated that permeable pavement could last up to 25 years if properly maintained, the Triangle Parking Lot, Ravinia, and Olympia case studies reported an expected lifetime of at least 50 years (although the Olympia study mentioned that some early mixes failed within five years).

For cost estimates that provide a base point and illustrate the importance of including maintenance costs in the project’s budget, see Table 14 in Appendix D.

5.2 Bioretention and Infiltration Practices

5.2.1 Overview

Bioretention and infiltration practices come in a range of sizes, from planter boxes to rain gardens to stormwater ponds. (For more information on permeable pavement, see Section 5.1). Descriptions of common bioretention and infiltration elements are included in Appendix F to provide context for those less familiar with green stormwater infrastructure (GSI). For more details, refer to the *integrated* Stormwater Management (iSWM) Technical Manual (http://iswm.nctcog.org/technical_manual.asp).

5.2.2 Potential Benefits

- **Environmental benefits such as flood mitigation and improved water quality from stormwater runoff reduction.** By storing and infiltrating stormwater, a bioretention or infiltration practice reduces stormwater runoff, which helps to mitigate flood impacts, reduce erosion, and improve water quality by preventing the pollution of local waterways. It also increases the potential for groundwater recharge. Available water supplies are increased by reducing the amount of water pumped for irrigation.

  Bioretention BMPs are a proven method of pollutant removal in the northern states, but how well do they remove pollutants in Texas, which has a different climate and different soil types? Interested in the answer to this question, the Texas Department of Transportation (TxDOT) asked the Texas A&M Transportation Institute to embark on an investigation. As part of a larger effort spanning five years, the research team created a pilot demonstration cell on a highway roadside. The results of the project, completed in August 2012, revealed that the BMP surpassed the state requirements of removing 80% of pollutants from runoff. In fact, it removed more pollutants by absorption than sand, a common BMP.

  Promising results have been seen in other pilots, such as a 2013 Texas A&M AgriLife project that evaluated the performance of permeable pavements and bioretention in a typical urban watershed in the Dallas-Fort Worth area, an area characterized by soil with a very high clay content, an underlying calcareous layer, and low permeability. The Texas A&M AgriLife pilot found decreases in runoff volume, contaminant loads, flow rate, and flooding and increased groundwater recharge in their systems. The bioretention BMP data showed runoff reduced by 50%, nitrate reduced by 78%, and TSS reduced by more than 80%.

This effectiveness has been seen in real-world projects in the North Texas region as well. The Green at College Park (University of Texas – Arlington) [CS 1], a 3-acre urban infill development on the campus border, provides a great example of reduced runoff and improved water quality. Previously a block of parking and dilapidated apartments contaminated with asbestos, it had 75% impervious surfaces. An eroded drainage channel flanking the western edge of the site was associated with considerable flooding issues. The stormwater management constraints became key opportunities in the final design, which includes an aesthetically-pleasing drainage garden and depressed gathering lawn in addition to a pedestrian walk paved with a pervious recycled glass material (see Figure 23). These elements serve as both a park amenity and stormwater management. The site is designed to improve runoff water quality by reducing total suspended solids 80% and stormwater quantity 25% in volume from a two-year, 24-hour storm.


Figure 23. The Green at College Park (University of Texas – Arlington).

Several GSI elements were implemented at the 104.6-acre Timber Creek High School campus [CS 15] in Fort Worth, Texas, which opened in 2009 and is a 2014 winning entry for the EPA Region 6 Green Infrastructure & Low Impact Development Poster Competition. The project site includes an internal loop road and a parking lot. A retention pond gathers stormwater for reuse in irrigation and controls peak discharges. Bioswales improve stormwater quality and remove silt and sediments. A desilting pond that controlled sediment and silt during construction now acts as the sediment forebay, and a sediment pond and silt dam removes additional silt and sediment. These elements remove 80% TSS and collect 100% of the site's stormwater. Ponds filled to capacity provide approximately two weeks of irrigation.

For the 2013 Bagby Street Reconstruction project [CS 20] in Houston, Texas, which was prompted by a 2008 drainage study to address flooding issues in the area, 33% of stormwater runoff enters the rain gardens. The rain gardens filter and remove pollutants from stormwater before it enters the storm sewers, bayous, and ultimately Galveston Bay, removing 75% of bacteria, 73% of phosphorus, 93% of oil, and 85% of TSS.

Stormwater runoff management can also be incorporated underground, which allows for it to be integrated with certain recreational facilities. The subsurface infiltration feature in the Clark Park Infiltration Bed/Basketball Court project [CS 33] in Philadelphia, Pa., manages runoff from the basketball court, an adjacent street, and a parking lot (32,517 ft^2 of impervious area). The system has been designed to capture about 1.5 inches of rainfall from the contributing drainage area, but with its well-drained soil, the project owners anticipate that actual stormwater capture will be much greater.

- **Substantial cost savings.** Integrating bioretention and infiltration features can lead to a substantial cost savings, whether through stormwater credits, a reduced or eliminated need for gray infrastructure, reduced spending on irrigation, avoided property damage due to flooding, or avoided costs related to impaired waters.

  For the City of Denton, Texas, GSI BMPs are part of its strategy to reverse declining water trends due to increased development pressures within the Hickory Creek watershed. The City aims to keep its drinking source, Lake Lewisville, off the Texas Commission of Environmental Quality (TCEQ) list of water-quality impaired waters. If the lake were deemed impaired, the necessary responses could cost the city millions of dollars, according to the City's environmental compliance coordinator.

Figure 24. Green infrastructure elements at the Dallas Urban Reserve.
Source: Kevin Sloan Studio.

The biofiltration street design at the Dallas Urban Reserve [CS 5] that incorporates an asymmetrical slope that directs stormwater into a system of rain gardens and sedimentation ponds (see Figure 24) shows that potential savings can benefit more than the project owner. The asymmetrical slope eliminates the need for inlets, catch basins, or stormwater plumbing along an entire street side, saving tax dollars. The replacement of water-thirsty landscapes with naturalizing ecologies can save households substantial sums that might otherwise go toward turf irrigation. The continuous use of a laydown curb profile eliminates the cost for curb cuts.

Timber Creek High School's GSI implementation achieved credits from the City of Fort Worth, which reduced its stormwater fee. The reuse of its captured stormwater is estimated to save the campus $130,000 on irrigation each year.

Birnamwood Drive [CS 21], a roadway project in Harris County, Texas, was one of the first roadway projects in the Houston area to implement these techniques. One goal was to make its implementation less expensive than that of a conventional design, and it succeeded. With the 32-foot depressed median in the middle of a four-lane concrete boulevard, Birnamwood Drive requires no off-site detention facilities, which saved the county more than $350,000 in land and excavation costs. The LID design resulted in a 7% cost reduction versus a traditional design (see Table 19 in Appendix F for more details).

- **Decreased need for water treatment, which leads to cost savings, energy savings, and reduced air pollution.** By reducing the volume and improving the quality of water entering treatment facilities, GSI decreases the need for water treatment, saving costs related to water treatment. It also saves energy that would be used for treatment; this, in turn, reduces air pollution by decreasing greenhouse gas emissions.

  A February 2014 case study of Lancaster, Pa., performed by the EPA found that installing green infrastructure in the combined storm sewer (CSS) area could reduce gray infrastructure capital investments by $120 million and associated wastewater pumping and treatment costs by $661,000 per year. Across the entire city, including the areas with municipal separate storm sewer systems, the green infrastructure plan was estimated to provide approximately $4.2 million in air quality, energy, and climate-related benefits each year.

- **Mitigation of the urban heat island effect, which can lead to energy savings, cost savings, and improved air quality.** Through evaporative cooling and shading, these green approaches can mitigate the urban heat island effect, reducing energy use and costs for cooling purposes, which in turn reduces pollutant emissions from power plants. Using green practices that reduce temperatures can mitigate smog and ozone formation. Urban vegetation also removes pollutants from the air.

  The U.S. Department of Agriculture (USDA) National Agroforestry Center promotes the use of vegetation in buffers, noting that they can reduce temperatures and reduce energy use for buildings. Vegetation also removes pollutants from the air by uptake and interception. The Center notes that a 65- to 600-foot-wide buffer may reduce particulate pollution by 40% to 75%.

The Bagby Street project in Houston (see Figure 25) leveraged the benefits of trees to positively impact air quality and increase human comfort in Texas summers. The project resulted in a 12˚F decrease in surface temperature.

The Dallas, Texas, Elm Street Streetscape [CS 6] design improvements include 26 rain gardens and many street trees and planting areas. Previously, the site was more than 90% hardscape. Given the significantly increased amount of plant materials onsite, the City of Dallas expects air quality to be improved.

Figure 25. Bagby Street Project. © Shau Lin Hon - Slyworks Photography/Walter P Moore.

- **Improved community livability, increased economic development, and increased property values.** Vegetated GSI can improve local aesthetics and also enhance recreational opportunities and public safety. Several of the region's case studies reported improved aesthetics, which supports economic development, and increased property values as project benefits.

  For the Green at College Park (University of Texas – Arlington), a redevelopment project incorporating rain gardens and a depressed lawn revitalized the site and provided a green public open space. The City of Fort Worth's improvements in the Historic Handley Urban Village Streetscape project [CS 13] included rehabilitating sidewalks close to storefronts, creating a more inviting location to shop (see Figure 26). The Elm Street Streetscape project widened sidewalks and narrowed streets to increase pedestrian safety while beautifying the site and improving the public realm experience. The City of Rowlett completed Merritt Road [CS 17] in 2013, which integrated a treatment train drainage system in approximately 1.7 miles of roadway improvements, using medians that contain native plantings, vegetated swales, and four bioretention systems. The project is intended to support the area as a technology corridor and to attract related business.

Figure 26. Historic Handley Urban Village Streetscape's rehabilitated sidewalks. Top image source: City of Fort Worth.

The Bagby Street Project, part of the City of Houston's Midtown Tax Increment Reinvestment Zone Capital Improvement Program, was much more than a drainage improvement and street reconstruction project to the design team. It was an opportunity to redevelop the Bagby corridor to better serve its diverse and mixed-use community. The project included a 38% increase in seating and social gathering areas, and has seen a 25% increase in rental market rates ($1.40 to $1.75 average per square foot per month). Since the announcement of the project, private development has increased by $25 million.

In St. Louis, Mo., a redevelopment of a diverse historic district called the South Grand Boulevard Great Streets Initiative transformed a six-block corridor into a vibrant destination. The Initiative's final boulevard design incorporated innovative stormwater management with enhanced walkability and opportunities for economic development.

- **Increased wildlife habitat and biodiversity.** Bioretention BMPs can create and improve habitat for wildlife and increase biodiversity. Green infrastructure approaches such as rain gardens and bioswales can act as patches of habitat in a matrix of urban landscape, supporting wildlife with appropriate plant choices.

  At the South Grand Boulevard Great Streets Initiative project in St. Louis, the expanded sidewalk provides room for not only more pedestrians and outdoor diners, but also for significantly larger tree boxes. The plants—native to the state, locally available, and able to withstand harsh street conditions—are expected to increase bird and butterfly populations.

  The design for the Perot Museum [CS 8] in Dallas, Texas, reflects a cross-section of the Texas landscape from west to east. This representation of the indigenous landscape provides habitat for the creatures that live in these systems. The landscape does not contain itself to the living roof or the plantings alongside the building; it moves into the parking lot, where bioswales collect stormwater runoff for a cistern system.

- **Public education opportunities.** Some project sites are perfect public education opportunities. Such is the case for the Perot Museum in Dallas with its mission to inspire minds through nature and science. Its parking lot bioswales are described on signage that visitors can read on their way in and out of the museum (see Figure 27). Teaching opportunities are also plentiful at the Green at College Park, where the flowing form of the park celebrates the movement and cycles of water and plant life that thrives from its drought and flood dynamics.

Figure 27. Educational signage about bioswales in the Perot Museum parking lot.


Figure 28. The Elmer Paseo Stormwater Improvement Project transformed an asphalt alley (top) into a green alley (bottom). Source: Council for Watershed Health.

The 2012 Elmer Paseo Stormwater Improvement Project in Los Angeles, Calif., [CS 23] transformed a degraded asphalt alley into a green alley with a pervious concrete pathway, a vegetated bioswale, a subsurface infiltration trench, and a palette of plants native to the watershed (see Figure 28). Although compact (under 6,000 ft^2), it captures stormwater from 20 acres. Used as an outdoor classroom, the project serves to educate not only the general public, but also the project owners. As a demonstration project, it acts as a living laboratory to test and demonstrate BMPs. The green practices are monitored to evaluate surface water quality improvements, water conservation, groundwater recharge, changes in property values, and other benefits.

The BMP demonstrations in the Texas A&M AgriLife pilot project also acted as a living laboratory. The researchers leveraged their experiences and findings in educational programming and presentations at conferences to help support an increased awareness by surrounding cities, engineers from major consulting firms, and the water resources community.

The Bagby Street case study notes that the rain gardens complement adjacent developments and introduce a natural element that offers both aesthetic and educational benefits. The design solutions implemented on the Bagby Street project demonstrate to the community, government entities, and the engineering profession the quantifiable benefits derived from applying focused engineering principles to context-specific, low-impact design (LID) strategies. The project further demonstrates that LID can be implemented within a highly urbanized area, improving quality of life and yielding positive economic impacts.

5.2.3 Limitations/Considerations

- **Challenges in obtaining approval of site controls for pioneer projects.** For pioneer projects, the unfamiliarity or relative newness of the approaches in this region may present challenges in obtaining approval for site controls.

The Rayzor Ranch Marketplace [CS 11], a 100-acre retail center within a 400-acre mixed use development in Denton, Texas, was the first major project in the city to incorporate

GSI features. It began in 2008; Phase 1 construction was completed in 2010. The project's site controls include a water quality pond, four bioretention areas, a pocket wetland, an enhanced swale, a filter strip, and several parking lot islands with filter strips. The project staff faced a challenge in coordinating with City staff and obtain buy-in across different departments and from the client. The landscape architects for Nashville's Deaderick Street (see Figure 29) also mentioned resistance from City staff, but, like the Rayzor Ranch case study, this issue was linked to the project being the first of its kind. (Deaderick Street was Tennessee's first green street.)

These challenges may lessen over time; now the City of Denton is leveraging several GSI features in its projects to reduce the likelihood of Lake Lewisville becoming impaired, and Nashville is building more green streets.

- **Potential for higher costs.** The initial cost (either of GSI materials or installation) may be higher than those for traditional gray infrastructure controls. Project costs may also be higher than expected due to unfamiliarity with the approaches and a lack of experience at various levels.

  When a new bus station relocated the transit hub from Deaderick Street, Nashville, Tenn., to one block north, the city took the opportunity to re-envision the street as a green streetscape [CS 40]. Its bioretention areas, 4-feet-deep planting zones with bioretention soils, and structural soils for trees treat approximately 1.2 million gallons of stormwater per year. However, the Deaderick case study that found a lack of trust in the engineering design resulted in overdesigned infrastructure and unnecessary costs.


Figure 29. Deaderick Street's green streetscape.
Source: Hawkins and Partners.

  In Texas A&M Transportation Institute's bioretention pilot project [CS 19] in Bryan, Texas, the researcher reported that the cost was originally estimated at $5,888, but the total cost increased to $8,978 because the person building the bioretention feature had not built one before. In a similar vein, the Texas A&M AgriLife pilot's construction bids came in much higher than the engineer's estimate. The AgriLife researcher noted that this was probably due to the constructor's lack of expertise in this relatively new field.

  However, increased costs are not a given. The Birnamwood case study reported that the Birnamwood project cost less than its gray counterpart. Its case study also noted that subsequent LID-based Harris County roadways have reduced costs even further, which suggests that as more GSI is implemented and the controls become more familiar, costs may come down.

- **Importance of understanding the project's site.** GSI is not a "one size fits all" approach. Well-designed bioretention and infiltration features capture all or nearly all of the precipitation that falls on the feature and its related drainage area. However, in an urban context, the percentage of rainfall that these features can accommodate depends on available square footage and locally-defined maximum ponding times. Determining a site-specific performance measure requires complex hydrological modeling. The Deaderick Street case study discovered that it is crucial to determine the percolation rate, soil type, and existing conditions through on-site testing. Because earthwork may have been completed since national soils data collection in the 1960s, soils maps are not always reliable.

- **Importance of choice and placement for plants.** Plants in bioretention features should be chosen with care. The design of the feature will also need to consider the best placement for the plants. Plants come in a range of sizes and grow to various heights, which may impact plant placement, especially with tall plants. For example, the design for the Merritt Road project in Rowlett, Texas, incorporates safe roadway geometrics by avoiding plantings in sight triangles at intersections, the consulting firm reports. Plants also have different tolerances for drought, heat, inundation, shade, and so on. In addition, they have different pollutant uptakes. It is important to understand plant characteristics and to choose plants wisely; otherwise, one should allow for some experimentation to figure out which plants work best, as the Fort Worth Nature Center and Refuge is currently doing with the parking lot bioswales [CS 12]. For more information on native and adapted plants, see Appendix F.

- **Potential for challenges emerging during design and construction.** As with many innovative approaches, challenges may emerge during design and construction. Yet with the sharing of knowledge and an increased familiarity, these challenges are expected to lessen over time, especially with pilot projects that aim to resolve specific issues.

  Several lessons learned were shared in the case studies.

  - For Dallas Urban Reserve, changing the rain gardens' grading so they could hold up to 12 inches of stormwater at their deepest point is one adjustment considered for the future. Other future considerations include selecting a plant that might save even more water and irrigation costs than the current horsetail reed and accounting for low water levels when considering the aesthetic of pond edges.

  - The Bagby Street team learned from past mistakes, ensuring their designs incorporated appropriate engineered soils and bridge aggregates and allowed for proper flow dissipation.

  - At Rayzor Ranch, the engineering and design firm found that it is vital to ensure that the contractor properly pours the paving around the islands and smooths the pavement between the sawtooth curbs. Otherwise, ponding at the curb face is a potential issue.

  - At Merritt Road, the consultants found that contractors should purchase products in advance to avoid cost increases. They also noted the importance of making sure that installers are available to guide the installation of the bioretention materials.

  - The Merritt Road and Birnamwood Drive case studies both mentioned the importance of understanding all possible impacts during the roadway's construction and maintenance. Vegetation needs to be established to prevent clogging. The Birnamwood Drive case study recommended installing BMPs last and supplying ample BMP protection when possible.

  These challenges and lessons learned are not necessarily negatives. They deepen the knowledge of an approach and open the door for improvements. During its investigation of bioretention in hot, semi-arid areas, the Texas A&M Transportation Institute converted its design into one that allowed for internal water storage (IWS) to improve the water quality and performance of bioretention. In the end, the researchers found its effectiveness to be better than that of sand, a common BMP. In Birnamwood, the need to maintain the vast majority of the bioswale under currently established maintenance protocols led to innovative problem solving. As a result, the team figured out how to make the system's footprint smaller.

- **Importance of maintenance, which does not always have well-established guidelines.** The budget should include maintenance costs, and the party responsible for maintenance should be determined during the planning process.

  For the Texas A&M Transportation Institute pilot, the lead researcher noted that maintenance of bioretention is an important item, and more time and research are needed to create guidelines.

  Many case studies underscored issues related to maintenance costs. Fort Worth's Historic Handley project owner foresees it as a challenge, noting that with budget constraints, long-term maintenance may not be achievable. The Deaderick Street landscape architect recommended that budgets include maintenance costs and that the party responsible for ongoing maintenance should be determined during the planning process (for example, the public works or parks department, another agency, or a contracted party).

  The Elmer Paseo project proposed that challenges related to inspection and maintenance funding could be resolved by valuing these projects as assets similar to gray infrastructure, which are funded for long-term maintenance. New York City's Department of Environmental Protection settled this issue by partnering with the Parks Department to maintain GSI in the right-of-way [CS 32]. The Elm Street project includes a two-year contract for maintenance; during this time, the maintenance crew will train a volunteer group to handle the upkeep after the contract ends. Denton has reduced costs by using volunteers. The design process for the Blue Hole Regional Park [CS 22] in

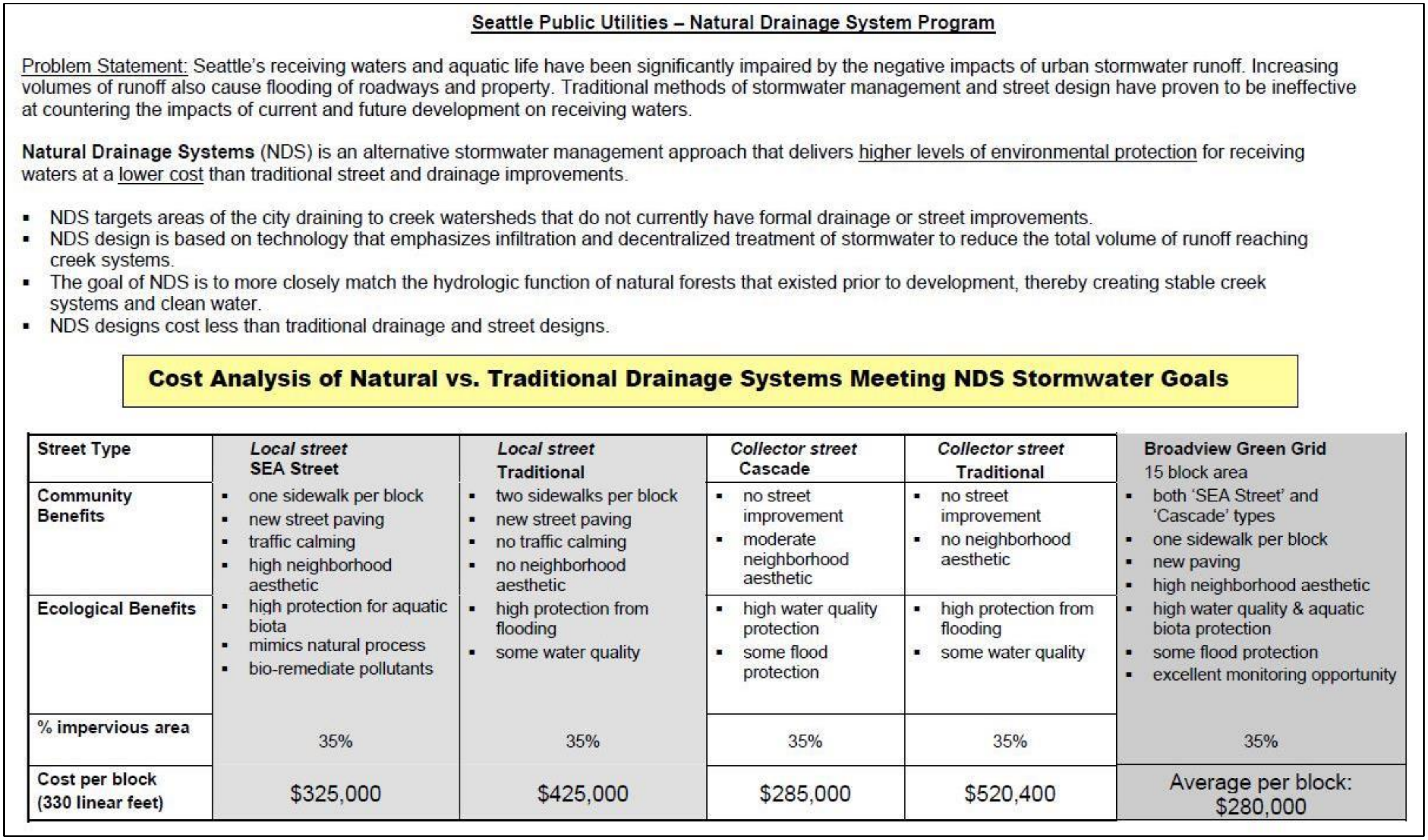
Wimberley, Texas, included the creation of an operation, management, and monitoring plan, which incorporated a budget. Long-term annual operation costs for maintenance and management are paid for by the park entrance fees and through an endowment.

For more information on maintenance costs, see the following Costs and Life Expectancy section.

5.2.4 Costs and Life Expectancy

As mentioned in the Limitations/Considerations section, the initial cost of green infrastructure practices may be higher than gray infrastructure. Project costs may also be higher than expected due to unfamiliarity with the approaches. However, this is not always the case. As highlighted on EPA's Cost-Benefit Resources webpage (http://water.epa.gov/infrastructure/greeninfrastructure/gi_costbenefits.cfm), green infrastructure may provide more benefits for less cost than single-purpose gray infrastructure.

Seattle Public Utilities examined the costs and benefits of traditional versus natural drainage systems (i.e., GSI projects using vegetated swales and narrow streets) and found that not only did the systems provide benefits such as traffic calming, improved neighborhood aesthetic, and high water quality protection, but the designs also cost significantly less than traditional drainage and street designs (see Figure 30).



Seattle Public Utilities – Natural Drainage System Program

Problem Statement: Seattle's receiving waters and aquatic life have been significantly impaired by the negative impacts of urban stormwater runoff. Increasing volumes of runoff also cause flooding of roadways and property. Traditional methods of stormwater management and street design have proven to be ineffective at countering the impacts of current and future development on receiving waters.

Natural Drainage Systems (NDS) is an alternative stormwater management approach that delivers higher levels of environmental protection for receiving waters at a lower cost than traditional street and drainage improvements.

- NDS targets areas of the city draining to creek watersheds that do not currently have formal drainage or street improvements.
- NDS design is based on technology that emphasizes infiltration and decentralized treatment of stormwater to reduce the total volume of runoff reaching creek systems.
- The goal of NDS is to more closely match the hydrologic function of natural forests that existed prior to development, thereby creating stable creek systems and clean water.
- NDS designs cost less than traditional drainage and street designs.

Cost Analysis of Natural vs. Traditional Drainage Systems Meeting NDS Stormwater Goals

Street Type	***Local street*** **SEA Street**	***Local street*** **Traditional**	***Collector street*** **Cascade**	***Collector street*** **Traditional**	**Broadview Green Grid** 15 block area
Community Benefits	▪ one sidewalk per block ▪ new street paving ▪ traffic calming ▪ high neighborhood aesthetic	▪ two sidewalks per block ▪ new street paving ▪ no traffic calming ▪ no neighborhood aesthetic	▪ no street improvement ▪ moderate neighborhood aesthetic	▪ no street improvement ▪ no neighborhood aesthetic	▪ both 'SEA Street' and 'Cascade' types ▪ one sidewalk per block ▪ new paving ▪ high neighborhood aesthetic
Ecological Benefits	▪ high protection for aquatic biota ▪ mimics natural process ▪ bio-remediate pollutants	▪ high protection from flooding ▪ some water quality	▪ high water quality protection ▪ some flood protection	▪ high protection from flooding ▪ some water quality	▪ high water quality & aquatic biota protection ▪ some flood protection ▪ excellent monitoring opportunity
% impervious area	35%	35%	35%	35%	35%
Cost per block (330 linear feet)	$325,000	$425,000	$285,000	$520,400	Average per block: $280,000

Figure 30. Seattle Public Utilities Cost Analysis of Natural vs Traditional Drainage Systems.
Source: Seattle Public Utilities, n.d.

One example of using GSI to reduce potential future costs can be seen in the City of Denton. Its goal is to keep Lake Lewisville's waters unimpaired because impairment would cost the City millions of dollars to resolve. EPA's webpage provides several resources and tools that demonstrate the potential for green infrastructure to improve not only the environmental outcome but also the financial performance and social impact at multiple scales.

One challenge in analyzing the costs gathered in NCTCOG's case study research is that bioretention and infiltration practices are often used together, so costs and benefits for each practice may not always be easily separated. For example, excavation costs for several pieces of the project are often consolidated, so it may not be clear how much to allot for one piece.

Treatment trains also work as a whole, so divvying up the cost between each included practice may not always be appropriate. In addition, designs, costs, and benefits are site-specific.

However, this specificity in site and design allows designers to use their ingenuity to reduce costs for installation or maintenance, as seen in the Merritt Road consultant's decision to use fewer inlets and eliminate sod in the median to reduce maintenance. See the previous Potential Benefits section for more case study examples of how green infrastructure can reduce costs or increase long-term savings. A more in-depth discussion of challenges related to cost analysis is available in Appendix C.

The *San Antonio River Basin Low Impact Development Technical Design Guidance Manual* provides the following common cost considerations in planning and designing BMPs. These are provided only as a starting point; the San Antonio manual points out that these numbers must be refined throughout the project's design phases.

- Planning: 10% of total project cost
- Design: 30% of total project cost
- Mobilization: 11% of total project cost
- Contingency: 20% of total project cost
- Site preparation:
  Cleaning and grubbing: \$0.24-0.50/ft^2
  Asphalt removal: \$2.32/ft^2
  Concrete removal: \$2.39/ft^2
  Sidewalk removal: \$1.21-2.39/ft^2

Using 2013 unit bid costs from TxDOT, the City of Austin, and the City of San Antonio, the following planning-level cost estimates were developed.

- Bioretention and bioswale: \$23.57-\$33.67/ft^2 (without underdrains) or \$24.72-\$34.82/ft^2 (with underdrains) plus \$18/ft for curb and gutter
- Planter box: \$23.62-\$33.72/ft^2 plus \$18/ft for curb and gutter
- Vegetated swale: \$1.87-\$1.94/ft^2
- Filter strip: \$0.82-\$0.89/ft^2

For a detailed list of items included in the above costs, see Table 15 in Appendix D.

Examples of Costs from Case Studies

When evaluating the costs provided by the case studies, the reader should be aware that the information provided by each case study varied. For example, one estimate did not provide planting or soil costs, while other estimates did not include excavation or grading costs because those could not be accurately calculated for a specific green element when the costs available were for the entire project.

Rayzor Ranch North – Denton, Texas – 2013-2014

Rayzor Ranch North (officially Rayzor Ranch Marketplace) is a 100-acre retail center in Denton, Texas, with an ultimate build-out of approximately 800,000 ft^2 of retailers, restaurants, and financial institutions. Rayzor Ranch North incorporates several iSWM site controls: a water quality pond, four bioretention areas, a pocket wetland, an enhanced swale, a filter strip, and several parking lot islands with filter strips as components in the treatment train. (An example of the parking lot island can be seen in Figure 31.) This case study highlights the project's parking lot islands and sawtooth curbs because the engineer/design firm had the most recent information available for those.

Figure 31. Parking lot island with sawtooth curbs at Rayzor Ranch North, Denton, Texas.
Source: Dunaway Associates.

These are early treatment train areas. The water runs off the pavement through rock, grass, and mulch, which then drain into a wye inlet and down the storm system. Some rock and landscaping in the interior portion is included to help filter water. Each 36 ft. x 18 ft. island costs around $5,716, or $8.82/ft^2. Details are included in Table 8.

Table 8. Costs of a parking lot island with sawtooth curbs at Rayzor Ranch North.

Item and quantity	Cost
108 linear feet concrete curb	$756
$10 per sawtooth opening at curb x 36 openings	$360
Wye inlet	$1,500
Trenching and haul off $55 per cubic yard x 15 cubic yard	$825
Furnishing and installing gravel fill $60 per cubic yard x 15 cubic yards	$900
Landscaping (excludes irrigation) and river rock	$1,375
Total	**$5,716**

Merritt Road – Rowlett, Texas – 2013

The design for Merritt Road integrates sustainable features, including medians that contain native plantings, vegetated swales, and four bioretention systems (see Figure 32). These features combine to form a "treatment train" drainage method: open vegetated swale, forebay sediment filtering, biological uptake of pollutants with native plantings, and filtration of water before discharge. The treatment train cost an estimated $270,700 for the 1.7 miles of roadway improvements. The system focuses on the application of low maintenance and cost-effective stormwater control design solutions aimed to improve water quality, reduce landscaping maintenance and irrigation demands, and provide cost savings. The life expectancy is 15 years without reduction in pollution removal efficiency.

Figure 32. The construction of bioswales in the median on Merritt Road, Rowlett, Texas.
Source: Freese & Nichols.

Elm Street Streetscape Improvements – Dallas, Texas – Spring 2015

As part of its Complete Streets Initiative, the City of Dallas is reconstructing a portion of Elm Street, narrowing the streets, widening the sidewalks, improving drainage, improving accessibility, and upgrading water and wastewater mains. The design includes 26 rain gardens with native plants, pedestrian walks, and permeable pavement around tree wells in portions of the sidewalk. Figure 33 shows a plan for one of the rain gardens. With the constraint on the downstream drainage system, the use of stormwater for rain gardens helps conserve water and mitigate downstream effects.

The 26 rain gardens cost a total of $378,000, or an average of $14,543 each. This estimate included bed preparation, top soil, compost, plants, mulch, rain garden inlets, and concrete bands. Other costs included irrigation and landscaping ($102,000) and maintenance over two years ($69,000).

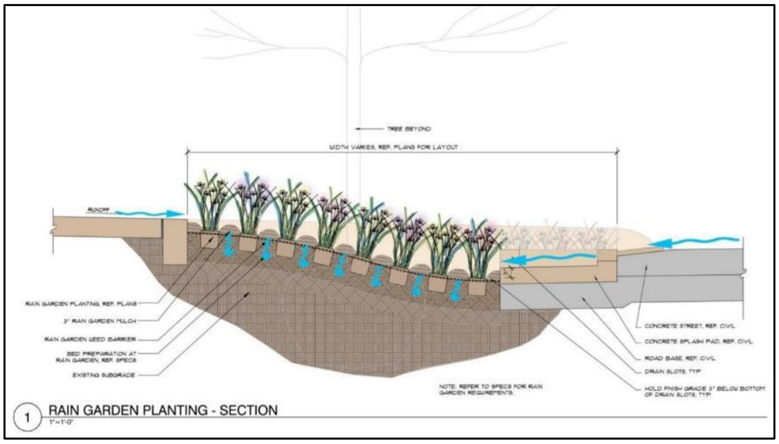


Figure 33. Plan of rain garden planting for the Elm Street streetscape improvements.
Source: CCA Landscape Architects.

Timber Creek High School – Fort Worth, Texas – 2009

The Timber Creek High School project includes several green infrastructure elements, including bioswales, a desilting pond, a sediment pond and silt dam, and a retention pond, which controls peak discharges and captures stormwater that will be reused for irrigation (see Figure 34). Costs associated with the ponds are listed in Table 9.

Figure 34. Green infrastructure elements at Timber Creek High School, Fort Worth, Texas.
Source: Teague Nall & Perkins.

Almost 90 acres drain into the pond system. The west pond's volume is 17.1 acre feet. It has three aeration devices to oxygenate water and connects to the Trinity Well Aquifer. The east pond's volume is 3.2 acre feet. It has one aeration device to oxygenate water and connects to the Paluxy Well Aquifer. Ponds filled to capacity provide approximately two weeks of irrigation before engaging the wells.

Table 9. Costs of green infrastructure improvements at Timber Creek High School.

Direct costs from the subcontractors that are part of the larger project	
Mass excavating including bioswales	$174,000
Boulder and gabions	$416,000
Wheaton wall	$108,000
Outfall structure	$54,029
Channel and dry creek bed	$20,000
Underground storm drainage	$117,000
Water wells drilling	$242,670
Well completion and pumps	$100,830
Subtotal	**$1,232,529**
10% for general conditions, insurance, etc.	$123,253
Total	**$1,355,782**

The project's green infrastructure saves money in two ways. First, the stormwater fee is reduced. Second, due to the reuse of stormwater in irrigation, the amount of potable water purchased is reduced. Annual demand is about 37.2 million gallons, which would cost $212,000 per year if purchased from the City supply, according to the case study's calculations. The well water cost, including electricity and maintenance, is $82,000 per year. The expected savings on water is $130,000 per year, a substantial savings that would pay for the above improvements in less than 11 years, even excluding the stormwater fee reduction.

For costs for the following case studies, see Appendix F:

- Perot Museum of Nature and Science – Dallas, Texas
- St. Stephen's Pedestrian Green – Austin, Texas
- Bioretention for Stormwater Quality Improvement in Texas – Bryan, Texas
- Bagby Street Reconstruction – Houston, Texas
- Birnamwood Drive – Houston (North Harris County), Texas
- SE Clay Green Street – Portland, Ore.
- Area-wide Right-of-way Bioswale – New York City, N.Y.
- Clark Park Infiltration Bed (Basketball Court) – Philadelphia, Pa.

Maintenance Costs

For a base point for costs, which illustrates the importance of including maintenance costs in the project's budget, see Table 16 in Appendix D. This is a condensed version of a table found in Appendix G, "Cost Estimates and Regulatory Guidance" of the *San Antonio River Basin Low Impact Development Technical Guidance Manual.* Maintenance costs were based on Water Environment Federation research with labor and equipment operating costs collected from TxDOT and municipalities. It does not include all bioretention and infiltration BMPs discussed in this guide. For examples of inspection and maintenance tasks for bioretention and bioswales, see Appendix F.

5.3 Trees: Structural Support and Runoff Retention

Figure 35. Native trees create a shady grove at St. Stephen's Pedestrian Green, Austin, Texas.
Source: Reese Hyde.

5.3.1 Overview

Preserving and enlarging the tree canopy has emerged as an important goal over the past several years, according to the 2008 U.S. Conference of Mayors report "Protecting and Developing the Urban Tree Canopy," which contained contributions from the cities of Frisco, McKinney, and Mesquite, Texas. This goal can also be seen in Dallas's Urban Forest Advisory Committee, whose mission is to conserve and promote Dallas's tree canopy, and Fort Worth's 2006 tree ordinance, which aims for 30% tree canopy coverage citywide.

Most recently, the Texas Trees Foundation and more than 40 North Texas cities partnered to create Tree North Texas. The Tree North Texas urban forestry initiative is the largest in the nation, aiming to plant 3 million trees in North Texas over the next 10 years. While that number seems immense, so is the number of trees lost during the 2011 Texas drought. Approximately 300 million rural trees and 5 million urban trees died, reported a Texas A&M Forest Service survey. In North Texas, the drought-related mortality was approximately 8.3%, which equals 30.9 million trees. In addition, other trees have reached the end of their natural lifespans, succumbed to disease or insects, or were removed to make room for development. In other words, those 3 million trees will be crucial in preserving the region's tree canopy.

5.3.2 Potential Benefits

- **Environmental benefits from rainfall interception and increased infiltration.** By intercepting rainfall and helping increase infiltration, trees reduce runoff volume and surface transport rates. A Tree City USA Bulletin states that the urban forest can decrease annual runoff by 2%-7%; furthermore, as much as 65%-100% of rainfall can be retained when trees are combined with other natural landscaping. Through their canopies and roots, trees contribute to soil stabilization, cleaner water, and groundwater recharge. Interception also helps reduce erosion of barren ground.

- **Reduced urban heat island effect and reduced energy consumption.** Trees help mitigate the urban heat island effect by releasing water into the atmosphere and providing shade, which can also help reduce energy consumption. Building surfaces have been shown to be cooled by up to 45°F, the Dallas Sustainable Skylines Initiative (DSSI) reports. Trees can also reduce wind speeds, which can have a significant impact on the energy needed for heating. A tree's ability to provide shade and block winds can result in reduced building energy consumption.

- **Improved air quality.** Because building energy consumption can be reduced with properly placed trees, trees help reduce greenhouse gas emissions, the Center for Neighborhood Technology reports. Trees can reduce atmospheric CO_2 levels through direct absorption. They also absorb pollutants and intercept particulate matter. In the 2014 article "Tree and Forest Effects on Air Quality and Human Health in the United States" by Nowak et al. (2014), researchers found that the total amount of pollution removed in 2010 by trees and forests in the conterminous United States was 17.4 million tons. States with the highest pollution removal amounts were California, Georgia, and Texas (see Figure 36).

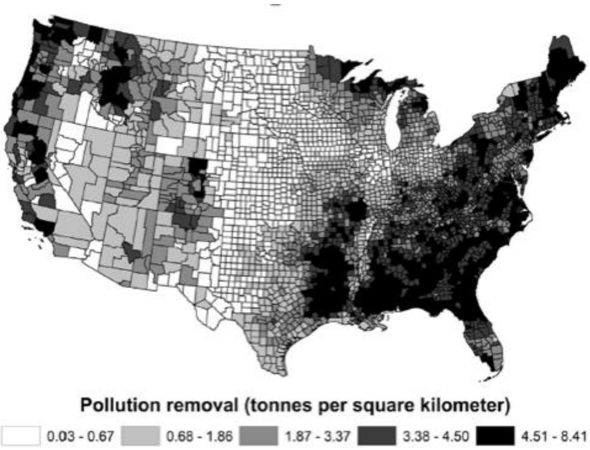


Figure 36. Estimated pollutant removal (NO_2, O_3, $PM_{2.5}$, SO_2) per square kilometer of land by trees per county in 2010.
Source: Nowak et al., Environmental Pollution. 2014.

- **Improved community and livability.** Trees can improve community aesthetics, provide a sense of place, and increase recreational opportunities by providing shade for hot areas.

They can also reduce local noise pollution by decreasing sound transmission. As an element of nature, trees can help restore the mind from mental fatigue. The movement pattern created by trees moving softly and rhythmically in a light breeze helps support a calm, stable mental state, which could in turn aid patients' recovery or improve worker or student productivity, a University of Washington research summary reports in its "Green Cities: Good Health" research division. The cooling functions of trees can also reduce heat-related illnesses and fatalities.

- **Provision of wildlife habitat, especially when native plant species are used.**

- **Economic benefits.** These benefits include energy savings, stormwater management, carbon storage, human health, quality of life, and air quality improvements. Trees can also increase property values.

  Although the initial cost of new tree plantings can be high, from $200 to $400 per tree, with maintenance, liability, and administration adding costs, the DSSI report stated that the net benefit can still outweigh the cost by as much as three to one. Estimated net annual benefits of street trees range from $30 to $90 per tree.

  Trees may increase property values up to 15%, the Missouri Department of Conservation reported, boosting a community's overall tax base and helping to pay for streets, schools, and police. Research by Kathleen L. Wolf at the University of Washington showed that shoppers in areas with street trees come more often, stay longer, and feel more positive about their purchases. Research by E. Gregory McPherson and Jules Muchnick noted that shade from trees protects pavement from high surface temperatures. Lowered surface temperatures make pavement less prone to rutting and cracking and increase pavement's durability. Their findings suggested that extensive shade can decrease the need for repaving, possibly by up to 25 years on a heavily shaded street, which translates into decreased spending.

  Nowak et al. (2014) found that the trees' pollutant removal of 17.4 million tons had a human health value of $6.8 billion. Most of the health values were derived from urban trees. The effects of reducing human mortality dominated these benefits; researchers found a national reduction of more than 850 incidences of human mortality. Other substantial health benefits include the reduction of more than 670,000 incidences of acute respiratory symptoms, 430,000 incidences of asthma exacerbation, and 200,000 school loss days.

For an example of quantified ecosystem service benefits, see Appendix F (Section F.2.1) for a summary of Southern Methodist University's campus tree inventory done by the Texas Trees Foundation.

5.3.3 Limitations/Considerations

To provide as many benefits as possible, trees need to live a full, healthy lifespan. Unfortunately, tree roots can suffer from soil compaction and lack of space in urban spaces, causing higher tree mortality and increased replanting costs. Structural soil, tree pits, and Silva Cells are a few ways to counter these issues. Planting the right tree in the right place is also key to obtaining the most benefits. For more information, see http://forestry.usu.edu/files/uploads/PlantingTreesEnergyConservation.pdf.

Structural Soil

Structural soil is a medium made of a mixture of rock and soils that can be compacted to pavement design and installation requirements while permitting root growth. According to a Tree City USA Bulletin, it is one of the most significant urban forestry developments in recent decades. Structural soil can be used under sidewalks and parking lots to provide the strength needed for paving or compaction while supplying tree roots with a comfortable environment.

The use of structural soil provides several benefits, according to the bulletin.

- It provides a reservoir for runoff that can then percolate deeper into the subsoil and potentially recharge groundwater. Notes: Soil type affects infiltration. With poor infiltration rates, drain pipes may be necessary.
- It allows deeper root development, which translates into larger tree canopies, more intercepted precipitation, and more uptake by roots for transpiration.
- It can be used under paved areas.
- Normal amounts of surface pollutants are intercepted before reaching waterways.
- The space can be shared with utilities.

Tree Pits

Traditional tree pits can also contribute to runoff retention, especially if they are engineered for water to drain into the pits with sloping pavement, curbs with inlets, and so on. The Tree City USA Bulletin recommends using greater soil volume, connecting pits with trenches, and ensuring that either the subsoil can receive percolating water or that a drain system is implemented to prevent drowning of the root system.

Silva Cells

Silva Cells, crate-like structures filled with soil, possess similar engineering attributes to structural soil and provide even more growing space for roots, the Tree City USA Bulletin reports. Acting as modular building blocks, they can contain healthy soil beneath paving while accommodating surrounding utilities and supporting traffic loads. According to DeepRoot Green Infrastructure, the manufacturer of Silva Cells, through soil filtration, bioremediation, and evapotranspiration, the Silva Cell helps treat stormwater on site, restoring ecosystem services and saving money while protecting an incredibly valuable resource.

Common applications include breakout zones, parking lots, streetscapes, and plazas. Installations in the North Texas region include Sundance Square Plaza in Fort Worth (installed in October 2013) and Main Street in downtown Rowlett (installed in July 2014).

5.3.4 Costs and Life Expectancy for Silva Cells

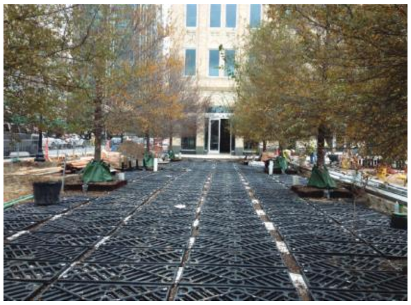


Figure 37. Sundance Square Plaza's Silva Cell installation.
Source: DeepRoot Green Infrastructure.

Converted from two old surface parking lots, the Sundance Square Plaza (see Figure 37) includes two rows of Cedar Elms along the plaza's perimeter. According to a case study done by DeepRoot, the project's landscape architect used 960 frames and 480 decks for the 18 trees to prevent soil compaction, foster growth, support a large canopy to provide shade, and use innovative irrigation techniques. The average soil volume per tree was 800 cubic feet.

For the Rowlett project (see Figure 38), trees previously installed in the area were not thriving due to poor soil condition, the landscape architect reported. Wanting the best possible outcome for the large investment in trees, the firm recommended the use of Silva Cells. The City installed enough cells to provide 61 trees with an average soil volume of 350 cubic feet. Rather than containing a tree in a 6 ft. x 6 ft. tree well, the trees in downtown Rowlett are all connected by 6 ft. x 80 ft. trenches, which gives the roots more space to grow. In addition, the adjacent concrete sidewalk is expected to need less maintenance because roots should have space to grow down rather than push the sidewalk up. The cost of the Silva Cells fror the contractor to furnish and install (including excavation, the Silva Cell material and miscellaneous materials such as drainage system, and aggregate) was $23 per cubic foot based on a quantity of 21,000 cubic feet for a total of $483,000.


Figure 38. Trees installed with Silva Cells in Rowlett, Texas.
Source: La Terra Studio.

Silva Cells' initial costs are much higher than that of standard tree installation. The design engineer for the Rowlett project estimated standard costs for trees and installation (without subsurface soil improvements) at $1,500 per tree. Costs of trees with Silva Cells, including Silva Cell material, excavation, and soil replacement of the entire Silva Cell installation, were estimated at $5,000 per tree. Costs depend on several factors, including site characteristics, the quantity of frames and decks, the tree size, and stormwater treatment goals. The manufacturer estimates that a Silva Cell system costs $14-$15 per cubic foot, not including the base course, the final paving, and the tree. (Each frame is 48 inches long by 24 inches wide by 16 inches high and holds about 10 cubic feet of soil.)

DeepRoot created a lifecycle analysis using the i-Tree tool, which is available at www.deeproot.com/silvapdfs/resources/articles/LifecycleCostAnalysis.pdf. The DeepRoot analysis shows the urban tree net lifecycle cost for a 50-year study period, based on typical costs and benefits for Minneapolis, Minn., to be approximately $3,000 for the tree without Silva Cells, and approximately $25,500 for the tree with Silva Cells. Even though installation costs and total maintenance costs of trees installed with Silva Cells are initially higher than those of a standard tree installation, the benefits from reduced building energy costs, stormwater interception, increased property values, and net value of carbon absorption are expected to provide a substantial cost savings. Unlike a traditional tree installation, Silva Cells can provide bioretention and help a project achieve a stormwater fee credit, providing further cost savings.

Trees are also expected to have a much longer lifespan—50 years versus 13 years. The longer lifespan gives trees the chance to grow to their full potential and provide more ecosystem service benefits, which also saves money due to the decreased frequency of purchasing and planting.

A Landscape Architecture Foundation (LAF) case study provides a real-world example: the Uptown Normal Street and Streetscape Project in Normal, Ill. This 2010 redevelopment project includes a new roundabout and Town green that incorporates stormwater management and public recreation into a vibrant gathering space (Figure 39). The streetscape features tree wells with Silva Cells. These cells provide 67 street trees with generous space for root growth in uncompacted soil, which also absorbs and filters runoff from downtown sidewalks.

Figure 39. Uptown Normal's new roundabout and Town green features tree wells with Silva Cells. Source: Town of Normal.

Some of the benefits listed by the LAF case study:

- Prevents 1.4 million gallons of stormwater per year from entering the municipal storm sewer by directing runoff into tree wells and planter areas with underground structural cells, which also recharges groundwater.
- Saves $61,000 in tree purchase and installation costs over 50 years by more than tripling the expected lifespan of street trees from 13 to 50+ years through the use of underground structural cells.
- Sequesters at least 10,790 pounds of carbon annually in 104 new trees.

FUNDING RESOURCES

The below list includes some funding resources related to green infrastructure. Webpage links are provided for further information.

- American Trails
  www.americantrails.org

  This website includes several webpages, including the “Funding and Resources” webpage (www.americantrails.org/resources/funding/index.html),
  that provides grant and funding opportunity information as well as tips on grant writing.

- NCTCOG’s Sustainable Development Funding Program
  www.nctcog.org/trans/sustdev/fundingprogram.asp

  This program is designed to address existing transportation system capacity, rail access, air quality concerns, and/or mixed use development in and around historic downtowns and Main Streets, in infill areas, along passenger rail lines, and at rail stations. Three Calls for Projects were conducted in 2001, 2006, and 2010 to fund Sustainable Infrastructure, Landbanking, and Planning projects.

- State Energy Conservation Office (SECO), Renewable Energy Incentives
  www.seco.cpa.state.tx.us/re/incentives.php

  The website as of March 2017 lists the following:

  - SECO funding opportunities for renewable energy, energy efficiency, and energy conservation projects and initiatives (www.seco.cpa.state.tx.us/funding/)
  - Texas Tax Code Incentives for Renewable Energy Systems with a listing of property tax exemptions, franchise tax exemptions, and franchise tax deductions (www.seco.cpa.state.tx.us/re/incentives-taxcode-statutes.php)
  - The Database of State Incentives for Renewable Energy (DSIRE), which provides information on federal & state efficiency incentives (http://www.dsireusa.org/)
  - U.S. Department of Agriculture (USDA) Rural Energy for America Program, which provides assistance for energy audits, renewable energy technical assistance, and renewable energy site assessments to agricultural producers and rural small businesses (http://www.rd.usda.gov/programs-services/rural-energy-america-program-energy-audit-renewable-energy-development-assistance) and provides guaranteed loan financing and grant funding to agricultural producers and rural small businesses to purchase and install renewable energy systems or make energy efficiency improvements (www.rd.usda.gov/programs-services/rural-energy-america-program-renewable-energy-systems-energy-efficiency)

- Nonpoint Source Grants for Cleaning Up or Preventing Water Pollution
  https://www.tceq.texas.gov/waterquality/nonpoint-source/grants/grant-pgm.html

  The Texas Commission on Environmental Quality and Texas State Soil and Water Conservation Board administer federal grants for activities that prevent or reduce nonpoint source pollution, such as development and implementation of watershed protection plans, implementation of both technology-based and water quality-based management measures, low-impact development practices, and retrofits of stormwater control structures.

- Texas Community Development Block Program (TCDP)
  https://www.texasagriculture.gov/GrantsServices/RuralEconomicDevelopment/RuralCommunityDevelopmentBlockGrant(CDBG).aspx and
  www.nctcog.org/envir/SEEDevEx/tcdp/index.asp

  The TCDP provides grant funding to cities and counties for improvement of water and sewer systems, other public facilities, and housing.

  - The Community Development Fund is available on a biennial basis through regional competition for assistance to eligible cities and counties to address public facilities and housing needs. Eligible activities include infrastructure projects such as sewer and water system improvements, street, bridge, and drainage improvements, and housing rehabilitation.
  - Other funds that may relate to green infrastructure: The Community Enhancement Fund, which includes enhancements that address public health, public safety, and renewable energy as part of a public facility; the Downtown Revitalization and Main Street Programs, for public infrastructure improvements that aid in the elimination of a blighted area; the Planning and Capacity Building Fund, which is for local public facility and housing planning activities to help prepare a comprehensive plan or any of its components; and the Small Towns Environment Program Fund, which provides assistance for solving water and sewer problems using self-help methods.

- Texas Department of Transportation’s Transportation Alternatives Set-Aside Call for Projects.
  www.txdot.gov/inside-txdot/division/public-transportation/local-assistance.html
  and www.nctcog.org/trans/sustdev/landuse/step/index.asp

  The TA Set-Aside, as administered by the department, provides funding for a variety of alternative transportation projects, including on- and off-road pedestrian and bicycle facilities, infrastructure for non-driver access to public transportation, projects that enhance mobility, and Safe Routes to School infrastructure projects.

- Texas Parks and Wildlife, Recreation Grants Program
  www.tpwd.state.tx.us/business/grants/trpa/

  These programs help to build new parks, conserve natural resources, provide access to water bodies, develop educational programs for youth, and much more. The National Recreation Trails Fund grant projects could include both motorized and non-motorized recreational trail projects such as the construction of new recreational trails, improvements to existing trails, development of trailheads or trailside facilities, and acquiring trail corridors.

- Texas Water Development Board's Clean Water State Revolving Fund (CWSRF)
  www.twdb.texas.gov/financial/programs/CWSRF/index.asp

  The CWSRF provides low-cost financial assistance for planning, design, and construction of wastewater infrastructure. Eligible applicants include cities, counties, districts, river authorities, other public bodies, and private entities. Financial assistance can be utilized for wastewater treatment facilities, collection systems, wastewater recycling and reuse improvements, stormwater pollution control, non-point source pollution control, estuary management project, and eligible green project reserve components.

- Texas Water Development Board's Green Project Reserve
  www.twdb.texas.gov/financial/programs/green/index.asp

  The Green Project Reserve aims to fund projects that utilize green or soft-path practices to complement and augment hard or gray infrastructure; adopt practices that reduce the environmental footprint of water and wastewater treatment, collection, and distribution; help utilities adapt to climate change; adopt more sustainable solutions to wet weather flows; provide mechanisms to reinvest savings from reductions in water loss and energy conservation; and promote innovative approaches to water management problems.

- U.S. Department of Agriculture's Rural Development Water and Waste Disposal Loan and Grant Program
  www.rd.usda.gov/programs-services/water-waste-disposal-loan-grant-program

  This program provides funding to households and businesses in eligible rural areas through long-term, low-interest loans and, if funds are available, grants combined with a loan for stormwater drainage and other systems.

- U.S. Department of Housing and Urban Development's Sustainable Communities Regional Planning (SCRP) Grant Program
  http://portal.hud.gov/hudportal/HUD?src=/program_offices/economic_resilience/sustainable_communities_regional_planning_grants

  This program supports locally led collaborative efforts that bring together diverse interests from many municipalities in a region to determine how best to target housing, economic and workforce development, and infrastructure investments to create more jobs and regional economic activity. One example is the Heart of Texas Council of Governments award to develop a regional plan that includes the following areas: housing; transportation; water; infrastructure; air quality; solid waste; community engagement and engagement resources; entrepreneurship and small business; community priorities, needs, and concerns; issues creating disparities in access; economic vulnerability points, both for physical communities and for characteristic communities; and climate vulnerability points, especially drought and subsequent flooding.

- U.S. Department of the Interior's River, Trails, and Conservation Assistance Program
  www.nps.gov/orgs/rtca/index.htm

  This program helps communities improve parks, establish trails, access rivers, and protect special places.

- U.S. Economic Development Administration (EDA) Public Works programs
  www.eda.gov/

  This program aims to empower distressed communities to revitalize, expand, and upgrade their physical infrastructure to attract new industry, encourage business expansion, diversify local economies, and generate or retain long-term, private sector jobs and investment.

- U.S. Environmental Protection Agency. *Getting to Green: Paying for Green Infrastructure – Financing Options and Resources for Local Decision-Makers.* December 2014. EPA 842-R-14-005. Available online at www2.epa.gov/sites/production/files/2015-02/documents/gi_financing_options_12-2014_4.pdf.

  This document summarizes various funding sources that can be used to support stormwater management programs or finance individual projects. Each type of funding source is illustrated by several municipal programs and contains a list of additional resources. A comparative matrix describes the advantages and disadvantages of the various funding sources.

APPENDIX A: NCTCOG CASE STUDIES

A.1 NCTCOG Questionnaire Sent to Case Studies

Contact Name:
Email Address:
Phone Number:

Entity and Relationship to Project:

Project Name:
Project Location:
Project Completion Date:
Size of Project (acres, miles, or square feet):
If you know the impervious area as well as the total size, please let us know both.

1. Project Description (one or two paragraphs)
If you prefer that we create the description, provide a link to a previous case study or preferred webpage.

2. Reasons the Project Used Green Practices Versus Traditional

3. Land Use/Project Type

☐ Park/open space
☐ Institutional
☐ Commercial
☐ Greyfield or brownfield redevelopment
☐ Transportation
☐ Streetscape
☐ Recreational trail
☐ Other: ________

4. Green Features (Note: The features should be relevant for transportation projects.)

☐ Permeable pavement in roadway, alley, parking lot, or sidewalk
☐ Permeable pavers in parking lot or sidewalk
☐ Recycled materials for roadway or trail construction
☐ Green trail materials—please list: ____________
Ex: Native soil with ecofriendly binder, specific recycled materials, porous pavement, etc.
☐ Bioretention or rain garden
☐ Bioswale
☐ Enhanced swale
☐ Grass channel (vegetated swale)
☐ Filter strip
☐ Infiltration trench
☐ Stormwater pond
☐ Xeric species

☐ Trees—with Silva Cells
☐ Trees—without Silva Cells
☐ LED lighting
☐ Solar lighting
☐ LED and solar lighting
☐ Other: ___________

5. Key Design Features

6. Costs

We'd like as much information as you can provide. Separate the costs for each element, if possible. If not possible, please provide what you can or send us bid tabulations.

Estimated cost of each green element:

Element:____________ Quantity: ________ Total cost: $_______
Element:____________ Quantity: ________ Total cost: $_______
Element:____________ Quantity: ________ Total cost: $_______

or green features as percentage of overall project cost ______%
or sending bid tabulation: ☐

B. Cost of entire project: $__________

7. Maintenance Requirements

8. Expected Lifetime of Green Elements (if known)

9. Project Challenges

☐ High material costs
☐ High maintenance
☐ Codes/ordinances
☐ Other: ____________

10. Lessons Learned (optional)

11. Social, Environmental, and Economic Benefits

☐ Water quality improvements
☐ Runoff reduction
☐ Groundwater recharge
☐ Stormwater peak rate reduction
☐ Reduced urban heat island effect
☐ Air quality improvements
☐ Increased open space
☐ Energy efficiency
☐ Reduced construction costs (compared to gray infrastructure)
☐ Increased property values
☐ Increased potential for economic development

☐ Traffic calming/pedestrian safety
☐ Public education opportunity
☐ Improved community aesthetics
☐ Other: _____________

If you have specific information about the above benefits you want to share, please include here:

12. Images

Do you have photos, images, or diagrams that you can give us permission to use? Please send them to us when you submit this form. Supply credits here:

13. Links

If you have one to two links you would like us to include for more information, please list them here:

A.2 Project Contacts and Links for More Information

Table 10. List of case studies, project contacts, and links for more information.

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
1	The Green at College Park	Arlington, Texas	Schrickel, Rollins & Associates (Landscape Architect, Architect, and Civil Engineer)	None
2	South Main Reconstruction Parking Lot	Carrollton, Texas	City of Carrollton (Project Owner)	None
3	Red Oak Creek Trail	Cedar Hill, Texas	City of Cedar Hill (Project Owner)	None
4	Congo Street Initiative	Dallas, Texas	bcWORKSHOP (Designer)	bcWORKSHOP webpage, "Congo Street Initiative," January 11, 2013: www.bcworkshop.org/posts/congo-street-initiative
5	Dallas Urban Reserve	Dallas, Texas	Kevin Sloan Studio (Landscape Architect, Planning Consultant)	Kevin Sloan Studio webpage: www.kevinsloanstudio.com/
6	Elm Street Streetscape Improvements	Dallas, Texas	City of Dallas (Project Owner)	None
7	Katy Trail	Dallas, Texas	City of Dallas (Project Owner) and Friends of the Katy Trail (Maintainer)	None
8	Perot Museum of Nature and Science	Dallas, Texas	Talley Associates (Landscape Architect)	Perot Museum of Nature and Science website: www.perotmuseum.org/ Talley Associates webpage, "Perot Museum of Nature and Science": http://talleyassociates.com/perot-museum.html

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
9	Trinity River Audubon Center	Dallas, Texas	City of Dallas (Project Owner) and Trinity River Audubon Center (Operator)	None
10	Oncor LED Streetlight Pilot and Technical Evaluation Program	Dallas-Fort Worth Area, Texas	Oncor (Project Owner)	Oncor LED Streetlight Pilot & Technical Evaluation Update, a 2012 presentation by Michael Navarro, Oncor Electric Delivery: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/msslc_dallas2012_navarro.pdf
11	Rayzor Ranch	Denton, Texas	Dunaway Associates (Engineer and Designer)	Post-Established iSWM Maintenance Plan for Rayzor Ranch North by Dunaway Associates: http://iswm.nctcog.org/Documents/iTools/Case_Studies/Rayzor/Rayzor_iSWM_Maint.pdf Final iSWM Study Report – Rayzor Ranch Addition: http://iswm.nctcog.org/Documents/iTools/Case_Studies/Rayzor/Rayzor_Ranch_iSWM_Report.pdf iswm Tools – Case Studies webpage “Local Projects Using iSWM Principles – Rayzor Ranch North”: http://iswm.nctcog.org/Documents/iTools/Case_Studies/Rayzor_CS.asp
12	Fort Worth Nature Center and Refuge Green Parking Lot	Fort Worth, Texas	Fort Worth Nature Center & Refuge (Project Owner)	Fort Worth Nature Center and Refuge webpage: www.fwnaturecenter.org/ Teague Nall & Perkins webpage on the Fort Worth Nature Center: www.tnpinc.com/project/fort-worth-nature-center/
13	Historic Handley Urban Village Streetscape Project	Fort Worth, Texas	City of Fort Worth (Project Owner)	None

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
14	Mountain Creek Lake Park Trail	Grand Prairie, Texas	City of Grand Prairie (Project Owner)	None
15	Timber Creek High School	Keller, Texas	Teague Nall and Perkins, Inc. (Engineer/Landscape Architect)	None
16	Downtown Rowlett Streetscape	Rowlett, Texas	La Terra Studio ((Landscape Architect) and Kimley-Horn (Design Engineer)	Downtown Rowlett Tour video: https://www.youtube.com/watch?v=8_q2R5QMDMw
17	Merritt Road	Rowlett, Texas	Freese and Nichols (Consultants)	Sustainable Public Right-of-Way Principles – Merritt Road presentation: www.nctcog.org/envir/SEEDevEx/pubworks/documents/2011/4-Dennis_Abraham_Merritt_Rd_PWR.pdf
18	St. Stephen's Pedestrian Green	Austin, Texas	Resource Design (Designer and Landscape Architect)	Resource Design's webpage: www.ResourceDesignAustin.com
19	Bioretention for Stormwater Quality Improvement in Texas	Bryan, Texas	Texas A&M University/Texas A&M Transportation Institute (Researcher)	Li, Ming-Han et al. Water Environ Res., May 2014, "Comparing Bioretention Designs With and Without an Internal Water Storage Layer for Treating Highway Runoff": www.ncbi.nlm.nih.gov/pubmed/24961065 Texas A&M Transportation Institute webpage "Bioretention For Highway Stormwater Quality Improvement in Texas": http://tti.tamu.edu/enhanced-project/bioretention-for-highway-stormwater-quality/

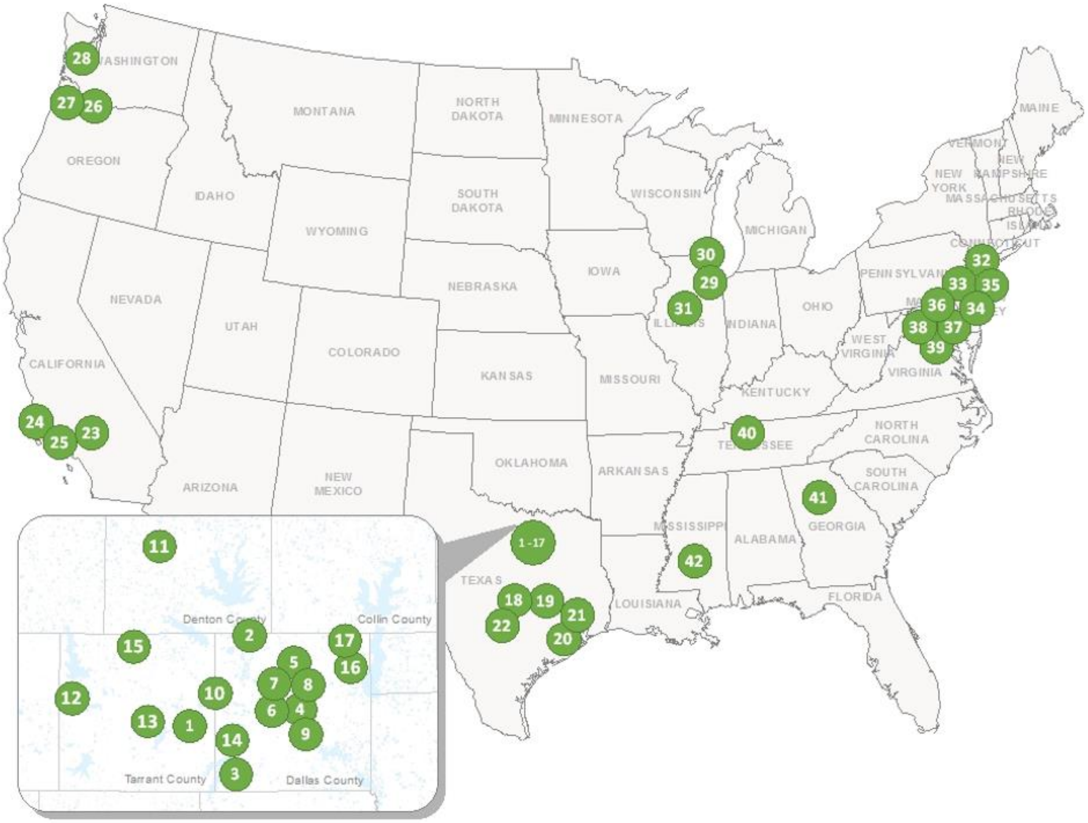
Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
20	Bagby Street Reconstruction	Houston, Texas	Walter P Moore (Designer)	ACF Environmental, “FocalPoint Biofiltration System Utilized in Urban Retrofit for Certified Greenroad Application”: www.acfenvironmental.com/App_Content/media/Greenroad_1SPP.pdf Greenroads webpage, “Bagby Street Reconstruction”: https://www.greenroads.org/141/49/bagby-street-reconstruction.html Ninmann, Tara. “Midtown Houston Street Receives Greenroads Silver Certification,” Sustainable Construction, Winter 2013: www.nxtbook.com/nxtbooks/cygnus/sc_2013winter/index.php?startid=29#/27 Spencer, Ingrid. GreenSource webpage, “A Game Changer for Houston Streets.” August 5, 2015: http://greensource.construction.com/news/2014/08/140805-bagby-street-changes-the-game-for-houston-streets.asp
21	Birnamwood Drive	Houston, Texas	Construction EcoServices (Construction)	Construction EcoServices project profile: http://cdn2.hubspot.net/hub/153600/file-23238001-pdf/resources/swq%20treatment/focalpoint_application_report_birnamwood_drive.pdf?t=1446564307735
22	Blue Hole Regional Park	Wimberley, Texas	Design Workshop (Planner, Designer, and Landscape Architect)	Blue Hole Regional Park website: www.blueholeregionalpark.com/ Center for Active Design, “Blue Hole Regional Park” webpage, http://centerforactivedesign.org/awards/blueholepark Landscape Architecture Foundation, Blue Hole Regional Park case study: http://landscapeperformance.org/case-study-briefs/blue-hole-regional-park

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
23	Elmer Paseo Stormwater Improvement Project	Los Angeles, Calif.	Council for Watershed Health (Secured Funding, Managed Stakeholder Collaboration)	Green, Emily. “The Dry Garden: Elmer Avenue Becomes Green Street, a Water-Wise and Solar-Lighted Community Effort” *Los Angeles Times*. July 23, 2010. http://latimesblogs.latimes.com/home_blog/2010/07/elmer-avenue-sun-valley.html Landscape Architecture Foundation, Elmer Avenue Neighborhood Retrofit case study: http://landscapeperformance.org/case-study-briefs/elmer-avenue-neighborhood-retrofit Belden, Edward et al. “Sustainable Infrastructure: The Elmer Avenue Neighborhood Retrofit.” *Urban Coast*. March 2012. http://watershedhealth.org/Files/document/793_2012%20Belden.pdf
24	Obern Trail Lighting Retrofit Project	Santa Barbara County, Calif.	Santa Barbara County (Owner)	None
25	Santa Monica Rubberized Sidewalk Program	Santa Monica, Calif.	City of Santa Monica (Owner)	None
26	LED-Mark Light Demonstration Project	Portland, Ore.	Portland Bureau of Transportation (Owner) and Saris (Product Provider)	Saris Guide Lights Sell Sheet: https://www.sarisparking.com/wp-content/uploads/2013/10/2013-Cycle-Guide-Light-Sell-Sheet.pdf
27	SE Clay Green Street: Water to 10th Avenues	Portland, Ore.	City of Portland (Owner)	The City of Portland, Ore., webpage “SE Clay Green Street Project”: www.portlandoregon.gov/bes/47012

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
28	Henderson Blvd. Sidewalk	Olympia, Wash.	City of Olympia (Owner)	Tosomeen, Craig. “Porous Concrete Sidewalks: How to Build Sidewalks and Not Stormwater Ponds.” City of Olympia. 2007. http://olympiawa.gov/~/media/Files/PublicWorks/Water-Resources/PorousConcreteSidewalks_BuildSidewalks_NotStormwaterPonds.ashx Tosomeen, Craig. “Sidewalk Projects.” City of Olympia. July 2007. http://olympiawa.gov/~/media/Files/PublicWorks/Water-Resources/Sidewalk%20Projects%20-%20Porous%20Concrete.ashx
29	Chicago Green Alley Program	Chicago, Ill.	Knight Engineers and Architects (Designer)	City of Chicago. *The Chicago Green Alley Handbook: An Action Guide to Create a Greener, Environmentally Sustainable Chicago.* 2010.. www.cityofchicago.org/dam/city/depts/cdot/Green_Alley_Handbook_2010.pdf
30	Ravinia Festival South Parking Lot	Highland Park, Ill.	SmithGroupJJR (Prime Consultant, Civil Engineer, Landscape Architect)	Landscape Architecture Foundation, Ravinia Festival South Parking Lot case study: http://landscapeperformance.org/case-study-briefs/ravinia-festival-south-parking-lot
31	Uptown Normal Street and Streetscape Project	Normal, Ill.	Town of Normal (Owner)	Landscape Architecture Foundation, Uptown Normal Circle and Streetscape case study: http://landscapeperformance.org/case-study-briefs/uptown-normal-circle-and-streetscape Landscape Architecture Foundation, Uptown Normal Circle and Streetscape case study methodology: http://landscapeperformance.org/sites/default/files/Uptown%20Normal%20Methodology.pdf
32	Area-wide Right-of-Way Bioswale	New York City, N.Y.	New York City Department of Environmental Protection (Owner)	New York City Department of Environmental Protection webpage, “Green Infrastructure Plan and Annual Reports” www.nyc.gov/html/dep/html/stormwater/nyc_green_infrastructure_plan.shtml

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
33	Clark Park Infiltration Bed (Basketball Court)	Philadelphia, Pa.	Philadelphia Water Department (Owner)	Philadelphia Water Department webpage, “Clark Park Infiltration Bed (Basketball Court)”: www.phillywatersheds.org/what_were_doing/green_infrastructure/projects/clark_park
34	Mill Creek Tree Trench	Philadelphia, Pa.	Philadelphia Water Department (Owner)	None
35	Penn Street Trail	Philadelphia, Pa.	Delaware River Waterfront (Manager and Maintainer)	Gates, Kellie Patrick. “Penn Street Trail Opens.” *PlanPhilly.* June 17, 2013. http://planphilly.com/articles/2013/06/17/penn-street-trail-opens
36	Green Tracks Pilot Project	Baltimore, Md.	Mahan Rykiel Associates (Landscape Designer)	Mahan Rykiel Associates webpage: www.mahanrykiel.com
37	GW Square 80	Washington, DC	Studio39 (Landscape Architect)	Sustainable SITES Initiative webpage, “Square 80 Plaza at the George Washington University”: www.sustainablesites.org/certified-sites/square80 American Society of Landscape Architects, “Green Infrastructure & Stormwater Management Case Study – GW Square 80 Public Plaza.” www.asla.org/uploadedFiles/CMS/Advocacy/Federal_Government_Affairs/Stormwater_Case_Studies/Stormwater%20Case%20163%20GW%20Square%2080%20Public%20Plaza,%20Washington,%20DC.pdf
38	Dora Kelley Park Trail Re-Surfacing Project	Alexandria, Va.	City of Alexandria (Owner)	Leonard, Rachel. “Recycled Tires Improve Trail at Dora Kelley; Former Trail Suffered From Erosion, Trip Hazards.” *West End Alexandria Patch.* Sept. 28, 2012. http://patch.com/virginia/westendalexandria/recycled-tires-improve-trail-at-dora-kelley

Case Study No.	Project Name	Location	Project Contact and Relationship to Project	Links Provided in Case Study Questionnaires for More Information
39	GW Solar Walk	Loudoun County, Va.	Studio39 (Landscape Architect)	GW Today, “GW Debuts Solar Walk on the Virginia Science and Technology Campus.” Oct. 1, 2013. http://gwtoday.gwu.edu/gw-debuts-solar-walk-virginia-science-and-technology-campus
40	Deaderick Street	Nashville, Tenn.	Hawkins Partners, Inc. (Landscape Architect)	Johnson, Elizabeth. “Renovated Deaderick Street Enhnaces Nashville’s City Core; City Planners Bring Back Connection Between Capitol and Courthouse.” *The Tennessean.* June 15, 2010. “http://archive.tennessean.com/article/20100615/DAVIDSON/100615071/Renovated-Deaderick-Street-enhances-Nashville-s-city-core Hawkins Partners, Inc. webpage, “Deaderick Street Discussed at StormCon 2010”: http://hpigreen.com/tag/deaderick-street/ re:Streets webpage, “Deaderick Street”: http://www.restreets.org/case-studies/deaderick-street
41	Triangle Parking Lot	Stone Mountain, Ga.	Robert and Company (Designer, Engineer, Landscape Architect)	Stone Mountain Park – Triangle Parking Lot video: https://www.youtube.com/watch?v=nxC6lXxv-zY
42	Hinds Community College Multipurpose Center	Pearl, Miss.	Weatherford/McDade (Landscape Architect)	None



North Central Texas

- ① Arlington, Texas - The Green at College Park
- ② Carrollton, Texas - South Main Reconstruction Parking Lot
- ③ Cedar Hill, Texas - Red Oak Creek Trail
- ④ Dallas, Texas - Congo Street Initiative
- ⑤ Dallas, Texas - Dallas Urban Reserve
- ⑥ Dallas, Texas - Elm Street Streetscape Improvements
- ⑦ Dallas, Texas - Katy Trail
- ⑧ Dallas, Texas - Perot Museum of Nature and Science
- ⑨ Dallas, Texas - Trinity River Audubon Center
- ⑩ Dallas-Fort Worth Area, Texas - Oncor LED Streetlight Pilot and Technical Evaluation Program
- ⑪ Denton, Texas - Rayzor Ranch
- ⑫ Fort Worth, Texas - Fort Worth Nature Center and Refuge Green Parking Lot
- ⑬ Fort Worth, Texas - Historic Handley Urban Village Streetscape Project
- ⑭ Grand Prairie, Texas - Mountain Creek Lake Park Trail
- ⑮ Keller, Texas - Timber Creek High School
- ⑯ Rowlett, Texas - Downtown Rowlett Streetscape
- ⑰ Rowlett, Texas - Merritt Road

Rest of Texas

- ⑱ Austin, Texas - St. Stephen's Pedestrian Green
- ⑲ Bryan, Texas - Bioretention for Stormwater Quality Improvement in Texas
- ⑳ Houston, Texas - Bagby Street Reconstruction
- ㉑ Houston, Texas - Birnamwood Drive
- ㉒ Wimberley, Texas - Blue Hole Regional Park

Rest of U.S.

- ㉓ Los Angeles, Calif. - Elmer Paseo Stormwater Improvement Project
- ㉔ Santa Barbara County, Calif. - Obern Trail Lighting Retrofit Project
- ㉕ Santa Monica, Calif. - Santa Monica Rubberized Sidewalk Program
- ㉖ Portland, Ore. - LED Mark Light Demonstration Project
- ㉗ Portland, Ore. - SE Clay Green Street: Water to 10th Avenues
- ㉘ Olympia, Wash. - Henderson Blvd. Sidewalk
- ㉙ Chicago, Ill. - Chicago Green Alley Program
- ㉚ Highland Park, Ill. - Ravinia Festival South Parking Lot
- ㉛ Normal, Ill. - Uptown Normal Street and Streetscape Project
- ㉜ New York City, N.Y. - Area-wide Right-of-Way Bioswale
- ㉝ Philadelphia, Pa. - Clark Park Infiltration Bed (Basketball Court)
- ㉞ Philadelphia, Pa. - Mill Creek Tree Trench
- ㉟ Philadelphia, Pa. - Penn Street Trail
- ㊱ Baltimore, Md. - Green Tracks Pilot Project
- ㊲ Washington, DC - GW Square 80
- ㊳ Alexandria, Va. - Dora Kelley Park Trail Re-Surfacing Project
- ㊴ Loudoun County, Va. - GW Solar Walk
- ㊵ Nashville, Tenn. - Deaderick Street
- ㊶ Stone Mountain, Ga. - Triangle Parking Lot
- ㊷ Pearl, Miss. - Hinds Community College Multipurpose Center

Figure 40: Map of NCTCOG case studies.

APPENDIX B: THE IMPACTS OF GROWTH AND NEED FOR GREEN PRACTICES

This section highlights the region's expected growth and key impacts of development and makes connections from those impacts to the need for green infrastructure practices. It does not specifically discuss climate change, but the impacts of climate change and development intersect. For example, green stormwater infrastructure (GSI) is one technique proposed by the U.S. Environmental Protection Agency (EPA) to help improve community resiliency in the areas of flood management and urban heat island reduction. For more information, please visit the EPA's webpage "Green Infrastructure for Climate Resiliency" at http://water.epa.gov/infrastructure/greeninfrastructure/climate_res.cfm. (The EPA uses the term *green infrastructure* instead of *green stormwater infrastructure*.)

B.1 Impacts of Expected Growth

The cities and suburbs in North Central Texas are growing rapidly. According to recent U.S. Census Bureau estimates, the Dallas-Fort Worth-Arlington metropolitan area added more residents than almost anywhere else in the nation (more than 131,000 people from July 1, 2013, to July 1, 2014), behind only Houston-The Woodlands-Sugar Land, reported the *Dallas Morning News* April 2015 article "Houston Area and Dallas-Fort Worth Top Nation's Fastest-Growth List." The four largest counties in the metropolitan area—Collin, Dallas, Denton, and Tarrant—showed strong growth over the past several years, as seen in Figure 41.

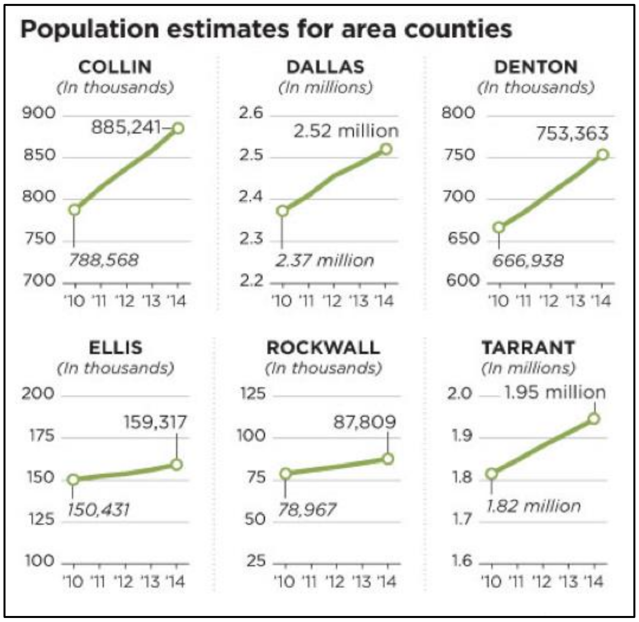


Figure 41. 2010-2014 population estimates for Dallas-Fort Worth area counties.
Source: Dallas Morning News. Created by Key Alcott, *Dallas Morning News* staff artist. 2015.

This growth is expected to continue. According to the North Central Texas Council of Government's 2040 Demographic Forecast, the Dallas-Fort Worth Metropolitan Planning Area can expect to grow from approximately 6.3 million residents in 2010 to more than 10.6 million residents in 2040; during that same time period, employment will increase from approximately 4.0 million to 6.7 million jobs.

While this expected growth may be beneficial in many ways, the development required to accommodate this growth will impact the region's already challenged roadways and waterways. With the use of green infrastructure practices, these impacts may be at least partially tempered.

The sections below provide information on how development can deplete natural resources, create urban heat islands, and decrease air quality. It also outlines how development ca increase stormwater runoff, leading to an increase in flooding, erosion and sedimentation, and water pollution.

B.1.1 Natural Resource Depletion

One issue resulting from increased development is a greater use of natural resources, which has been identified as a problem for transportation projects for at least two decades. Rebecca Davio, writing in *Public Roads* about the Texas Department of Transportation's recycling initiative, cited a 1998 U.S. Geological Survey (USGS) economic assessment for construction applications. The assessment noted the mining of stone was already "increasingly being constrained by urbanization, zoning regulations, increased costs, and environmental concerns." The supply of local stone has been exhausted in some parts of the country, requiring long hauls and higher prices, Davio continued.

Figure 42. The rocks excavated at Timber Creek High School were repurposed, reducing transportation costs and emissions.
Source: Teague Nall & Perkins.

B.1.2 Urban Heat Islands, Decreased Air Quality, and Public Health Risk

Another issue associated with development is the urban heat island (UHI) effect. An urban heat island is a built-up area that is hotter than nearby rural regions. As cities develop, surfaces are paved or built up while vegetation is lost, resulting in less shade and moisture that can keep places cool. In the evening, the difference in temperatures can be as much as 22°F, the EPA reports in its publication *Reducing Urban Heat Islands: Compendium of Strategies*. Temperatures are highest at rooftops and unshaded pavement. High pavement and rooftop surface temperatures can heat stormwater runoff as well, which can affect all aspects of aquatic life, according to the EPA. With extreme heat, infrastructure also can be impacted (for example, road pavement buckling).

In recent years, several initiatives to mitigate the urban heat island effect have developed in North Central Texas. Examples include the Urban Heat Island Project identified by the Dallas Sustainable Skylines Initiative (DSSI), a three-year partnership between the City of Dallas, the EPA, and NCTCOG; Dallas's Adopt-a-Median Tree Planting Program; the Tree North Texas Initiative; the City of Frisco's Green Building Program; and the City of Fort Worth's Better Building Challenge.

As seen in the following graph from the DSSI report (Figure 43), dense urban areas with their lower tree cover and greater paved surfaces can be 6°F to 8°F hotter on average than nearby rural regions. The graph also evidences that not only big cities, but also suburbs are affected.

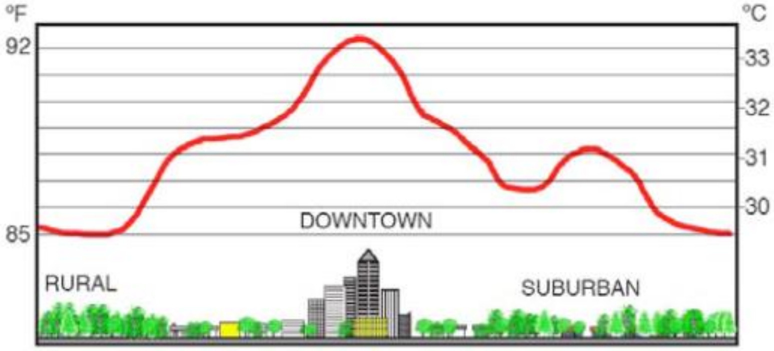


Figure 43. Urban heat island effect.
Source: Dallas Sustainable Skylines Initiative, 2009.

Higher temperatures can lead to rising energy costs, requiring more electricity for air conditioning. According to the 2009 DSSI report, energy costs may amount to several hundred million dollars per year for Dallas. Dr. Brian Stone, an associate professor at the School of City and Regional Planning at the Georgia Institute of Technology, discussed this issue during the May 2014 "Grey to Green: Creating Cool Cities" conference in Dallas. According to Dr. Stone, while air conditioning is the primary adaptive strategy to deal with the threat of heat, the electric grid is becoming less resilient as seen in the Northeast Blackout of 2003. Dr. Stone pointed to some of the impacts during that blackout; not only was there no air conditioning, but it also became harder to purify water, backup systems failed, and gas could not be pumped into cars.

High temperatures are also associated with high levels of ground-level ozone, a key pollutant of concern for the Dallas-Ft. Worth area. In 2012, the EPA designated 10 North Central Texas counties—Collin, Dallas, Denton, Ellis, Kaufman, Johnson, Parker, Rockwall, Tarrant, and Wise—as nonattainment for ozone based on the 2008 8-hour ozone National Ambient Air Quality Standards (NAAQS) (Figure 44).

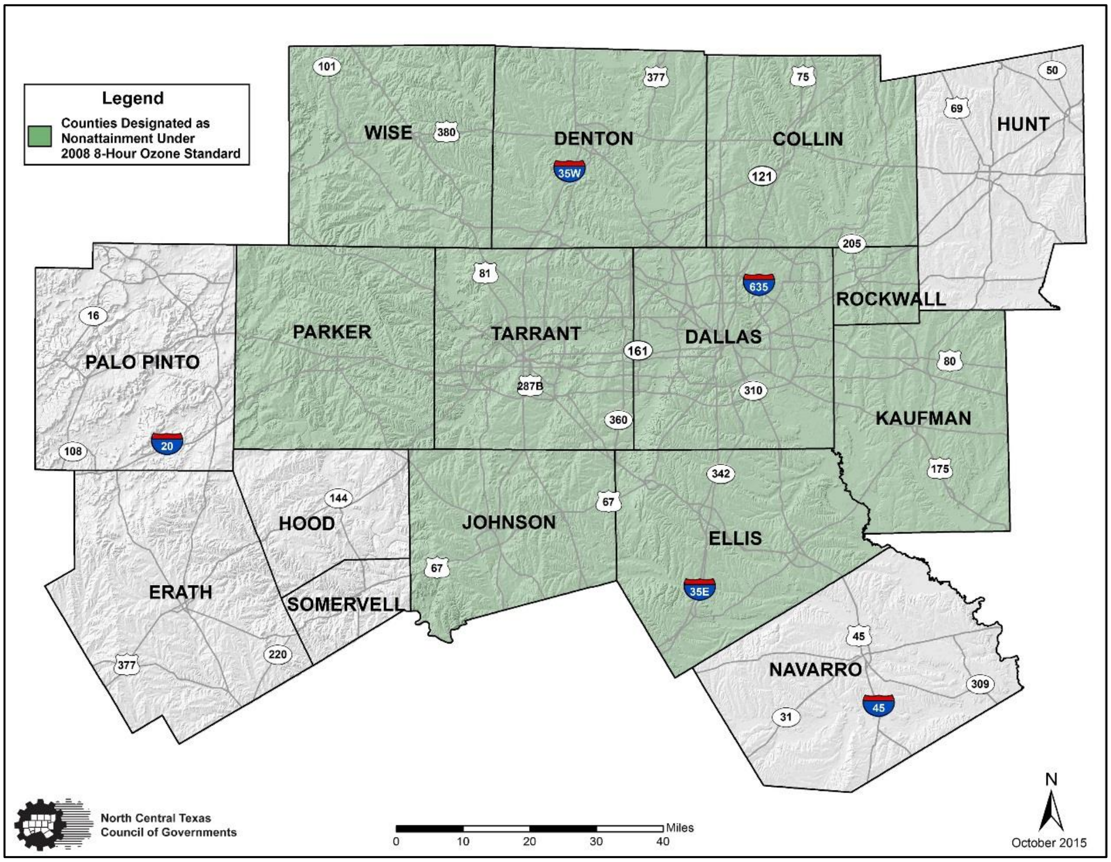


Figure 44. Dallas-Fort Worth 8-Hour Ozone Nonattainment Area.
Source: NCTCOG, October 2015.

The increased daytime temperatures, reduced cooling at night, and higher air pollution levels associated with heat islands can also negatively affect human health, contributing to respiratory difficulties, heat stroke, and heat-related mortality. According to a 2011 report from the Union of Concerned Scientists (UCS), if temperatures continue trending upward, Americans could contend with 2.8 million more occurrences of acute respiratory symptoms by 2020, with seniors and infants especially impacted. The UCS report projected up to 147,140 to 431,000 occurrences in Texas, and healthcare costs could potentially exceed one billion dollars.

Recent research reveals that this issue may only worsen. During the “Grey to Green: Creating Cool Cities” conference, Dr. Stone reported that not only are urban areas hotter than rural areas, but they also are warming more rapidly over time. His research suggested Dallas has the third most rapidly growing heat island in the United States, as shown in the Figure 45.

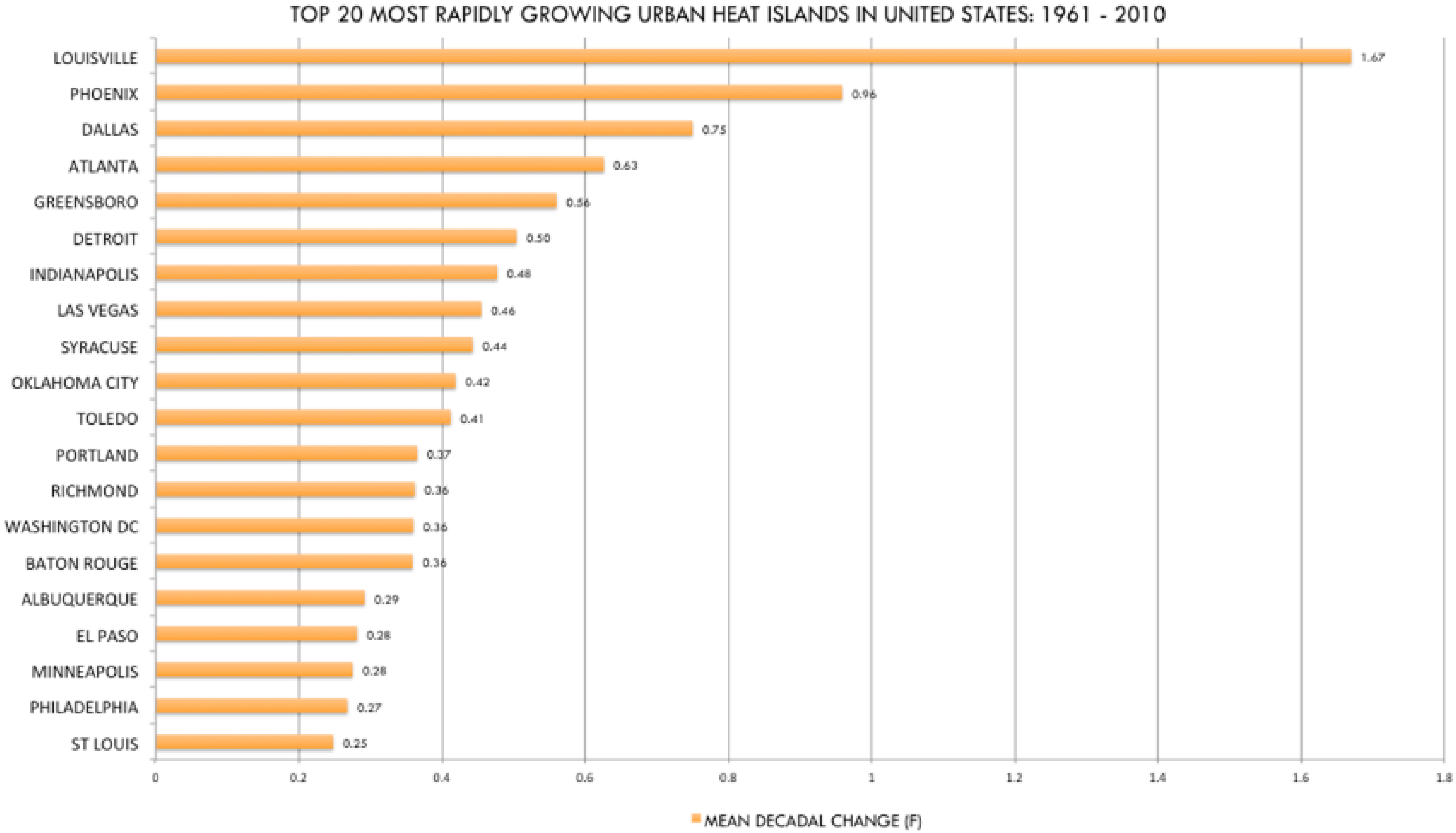


Figure 45. Top 20 Most Rapidly Growing Urban Heat Islands in the United States, 1961-2010.
Source: Urban Climate Lab, Georgia Institute of Technology. From a presentation at the 2014 conference “Grey to Green: Creating Cool Cities.”
Note: Dallas had less data than other cities for part of the period, but the trends reported should still be accurate at the decadal time period, according to Dr. Stone.

B.1.3 Increased Flooding, Erosion and Sedimentation, and Water Pollution

With development comes an increase of impervious surfaces (for example, parking lots, road surfaces, and rooftops), soil compaction, and tree and vegetation removal.

The decrease in trees, other vegetation, and surface soil results in reduced interception (water temporarily held on leaves and stems), evapotranspiration (the sum of water evaporated from soil and plant surfaces and water transpired by the plant), and infiltration (water absorbed into the soil). This produces a corresponding increase in stormwater runoff.

According to an EPA fact sheet on urban non-point source runoff, a typical city block generates over five times more runoff than a woodland area of the same size. In fact, most stormwater runoff is due to development, and the majority of runoff is not coming from buildings. The EPA's publication "Managing Wet Weather with Green Infrastructure—Municipal Handbook: Green Streets" states that urban roads and travel surfaces are estimated to comprise almost two-thirds of total impervious cover and contribute a similar ratio of runoff.

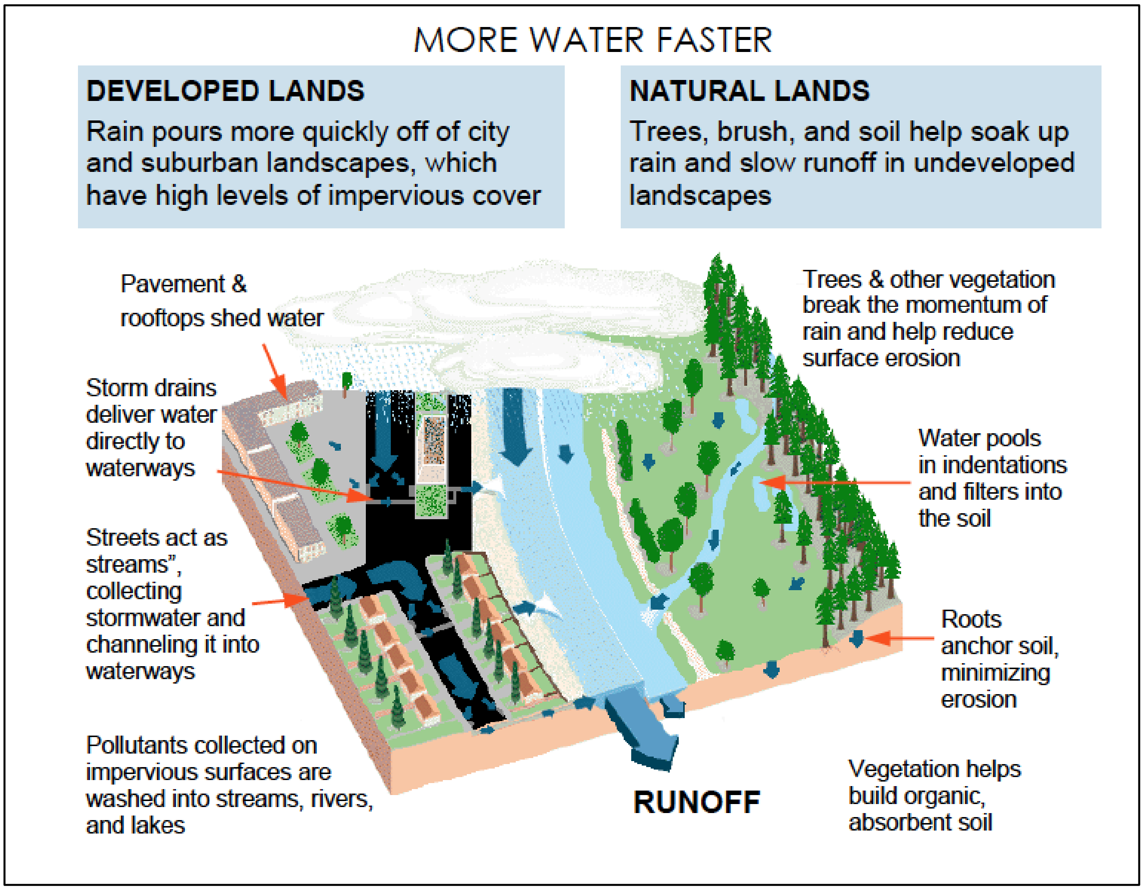


Figure 46. A comparison of water movement on developed lands and natural lands.
Source: California Water & Land Use Partnership, "How Urbanization Affects the Water Cycle." (n.d.)

Figure 46 shows several important differences between developed lands and natural lands. In developed lands, water runs off impervious surfaces, accumulating pollutants. Streets collect and channel stormwater into storm drains that convey water directly to local waterways without treatment. In natural lands, trees, brush, and soil help soak up rain and slow/filter the runoff.

The hydrograph shown in Figure 47 compares stormwater peak discharges in an urban watershed (red line) to those in a less developed watershed (yellow line). Large amounts of impervious surface are accompanied by a faster rate of discharge and increased volume, which translates into a substantial increase in stormwater runoff. See the following sections for more information on the consequences of higher runoff volume and velocity.

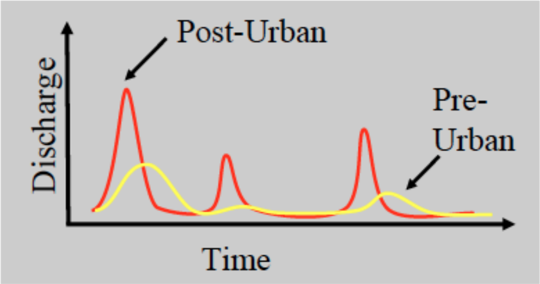


Figure 47. A hydrograph showing pre- and post-urban discharge rates.
Source: California Water & Land Use Partnership, “How Urbanization Affects the Water Cycle.” (n.d.)

Flooding

The potential for flooding is one problem of “more water faster.” While this region may not be as highly affected by flooding as areas such as Houston, it has experienced its share of flooding-related disasters, as shown in Figure 48.

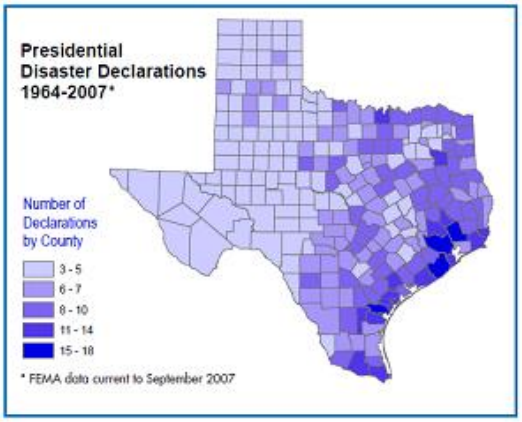


Figure 48. Presidential disaster declarations for Texas flood events, 1964-2007.
Source: Texas Floodplain Management Association, 2008.

According to a 2008 TFMA floodplain management guide, since 1988 more than 400 people have died and more than $4 billion in damage has occurred in Texas due to flood-related incidents. In an Associated Press report on the May 2015 storms, a Texas Department of Transportation spokesperson said that roadways in 167 of the state’s 254 counties suffered some form of storm damage, and that the infrastructure damage estimate was at least $27 million. It is important to note that the map in Figure 48 shows only major disasters. Many floods are local, affecting a few watersheds or a small area. Flood-prone areas have been identified throughout Texas, according to the Texas Floodplain Management Association (TFMA).

The City of Highland Village's webpage on the dangers of flooding notes that while flash flood events in North Texas are most common in May and June, the potential for flooding exists throughout the year. It cites the heavy rains of September 2010, which led to damage so severe that a portion of Highland Village Road needed to be rebuilt; in addition, many homes experienced flooding from drainage system backups as well as structural damage.

Erosion and Sedimentation

As seen in the previous hydrograph (Figure 47), runoff flow rates increase as watersheds are developed. Fast-flowing water eats away at its channels more rapidly, especially if the vegetation that normally anchors soil together is absent. This accelerates silt loading to water bodies. An example of this sedimentation is shown in Figure 49.

Figure 49. An example of the impacts of erosion and sedimentation on a water body.
Source: Texas Aquatic Science/Texas Parks and Wildlife Department. (n.d.)

John Ostdick's July 2007 article "White Rock's Second Chance" in *Texas Parks and Wildlife* provides an excellent real-world example of how development contributes to erosion and sedimentation at White Rock Lake in Dallas, Texas.

The City of Dallas constructed the 1,100-acre White Rock Lake, now a recreational hub, as a water source in 1911. When it was no longer adequate to meet the city's water demands, the City designated White Rock Lake as a city park in 1929 after the construction of Lake Dallas (now Lewisville Lake).

White Rock Lake's watershed is a narrow 100-square-mile band along the 30-mile-long White Rock Creek. It extends from its upper reaches in Frisco through Plano, Richardson, and North Dallas, and empties eight miles south into Trinity River's Elm Fork. The northern portion of White Rock's watershed has exploded in population in the past few decades; for example, Plano's population in 1970 was 17,872, and it doubled in size every five years into the 1980s. Frisco's population in 1970 was 1,845; in

2010, it was 116,989.

The scraping and development of wooded areas, farms, and ranches over the past three decades contributed considerably to sediment flows, nutrient runoffs, and erosion problems in the creeks that feed the lake. It has been dredged several times over the decades. By the 1990s, the lake's sediment had reduced its north end's depth to less than a foot. In 1994, the City of Dallas used an EPA grant to conduct a study that verified the lake's high sediment levels and found that during summertime, the lake's dissolved oxygen could drop, threatening the fish population. A $9 million bond package paid for the last dredging in 1998, and it filled up 200 acres of pits with up to five feet of sediment.

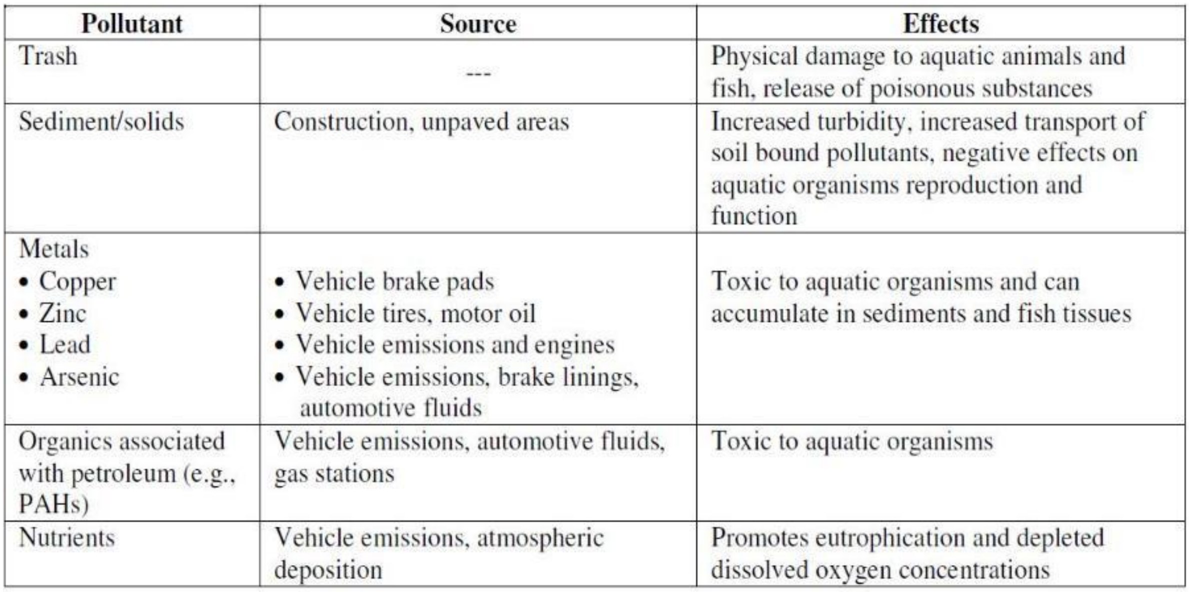
White Rock Lake is not alone. As of the article's publication, the dredging company had completed about 17 other projects in the state since White Rock.

While the City of Dallas has begun armoring the creek banks to curtail erosion problems, a broader look at what else can be done to prevent future siltation is warranted.

Water Pollution

One problem related to stormwater runoff is water pollution. Stormwater has been identified by the EPA as a leading source of pollution for all waterbody types in the United States. It often contains pathogens and bacteria, chemicals and heavy metals, gas and oil, and fertilizers and pesticides, which foul waters and put human and wildlife health at risk. A wide range of pollutants is collected from road surfaces as seen in Table 11.

Table 11. Stormwater Pollutants Typical of Roads.



Pollutant	Source	Effects
Trash	---	Physical damage to aquatic animals and fish, release of poisonous substances
Sediment/solids	Construction, unpaved areas	Increased turbidity, increased transport of soil bound pollutants, negative effects on aquatic organisms reproduction and function
Metals • Copper • Zinc • Lead • Arsenic	• Vehicle brake pads • Vehicle tires, motor oil • Vehicle emissions and engines • Vehicle emissions, brake linings, automotive fluids	Toxic to aquatic organisms and can accumulate in sediments and fish tissues
Organics associated with petroleum (e.g., PAHs)	Vehicle emissions, automotive fluids, gas stations	Toxic to aquatic organisms
Nutrients	Vehicle emissions, atmospheric deposition	Promotes eutrophication and depleted dissolved oxygen concentrations

Source: EPA, "Managing Wet Weather with Green Infrastructure—Municipal Handbook: Green Streets," 2008.

As runoff flows over impervious surfaces such as paved streets and parking lots, it gathers pollutants that can negatively affect water quality, not only creating water quality challenges but also increasing costs. According to the 1998 paper “Costs of Water Treatment Due to Diminished Water Quality: A Case Study in Texas,” which studied 12 water treatment plants in Texas for a three-year period, the chemical cost of water treatment increased by $95 per million gallons from a base of $75 due to regional raw water contamination.

While the dollar amounts have likely changed since 1997, the costs of diminished water quality—both financial and related to quality of life—continue to be important challenges associated with growth.

B.2 Problems with Depending Solely on Gray Infrastructure

Traditional approaches to stormwater management use “gray” infrastructure (pipes, gutters, ditches, detention basins, and storm sewers, for example), but managing runoff solely through gray infrastructure can present a variety of challenges, the 2013 EPA report “Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs” notes. One challenge is the high cost of construction, maintenance, and repair.

Another issue is that gray infrastructure only captures and conveys stormwater runoff. It fails to adequately treat for pollutants of concern because the water is not filtered through layers of soil. In addition, the EPA report warns that changing weather patterns, increasing energy costs, aging water infrastructure, and new environmental concerns will bring new challenges as will increases in population and development.

The EPA report recommends the use of low impact development (LID) and GSI as an integrated approach to stormwater management, highlighting the financial, social, and environmental benefits that it can provide to multiple stakeholders. The Texas A&M AgriLife report on its stormwater best management practices (BMPs) in a typical urban watershed in the Dallas-Fort Worth area, “Upper Trinity Watershed Low Impact Development Infrastructure for Stormwater Management,” underscores the need to evaluate stormwater management in this region. The report notes that the Upper Trinity River that drains the Dallas-Fort Worth Metroplex has been designated as impaired for chlordane, polychlorinated biphenyls (PCBs) and bacteria and that total phosphorus, nitrate, chlorophyll-a, and orthophosphate were considered pollutants of concern.

In addition, as the EPA points out on their “Cost-Benefit Resources” webpage (http://water.epa.gov/infrastructure/greeninfrastructure/gi_costbenefits.cfm), GSI can often supply more benefits for less cost than gray infrastructure. (The page provides links to several reports for support, including ECONorthwest’s “The Economics of Low-Impact Development: A Literature Review,” the EPA’s “Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs,” and Center for Neighborhood Technology’s “The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental, and Social Benefits.”)

Stormwater management does not have to be exclusively green or gray. New York City's Green Infrastructure Plan uses a hybrid approach to reducing the city's combined sanitary and storm sewer system overflows. The Plan demonstrates that this adaptive approach to its combined sewer overflow mitigation is more cost-effective than traditional gray projects alone while also pointing out that GSI provides multiple co-benefits such as improved air quality and neighborhood beautification.

GSI may not always be the only appropriate solution, but it can provide many benefits that increase community resiliency, such as helping to reduce flooding, reduce water pollution, improve groundwater recharge, and lessen the urban heat island (UHI) effect.

B.2.1 Green Stormwater Infrastructure's Integration in Transportation Projects

Figure 50. Congo Street's new design incorporating green stormwater infrastructure elements.
Source: bcWORKSHOP.

Roads, parking lots, and sidewalks offer many opportunities for employing GSI. Green streets and alleys integrate green infrastructure elements such as permeable pavement, bioswales, rain gardens, planter boxes, and trees into the design to store, infiltrate, and evapotranspire stormwater. Permeable pavements can be installed in a sidewalk or parking lot, and rain gardens and bioswales can be included in medians and along the perimeter of a parking lot.

As urban infrastructure continues to expand and increasingly age, green stormwater approaches like "green streets" provide models that lessen the load put on water management and road infrastructure through more naturally integrated systems. New York's Greenstreets program, Seattle's pilot Street Edge Alternative Project (SEA Streets), Chicago's Green Alley Program, and Philadelphia's Green Streets program are well known for their commitment to green stormwater management strategies, but the North Central Texas region is also seeing an increase in GSI implementations in transportation projects.

As with many new or unfamiliar methods, there will likely be hesitancy and challenges to overcome in GSI adoptions. The design of stormwater BMPs should be tailored to local climate and soil conditions and evaluated over time to ensure proper performance. According to the Texas A&M AgriLife report, the North Texas region is a humid subtropical climate with mostly excessively clayey and alkaline soils that experiences extreme variability in precipitation and temperature, which complicates matters such as plant selection and infiltration rates due to the soil's shrinking and swelling. Luckily, stormwater BMPs in this region are already being field-tested; Texas A&M AgriLife is evaluating BMP performance for North Central Texas conditions and conducting outreach to share its results and knowledge gained.

One regional pioneer project was Congo Street [CS 4], now recognized as Dallas's first green street (see Figure 50). In 2008, bcWORKSHOP began working with the residents on Congo Street to craft an alternative strategy that focused on rebuilding the homes and street infrastructure. The one-block-long street that had been inadequately and poorly designed could not handle the stormwater demands placed on it. Congo Street and several homes had been targeted for demolition and redevelopment.

The Congo Street design incorporated permeable pavement, biofiltration, and retention basins as strategies to manage stormwater (see Figure 51). The main goals for street improvements were to create a safer street, allow more space for pedestrians, resolve persistent issues of flooding, address poor paving conditions, and eliminate the 10-foot bottleneck at the end of the street. Congo Street features stormwater bumpouts that function as bioswales and definitions for the permeable parallel parking areas and drive approaches.

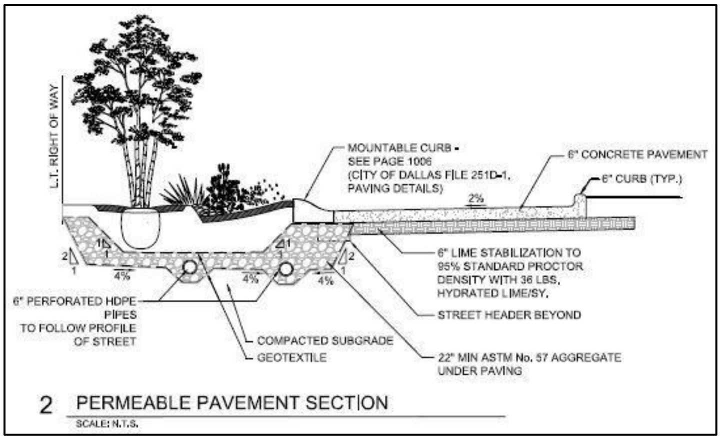


Figure 51. Plan details for a permeable pavement section of Congo Street, Dallas, Texas.
Source: Nigel Nixon and Partners, Inc.

The Congo Street houses along with the green street have garnered local and national awards and sparked new investments in the Jubilee and Dolphin Heights neighborhoods. To push the standards of common practice, the project initiated relationships between users, designers, and municipalities that allow for increased technical knowledge and skills to use similar systems in Dallas and across the country.

With projects like Congo Street and pilots like Texas A&M AgriLife's BMP evaluation and Texas A&M Transportation Institute's Bioretention for Stormwater Quality in Texas (a study looking at the application of bioretention in hot, semi-arid areas), transportation and development professionals can learn which GSI approaches and techniques are the most appropriate, cost-effective, and beneficial for the region.

APPENDIX C: COST/BENEFIT ANALYSIS

This guide provides examples of costs for transportation-related green practices based on both case studies throughout the United States and research from literature reviews. It also examines the practices' benefits and, when possible, the costs of comparable gray infrastructure. It does not incorporate compliance incentives, credits, or other tax benefits, but those may affect a project's bottom line.

According to a survey by the American Society of Landscape Architects (ASLA) that compared the performance of green stormwater infrastructure (GSI), also known as *green infrastructure*, and gray infrastructure approaches, green practices can potentially reduce the following costs:

- Land acquisition
- Built capital (equipment, installation)
- Operation
- Repair and maintenance
- External (off-site, imposed on others)
- Infrastructure replacement (potential for longer life of investment)

ASLA's findings also pointed out that the design and performance of GSI is generally more context-specific than gray, so while green controls must be designed and constructed to suit the specific site's soil, terrain, and hydrologic conditions, they also provides flexibility in addressing local concerns. GSI also allows for low impact design, which could result in a reduction in materials needed for roads, curbs, and gutters as well as a reduction in the size and cost of flood-control structures.

C.1 Challenges in Cost Analysis

Examples of GSI that cost less than gray infrastructure can be found in many reports, such as a 2013 economic analysis by the EPA, a 2010 report by the Center for Neighborhood Technology, and the University of Louisville's tool-box module on low-impact development. However, several of these researchers also point out the lack of a consistent and accessible methodology to compare green with gray infrastructure, and note that further research was needed. While the valuation of GSI's monetary benefits has advanced substantially in recent years, the field is still evolving.

Many projects that incorporate a green element did not evaluate the cost of its traditional counterparts, and a comparison of costs from one green project versus another traditional project may not be possible due to a number of factors. Another problem lies with the uncertainties related to costs of certain green practices, especially with newer technology or unknown maintenance costs.

Additionally, some projects might compare costs of green to gray elements using only initial construction costs, which is the simplest yet incomplete type of comparison. Another comparison might add planning, design, installation, operation, maintenance, and decommissioning costs for a lifecycle cost analysis. However, that analysis still excludes economic, environmental, and social benefits as well as differences in effectiveness.

The most comprehensive comparisons—a cost/benefit analysis or triple-bottom line analysis—require the most resources to produce; many project either do not have or lack an incentive to use resources for this purpose. In addition, those comprehensive comparisons still have several complications.

Issues in analysis include:

- An absence of a uniform baseline with which to compare the costs and benefits of green practices against those of conventional practices
- Analyses that differ depending on resources, goals, and availability of data
- The site-specific nature of green infrastructure and the influence of local and regional variables
- Uncertainties related to benefits of certain green practices, given their organic nature (for example, as an urban grove of trees matures, it may improve at cooling down the urban heat-island effect, or certain trees may not thrive and need to be replaced)
- Difficulties in monetizing environmental and social goods and services

Additional issues related to analyzing specific green practices include:

- The scarcity of projects that consider actual practice-by-practice costs separately (material and labor costs being typically calculated for an entire site rather than for each element)
- The potential for double counting benefits because many benefits are interconnected

However, despite these uncertainties, research done by the EPA in 2007 found that costs of well-chosen green practices were both fiscally and environmentally beneficial to developers, property owners, and communities.

One regional example of a project that incorporated several green elements cost effectively is the Green at College Park (University of Texas - Arlington) [CS 1], a 3-acre urban infill development completed in 2011. The case study provided the total project cost of approximately $2.2 million, with its green elements accounting for only about 16% of the total cost. Prior to the construction, this site was neglected, consisting of 75% impervious surfaces (parking and dilapidated apartments), with an eroded drainage channel associated with considerable flooding issues in the area flanking one edge. The firm charged with revitalizing the area perceived the stormwater management constraints as key opportunities, creating a final design that celebrates the paths of water and the plant life that thrives in its drought and flood dynamics. The site, now an inviting gateway between the city and the campus, includes an outdoor classroom with layers of seating, a pedestrian promenade, high-albedo pavement, animated LED lighting, recycled glass pervious paving, rain gardens and planters, and a spacious oval lawn for events.

Green practices may not always have the lowest capital investment. Exact cost savings will be affected by many site-specific variables, including topography, soil type, rainfall distribution, and local materials costs. However, as green practices become more common and as technologies and understanding of best practices improve, the costs of design and construction are likely to decrease. The costs of maintenance for green practices may also be less than traditional practices, or they may be initially high but decrease over time (for example, a tree may need to be irrigated for its first two years but only need annual pruning after that initial period).

C.2 Cost/Benefit Resources

- Center for Neighborhood Technology’s Green Value Calculators
  http://greenvalues.cnt.org
- ECONorthwest’s 2007 “The Economics of Low-Impact Development: A Literature Review”
- EPA webpage “Cost-Benefit Resources”
  water.epa.gov/infrastructure/greeninfrastructure/gi_costbenefits.cfm
- EPA’s 2013 “Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs”

APPENDIX D: NCTCOG COST MATRIX

Table 12. Cost Matrix – Costs from Case Study Estimates and Other Sources .

		Case Study Number	Project	Location	Unit	Green Feature Cost^	Traditional Feature Cost^	Project Year
LIGHTING	**Lights without Poles**							
	LED Streetlight (200W Equiv.) (Top Only)	10	Oncor LED Streetlight Pilot and Technical Evaluation Program	Dallas-Fort Worth, TX	Each	$525 - $850		2010
	LED Residential (57, 78 and 86 Watt LED) (Top Only)	10	Oncor LED Streetlight Pilot and Technical Evaluation Program	Colleyville, TX	Each	$624		2011
	Solar Powered LED Flush Mounted Guide Lights (including Epoxy)	26	LED-Mark Light Demonstration Project	Portland, OR	Each	$127- $155		2013
	LED Street Light Fixture (81 Lm/W)	23	Elmer Paseo Stormwater Improvement Project	Los Angeles, CA	Each	$245		2012
	Solar-Powered Flashing Beacon	31	Uptown Normal Street and Streetscape Project	Normal, IL	Each	$5,700		2010
	Photovoltaic Panels	39	GW Solar Walk	Ashburn, VA	SF	$125		2012
	LED Streetlight 50 W (70 - 200W Equiv.) (Entire Fixture)	N/A*	NCTCOG Quote		Each	$454		2015
	LED Streetlight 78 W (200 - 400W Equiv.) (Entire Fixture)	N/A*	NCTCOG Quote		Each	$454		2015
	LED Streetlight 105 W (320 - 400W Equiv.) (Entire Fixture)	N/A*	NCTCOG Quote		Each	$520		2015
	LED Streetlight 125 W (350 - 400W Equiv.) (Entire Fixture)	N/A*	NCTCOG Quote		Each	$540		2015
	LED Streetlight 150 W (350 - 400W Equiv.) (Entire Fixture)	N/A*	NCTCOG Quote		Each	$540		2015
	Acorn Style LED Streetlight (72 Watt) (Globe, Light, Driver)	N/A*	NCTCOG Quote		Each	$840		2015
	Solar Street Light (40 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$3,440		2015
	Solar Street Light (50 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$3,450		2015
	Solar Street Light (60 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$3,465		2015
	Solar Street Light (70 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$3,560		2015
	Solar Street Light (80 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$5,640		2015
	Solar Street Light (90 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$5,790		2015
	Solar Street Light (100 Watt LED Light Fixture, Battery, Solar Panel, Charge Controller)	N/A*	NCTCOG Quote		Each	$5,800		2015
	Lights with Poles							
	Light Pole with LED Luminaire and Solar Panel Fixtures	N/A*	Klyde Warren Park	Dallas, TX	Each	$17,000		2012
	Solar LED Street Light (with 20' pole)	N/A*	Solar Illuminations Website	NCTCOG Quote	Each	$1,600		2014
	Solar LED Street Light (24 ft. Carmanah EverGEN 1520, include maintenance)	N/A*	Lockheed Martin Facility Roadways	Orlando, FL	Each	$9,771		2009
	Light Pole with Cylindrical Solar PVs and LED Luminaire	35	Penn Street Trail	Philadelphia, PA	Each	$13,500		2013
	LED Pole Lights	18	St. Stephen's Pedestrian Green	Austin, TX	Each	$1,500		2012
	LED, Solar Powered Lights (includes light, pole, battery, solar panel, hardware)	24	Obern Trail Lighting Retrofit Project	Santa Barbara County, CA	Each	$3,890		2013
	Lights without Poles							
	250 MW energy-efficient/dark sky compliant lamps mounted on utility poles	29	Chicago Green Alley Program	Chicago, IL	Each		$600	2010
	Metal Halide Luminaire, Pendant Mount, 250 Watt	31	Uptown Normal Street and Streetscape Project	Normal, IL	Each		$600	2010
	Metal Halide Luminaire, Pendant Mount, 175 Watt	31	Uptown Normal Street and Streetscape Project	Normal, IL	Each		$995	2010
	100 Watt Fixture	N/A*	City of Arlington, TX	Arlington, TX	Each		$105	2010
	150 Watt Fixture	N/A*	City of Arlington, TX	Arlington, TX	Each		$180	2010
	Pedestrian Light Fixture	6	Elm Street Streetscape Improvements	Dallas, TX	Each		$5,300	2014
	Flashing Beacon	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$10,010	2013
	Flashing Beacon RRFB	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$22,250	2013
	Pedestrian Hybrid Beacon	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$57,680	2013
	In-pavement lighting	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each System		$17,620	2013
	Lights with Poles							
	AC Powered Streetlights (includes new wiring, electricity costs, maintenance)	N/A*	Lockheed Martin Facility Roadways	Orlando, FL	Each		$16,086	2009
	25' Decorative Light Pole	31	Uptown Normal Street and Streetscape Project	Normal, IL	Each		$4,035	2010
	Streetlight	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$4,880	2013
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Arlington, TX	Arlington, TX	Each		$7,000	2010
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Dallas, TX	Dallas, TX	Each		$2,263	2010
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Dallas, TX	Dallas, TX	Each		$6,855	2010
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Dallas, TX	Dallas, TX	Each		$6,710	2010
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Frisco, TX	Frisco, TX	Each		$6,826	2010
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Grapevine, TX	Grapevine, TX	Each		$2,558	2007
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Arlington, TX	Arlington, TX	Each		$4,850	2010
	Decorative Street Lighting (includes base, poles, light fixtures)	N/A*	City of Duncanville, TX	Duncanville, TX	Each		$3,214	2009
	Pole Street (27") Local Street	N/A*	City of Arlington, TX	Arlington, TX	Each		$1,300	2010
	Pole Steel (33') Local Street	N/A*	City of Arlington, TX	Arlington, TX	Each		$1,800	2010
	40' Galvanized Steel Light Post	31	Uptown Normal Street and Streetscape Project	Normal, IL	Each		$5,050	2010

^Most costs include construction costs only and do not account for maintenance. Some costs provided do account for either the product or the product and installation cost. Because most case studies did not identify these components separately, the cost estimates provided here assume the construction cost (product and installation).

N/A* - Resources used to compile costs estimates and comparisons but not included as case studies.

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		Case Study Number	Project	Location	Unit	Green Feature Cost^	Traditional Feature Cost^	Project Year
TRAIL MATERIALS	Decomposed Granite Trail (10 ft. width)	3	Red Oak Creek Trail	Cedar Hill, TX	LF	$12.50		2014
	5 ft. Decomposed Granite	22	Blue Hole Regional Park	Wimberley, TX	LF	$17.41		2012
	4 ft. Decomposed Granite	22	Blue Hole Regional Park	Wimberley, TX	LF	$16.46		2012
	6 ft. Decomposed Granite (stone edges - both sides)	22	Blue Hole Regional Park	Wimberley, TX	LF	$38.03		2012
	4-Inch-Thick Decomposed Granite Trail	9	Trinity River Audubon Center	Dallas, TX	LF	$33.00		2008
	Recycled Crushed Concrete (from City Landfill)	14	Mountain Creek Lake Park Trail	Grand Prairie, TX	TON	$1,866.00		2013
	Filterpave Recycled Glass (assuming 4 ft. wide)	1	The Green at College Park	Arlington, TX	LF	$67.04		2011
	1/2-Inch Rubberized Surface on Concrete Base	7	Katy Trail	Dallas, TX	LF	$35.60		2007
	TerreWalk Rubberized Pavers	25	Santa Monica Rubberized Sidewalk Program	Santa Monica, CA	Each	$18.50		2009
	Flexi-Pave (from Recycled Tires) (6 ft. wide)	38	Dora Kelley Park Trail Re-Surfacing Project	Alexandria, VA	LF	$96.00		2012
	Native Soil (assuming 4 ft.- 6 ft. wide)	N/A*	Violet Crown Trail	Austin, TX	LF	$10.00 - $12.00		2010
	Wood Fiber (assuming 6 ft.- 8 ft. wide)	N/A*	Violet Crown Trail	Austin, TX	LF	$12.00 - $15.00		2010
	Soil Cement (assuming 8 ft.-10 ft. wide)	N/A*	Violet Crown Trail	Austin, TX	LF	$15.00 - $20.00		2010
	Granular Stone (assuming 10 ft. wide)	N/A*	Violet Crown Trail	Austin, TX	LF	$20.00 - $40.00		2010
	TREX Decking Boardwalk Trail	9	Trinity River Audubon Center	Dallas, TX	LF	$64.00		2008
	TREX Decking Composite Board	N/A*	Home Depot Website Cost	N/A	LF	$3.92		2015
	Wood Boardwalk (assuming 10 ft. wide)	N/A*	Violet Crown Trail	Austin, TX	LF	$280.00 - $380.00		2010
	Boardwalk (Assume 8 ft. wide)	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF	$420.00		2013
	Pervious Concrete Sidewalk (including underdrain and separation fabric) (8 ft. wide)	28	Henderson Blvd. Sidewalk	Olympia, WA	LF	$72.00 - $80.00		2012
	Multi-Use Trail Unpaved (assuming 8 ft. wide)	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$22.96	2013
	Multi-Use Trail Paved (assuming 8 ft. wide)	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$88.00	2013
	Asphalt Sidewalk	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$35.00	2013
	Mulch (assuming 4 ft.-6 ft. wide)	N/A*	TX Department of Transportation	State	LF		$1.32 - $1.98	2014
	Concrete Sidewalk (5 ft. wide, 4-inch depth)	N/A*	TX Department of Transportation	State	LF		$18.00	2014
	4-Inch Reinforced Concrete Sidewalks (4.5 ft. wide)	17	Merritt Road	Rowlett, TX	LF		$16.02	2013
	5-Inch Reinforced Concrete Sidewalk (assuming 4.5 ft. wide)	17	Merritt Road	Rowlett, TX	LF		$16.97	2013
	Concrete Sidewalk (5 ft. wide, 6-inch depth)	N/A*	TX Department of Transportation	State	LF		$27.29	2014
	Concrete Sidewalk (assuming 4 ft. wide)	2	South Main Reconstruction Parking Lot	Carrollton, TX	LF		$20.00	2011
	Concrete Sidewalk	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$32.00	2013
	Concrete Sidewalk and Curb	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$150.00	2013
SILVA CELLS	System Installed (all but base course, final paving, and tree)	N/A*	Fort Worth Sundance Square Plaza	Fort Worth, TX	CF	$14 - $18.00		2013
	System Installed	16	Downtown Rowlett Streetscape	Rowlett, TX	CF	$23.00		2014
	Silva Cells (2 Stacked)	31	Uptown Normal Street and Streetscape Project	Normal, IL	Each	$160.00		2010
PAVEMENT OPTIONS	Permeable Pavers	30	Ravinia Festival South Parking Lot	Highland Park, IL	SF	$5.30		2010
	Permeable Pavers With Bedding Course and Filer Stone	6	Elm Street Streetscape Improvements	Dallas, TX	SF	$5.67		2015
	Permeable Pavers	4	Congo Street Initiative	Dallas, TX	EA	$6.50		2012
	Pervious Pavers	41	Triangle Parking Lot	Stone Mountain, GA	SF	$6.85		2008
	Pervious Pavers	18	St. Stephen's Pedestrian Green	Austin, TX	SF	$12.22		2012
	Permeable Pavers	29	Chicago Green Alley Program	Chicago, IL	SF	$18.00		2010
	Permeable Clay Pavers	39	GW Solar Walk	Ashburn, VA	SF	$18.00		2012
	Permeable Pavers (Construction Cost Only)	N/A*	Center for Neighborhood Technology	Various	SF	$5.30 - $12.00		Various
	Permeable Interlocking Concrete Pavement (PICP) Material Only	N/A*	SARB Technical Guidance Manual*	SARA**	SF	$3.00		2013
	EcoGrid Concrete Pavers	37	GW Square 80	Washington, D.C.	SF	$15.00		2010
	Plastic Grid Pavers (Material Only)	N/A*	SARB Technical Guidance Manual*	SARA**	SF	$2.50		2013
	Grasstone Permeable Pavers	2	South Main Reconstruction Parking Lot	Carrollton, TX	EA	$48.70		2011
	Grid Permeable Pavement	9	Trinity River Audubon Center	Dallas, TX	SF	$1.25		2008
	Permeable Pavement	N/A*	Chicago Green Alley Handbook	Chicago, IL	SF	$3 - $15.00		2010
	Permeable Paving	37	GW Square 80	Washington, D.C.	SF	$23.00		2010
	Pervious Asphalt (Material Only)	N/A*	SARB Technical Guidance Manual*	SARA**	SF	$2.00		2013
	Grasspave2 Porous Pavement	37	GW Square 80	Washington, D.C.	SF	$8.00		2010
	Gravelpave Porous Pavement	37	GW Square 80	Washington, D.C.	SF	$10.00		2010
	Porous Asphalt (Construction Cost Only)	N/A*	Center for Neighborhood Technology	Various	SF	$5.50 - $8.13		Various
	Porous Concrete (Construction Cost Only)	N/A*	Center for Neighborhood Technology	Various	SF	$5.50 - $11.60		Various
	Pervious Concrete	28	Henderson Blvd. Sidewalk	Olympia, WA	SF	$7 - $8.00		2012
	Pervious Concrete (Material Only)	N/A*	SARB Technical Guidance Manual*	SARA**	SF	$6.00		2013
	Permeable Gravel (Construction Cost Only)	N/A*	Center for Neighborhood Technology	Various	SF	$1.72 - $6.00		Various
	High-Albedo Portland Cement Concrete Pavement (8")	29	Chicago Green Alley Program	Chicago, IL	SF	$7.20		2010
	Granite Accent Paving	37	GW Square 80	Washington, D.C.	SF		$65.00	2010
	Granite Cobble Paving	37	GW Square 80	Washington, D.C.	SF		$75.00	2010
	Concrete Paving (Pedestrian and Vehicular)	37	GW Square 80	Washington, D.C.	SF		$8 - $12	2010
	Concrete Pedestrian Paving	39	GW Solar Walk	Ashburn, VA	SF		$5.00	2012
	4" Reinforced Concrete Pavement (Textured/Colored)	17	Merritt Road	Rowlett, TX	SF		$10.00	2013
	6" Reinforced Concrete Driveways (Including 1" sand cushion)	17	Merritt Road	Rowlett, TX	SF		$3.77	2013
	Bomanite Imprinted Concrete (Alternate to Pavers)	6	Elm Street Streetscape Improvements	Dallas, TX	SF		$11.10	2014
	Interlocking Pavers (with sand and bedding)	6	Elm Street Streetscape Improvements	Dallas, TX	SF		$4.16	2014
	Pavers Vehicular Crosswalk - Lugged	6	Elm Street Streetscape Improvements	Dallas, TX	SF		$3.88	2014
	Sidewalk Pavers	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$80.00	2013
	Clay Pavers	39	GW Solar Walk	Ashburn, VA	SF		$16.00	2012
	Brick Sidewalk	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	LF		$60.00	2013
	Stone Paving	22	Blue Hole Regional Park	Wimberley, TX	SF		$11.24	2012

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N/A* - Resources used to compile costs estimates and comparisons but not included as case studies.

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		Case Study Number	Project	Location	Unit	Green Feature Cost^	Traditional Feature Cost^	Project Year
BIOSWALE	Bioswales with Sawtooth Curbs	11	Rayzor Ranch	Denton, TX	SF	$9.00		2014
	Parking Lot Bioswales	8	Perot Museum of Nature and Science	Dallas, TX	SF	$12.00		2012
	Red Oak Creek Trail	3	Red Oak Creek Trail	Cedar Hill, TX	SF	$4.80		2014
	Bioswales (Parking Lot and Roadside Construction Cost Only)	N/A*	Center for Neighborhood Technology	Various	SF	$5.50 - $24		Various
	Bioswales and Vegetated Swales	N/A*	Chicago Green Alley Handbook	Chicago, IL	LF	$8 - $30.00		2010
	Bump Outs Bioswales	4	Congo Street Initiative	Dallas, TX	Average	$5,749.00		2012
	Stormwater Curb Extensions and Filterra Stormwater Bioretention Filtration	27	SE Clay Green Street: Water to 10th Avenues	Portland, OR	Average	$16,113		2013
	Typical 20'5' Right-of-Way Bioswale (Includes Design, Construction, Management)	32	Area-wide Right-of-Way Bioswale	New York City, NY	Average	$25,000		2013
	Bioretention/Enhanced Swale (Includes Materials and Median Plantings)	17	Merritt Road	Rowlett, TX	Average	$54,138		2013
	Bioswale	42	Hinds Community College Multipurpose Center	Pearl, MS	Average	$1,298,356		2009
RAIN GARDENS	Rain Garden	N/A*	Chicago Green Alley Handbook	Chicago, IL	SF	$3 - $6.00		2010
	Rain Garden Construction Estimate	N/A*	Stormwater Management Rain Gardens, AgriLife Extension	N/A	SF	$6.00		2012
	Rain Garden (Construction Cost Only)	N/A*	Center for Neighborhood Technology	Various	SF	$5.15 - $16.05		Various
	Rain Garden with Plants, Mulch/Soil, Terrace Walls	18	St. Stephen's Pedestrian Green	Austin, TX	SF	$40.00		2012
	Rain Garden (includes labor, equipment, materials)	19	Bioretention for Stormwater Quality Improvement in Texas	Bryan, TX	SF	$13.40		2012
	Rain Garden Infrastructure (without plants)	20	Bagby Street Reconstruction	Houston, TX	SF	$30.00		2013
	Rain Garden	39	GW Solar Walk	Ashburn, VA	SF	$32.00		2012
	Rain Garden/Underground Stone Pocket Storage Area	35	Penn Street Trail	Philadelphia, PA	SF	$78.09		2013
	Rain Garden	37	GW Square 80	Washington, D.C.	SF	$120.00		2010
	Rain Garden (Includes Biofiltration System and Landscape Planting)	21	Birnamwood Drive	Houston, TX	SF	$99.53		2012
	Rain Garden	5	Dallas Urban Reserve	Dallas, TX	LF	$188.00		2009
	Rain Garden Bioretention Trench	13	Historic Handley Urban Village Streetscape Project	Fort Worth, TX	LF	$371.00		2014
	Rain Garden (Includes Landscape Maintenance)	6	Elm Street Streetscape Improvements	Dallas, TX	Average	$14,543		2015
OTHER INFRASTRUCTURE	*OTHER TRADITIONAL INFRASTRUCTURE THAT COULD BE CONSIDERED FOR INTEGRATING GREEN INFRASTRUCTURE PRACTICES*							
	Median	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	SF		$7	2013
	Island (Median Island)	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	SF		$10	2013
	Curb Extension/Choker/Bulb-Out	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$13,000	2013
	Chicanes	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$9,960	2013
	Roundabout/Traffic Circle	N/A*	UNC Highway Safety Research Center (Average Cost)	Various	Each		$85,370	2013

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D.1 Construction Cost Estimate Details for Permeable Pavement

Table 13. Cost Estimate Details for Permeable Pavements.

Components/Activities	Cost Estimates
Excavation	\$1.10-\$2.25/ft^2
Hydraulic restriction layer	30-mil liner: \$0.35/ft^2 Concrete barrier: \$12/ft^2
Permeable pavement materials	Porous asphalt \$2/ft^2, porous concrete \$6/ft^2, pervious interlocking concrete pavers \$3/ft^2, plastic grid pavers \$2.50/ft^2
Bedding layer	Washed sand (2-inch layer): \$0.20/ft^2 No. 8 aggregate (min. 2 inches thick): \$0.22/ft^2 No. 57 stone (min. 6 inches to 1 foot): \$0.83-\$1.67/ft^2

Source: *San Antonio River Basin Low Impact Development Technical Design Guidance Manual,* Appendix G, 2013.

D.2 Maintenance Cost Estimates for Permeable Pavements

Table 14, a portion of the table found in Appendix G, "Cost Estimates and Regulatory Guidance" of the *San Antonio River Basin Low Impact Development Technical Guidance Manual*, provides a base point for costs and illustrates the importance of including maintenance costs in the project's budget. Maintenance costs were based on the Water Environment Federation research, with labor and equipment operating costs collected from the Texas Department of Transportation (TxDOT) and municipalities. For an example of operation and maintenance tasks for permeable pavement, see Appendix F.

Table 14. Maintenance Cost Estimates for Permeable Pavements.

Permeable Pavement	
Routine Maintenance (required monthly to every 2 years)	
Small	\$5.32/ft^2
Medium	\$1.33/ft^2
Large	\$0.67/ft^2
Intermediate Maintenance (required every 6 to 10 years)	
Small	\$3.71/ft^2
Medium	\$1.85/ft^2
Large	\$1.85/ft^2
Replacement (service life of 20 years)	
Small	\$6.50-\$9.50/ft^2
Medium	\$6.50-\$9.50/ft^2
Large	\$6.50-\$9.50/ft^2
Small system = 500 ft^2, medium system = 2,000 ft^2, large system = 4,000 ft^2.	

Source: *San Antonio River Basin Low Impact Development Technical Design Guidance Manual,* Appendix G, 2013.

D.3 Construction Cost Estimate Details for Bioretention Practices

Table 15 provides details associated with the cost estimates given in the *San Antonio River Basin Low Impact Development Technical Design Guidance Manual*.

Table 15. Cost estimate details for bioretention, bioswale, planter box, vegetated swale, and vegetated filter strip.

Components/ Activities	Bioretention and Bioswale	Planter Box	Vegetated Swale	Vegetated Filter Strip
Excavation	\$2.75-\$5.00/ft^2 without underdrains, \$3.90-6.15/ft^2 with underdrains	\$3.90-\$6.15/ft^2	\$0.80/ft^2	
Fine grading			\$0.25/ft^2	
Soil media	Recommended mix: \$2.40-\$4.75/ft^2; with engineered media: \$3.40-\$6.80/ft^2	Recommended mix: \$2.40-\$4.75/ft^2; with engineered media: \$3.40-\$6.80/ft^2		
Soil media barrier	Geotextile: \$0.45/ft^2 Washed sand (2-inch layer): \$0.20/ft^2 No. 8 aggregate (min. 2 inches thick): \$0.28/ft^2	Geotextile: \$0.45/ft^2 Washed sand (2-inch layer): \$0.20/ft^2 No. 8 aggregate (min. 2 inches thick): \$0.28/ft^2		
Underdrain pipe (including drainage stone, assumes 5-ft. spacing)	\$3.60/ft^2	\$3.60/ft^2		
Curb and gutter	\$18/ft.	\$18/ft.		
Mulch (native hardwood)	\$0.24-\$0.39/ft^2	\$0.24-\$0.39/ft^2		
Hydraulic restriction layer	Filter fabric: \$0.45/ft^2 Clay: \$0.65/ft^2 30-mil liner: \$0.35/ft^2 Concrete barrier: \$12/ft^2	30-mil liner: \$0.35/ft^2 Concrete barrier: \$12/ft^2		
Vegetation	\$0.20-\$3.50/ft^2	\$0.20-\$3.50/ft^2	Sod (buffalo): \$0.67/ft^2 Seeding: \$0.15-0.22/ft^2	Sod (buffalo): \$0.67/ft^2 Seeding: \$0.15-0.22/ft^2

Source: *San Antonio River Basin Low Impact Development Technical Design Guidance Manual,* Appendix G, 2013.

D.4 Maintenance Cost Estimates for Bioretention Practices

Table 16. Maintenance cost estimates from San Antonio River Basin manual.

	Bioretention, Bioswale, and Planter Box	Vegetated Swale and Vegetated Filter Strip
Routine Maintenance (required monthly to every 2 years)		
Small	\$7.62/ft^2	\$3.73/ft^2
Medium	\$1.91/ft^2	\$1.40/ft^2
Large	\$1.91/ft^2	1.01/ft^2
Intermediate Maintenance (required every 6 to 10 years)		
Small	\$5.62/ft^2	
Medium	\$2.94/ft^2	
Large	\$2.50/ft2	
Replacement (service life of 20 years)		
Small	\$10.52/ft^2	\$4.17/ft^2
Medium	\$10.17/ft^2	\$2.33/ft^2
Large	\$10.11/ft^2	\$2.02/ft^2
Small system = 500 ft^2, medium system = 2,000 ft^2, large system = 4,000 ft^2.		

Source: *San Antonio River Basin Low Impact Development Technical Design Guidance Manual,* Appendix G, 2013.

For specific cost information provided by case studies, see the appropriate section in the guidebook. Due to space constraints, green stormwater infrastructure case study information is included in both the guidebook's Section 5 and Appendix F.

APPENDIX E: RECYCLED CONSTRUCTION MATERIALS - A CLOSER LOOK AT ASPHALT

While this guidebook does not provide details for every recycled material type, a deeper look at recycled asphalt is warranted. According to the Texas Asphalt Pavement Association (TAPA), asphalt is the most common pavement type in the United State; it is used in 94% of paved roads and 85% of parking lots.

Asphalt can include:

- **Recycled asphalt pavement (RAP),** which is simply asphalt pavement that has been salvaged, milled, pulverized, broken, or crushed. It is 100% recyclable.
- **Recycled asphalt shingles (RAS),** which are asphalt roofing shingles from manufactured waste or roofing tear-offs.
- **Warm mix asphalt (WMA)**. This is not necessarily recycled; however, because it is produced at lower temperatures than hot mix asphalt, it also has lower carbon emissions.
- **Glass.**
- **Rubber from used tires.** Scrap tire rubber can be used as part of the asphalt rubber binder (also known as asphalt rubber), sealcoat, cap seal spray or joint and crack sealant, or as an aggregate substitution.
    - **Rubberized asphalt concrete (RAC)**, which contains ground tire rubber, asphalt binder, and other aggregates, has been used for road rehabilitation projects for more than 30 years.
    - **Tire-derived aggregate (TDA)**, made from shredded scrap tires, is used for projects such as retaining wall backfill, lightweight embankment fill, landslide stabilization, and vibration mitigation.

TAPA notes that asphalt mix prices in Texas could potentially be reduced 10%-30% when RAP, RAS, and binder substitution are used—a savings of between $50 million to $150 million in Texas alone. It also notes that in the United States, the asphalt industry reclaims about 100 million tons of its own product annually, reusing or recycling approximately 95 million tons. However, there may be potential for even more recycling, especially of used tires.

The Texas Department of Transportation (TxDOT) promotes the use of waste tire rubber, perceiving its use to align with its goals of **enhancing its roadway safety, supporting an environmentally sustainable economy** in Texas, and increasing the value of its roadway through **greater durability (longer lasting road surfaces and reduced road maintenance)**. The Texas Commission on Environmental Quality (TCEQ) oversees the processing of more than 24 million discarded tires each year in Texas, and asphalt rubber is the largest single market for ground rubber.

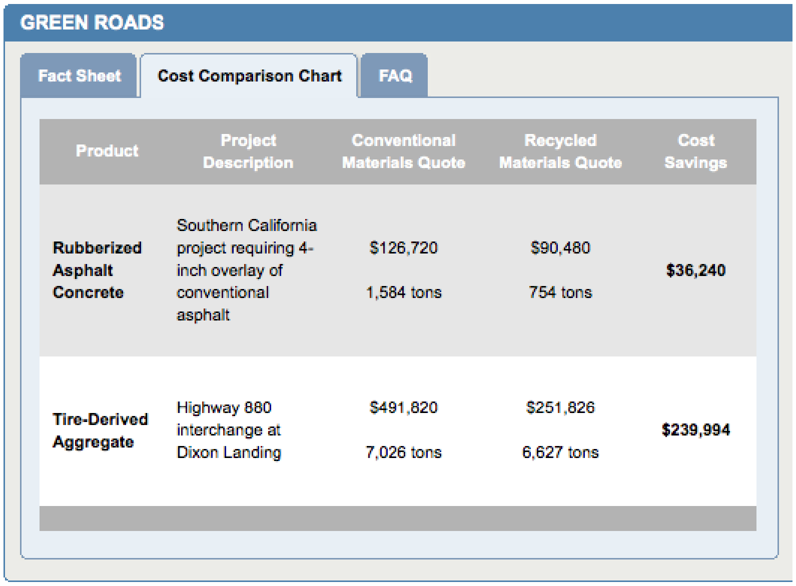
The Common Wastes & Materials web pages published by the U.S. Environmental Protection Agency (EPA) highlight the following additional benefits:

- **Cost effectiveness** over the long term
- **Shorter braking distances** (which may translate to increased safety)
- **Lower road noise**

- **Decreased risk for environmental hazards and public health and safety issues** associated with scrap tires

  Tire fires can pollute air, soil, and water, releasing toxic gases, heavy metals, and oils. The fires are difficult to extinguish and have cost the EPA, states, municipalities, and private companies millions of dollars to clean up. Other problems with waste tires include illegal dumping and disease vectors such as mosquitoes and rats.

According to CalRecycle, RAC is durable, long-lived pavement that resists cracking, rutting, and shoving, and it can be used at reduced thickness compared to conventional asphalt. TDA can be less expensive than other lightweight fill materials.



Product	Project Description	Conventional Materials Quote	Recycled Materials Quote	Cost Savings
Rubberized Asphalt Concrete	Southern California project requiring 4-inch overlay of conventional asphalt	$126,720 1,584 tons	$90,480 754 tons	**$36,240**
Tire-Derived Aggregate	Highway 880 interchange at Dixon Landing	$491,820 7,026 tons	$251,826 6,627 tons	**$239,994**

Figure 52. Cost comparison chart: Rubberized asphalt concrete versus tire-derived aggregate.
Source: California Department of Resources Recycling and Recovery webpage, “Green Roads: Paving the Way with Recycled Tires,” page last updated 2011.

As with any new material, a new recycled material needs to be studied to ensure environmental and public safety. A New York state department study found that crumb rubber (ground rubber recovered from scrap tires) derived entirely from truck tires may have an impact on aquatic life through leaching, the release of chemicals into surface water and groundwater. However, for crumb rubber made from mixed tires; potential leaching impacts are insignificant.

A 2014 National Science Foundation article highlighted the research efforts of Magdy Abdelrahman, an associate professor of civil and environmental engineering at North Dakota State University. Abdelrahman is experimenting with crumb rubber and other components to improve rubberized road materials, to evaluate the properties of crumb rubber-additive compounds, and to determine leaching potential under certain conditions. “We already know that the technology [rubberized roads] is proven to work, but we want to make it work much, much better,” Abdelrahman said. “We are trying to find the scientific and engineering aspects to make it better and, at the same time, be sure it is environmentally friendly.”

APPENDIX F: GREEN STORMWATER INFRASTRUCTURE & VEGETATION

F.1 Green Stormwater Infrastructure

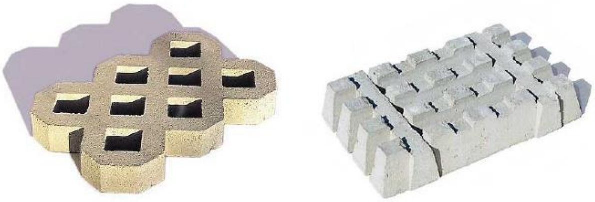
F.1.1 Descriptions of Permeable Pavements

Pervious concrete is a mixture of Portland cement, coarse aggregate, and water that allows for infiltration and overlays a stone aggregate reservoir. According to the webpage “Pervious Concrete Pavement” published by the U.S. Environmental Protection Agency (EPA), pervious concrete is durable and low maintenance with a low lifecycle cost when it is constructed properly.

Porous asphalt is standard hot-mix asphalt with reduced sand or fines that permits water to drain through it. Porous asphalt over an aggregate storage bed will decrease the runoff volume, rate, and pollutants from stormwater. The EPA notes that when porous asphalt is properly constructed, it is a durable and cost-competitive alternative to conventional asphalt.

Modular porous pavers are structural units such as concrete blocks, bricks, or reinforced plastic mats. These units have regularly interspersed void areas filled with pervious materials (gravel, sand, or grass turf) that allows for stormwater infiltration. Typically, they are placed on a gravel base course that acts as a storage reservoir.

Many different types of porous pavers are available from various manufacturers. See Figure 53 for several examples.



Concrete Paver Block

Castellated Block

Lattice Block

Grass / Gravel Paver Mat

Figure 53. Examples of porous pavers.
Source: iSWM Technical Manual, 2010.

F.1.2 Descriptions of Different Types of Bioretention Elements

Rain Gardens and Bioretention

What is it and how does it work?
A rain garden or bioretention is a shallow, vegetated stormwater basin or landscaped area that gathers and absorbs runoff from streets, sidewalks, and rooftops (see Figure 54). The treatment area usually consists of a grass filter, sand bed, ponding area, organic/mulch layer, planting soil, and vegetation. It uses engineered soils and vegetation to capture and treat runoff (see Figure 55 for a typical cross section of a rain garden). It mimics natural hydrology by allowing runoff to infiltrate and evapotranspire.

Where can you put it? It can be installed in almost any unpaved space. A rain garden is often located in “landscaping islands” and is suitable for highly impervious areas. It has good retrofit capabilities. The *integrated* Stormwater Management (iSWM) Technical Manual recommends that the contributing drainage area be less than 2 acres. Rain gardens are not recommended for steep slopes.

Figure 54. A newly planted bioretention area after a storm.
Source: iSWM Technical Manual. 2010.

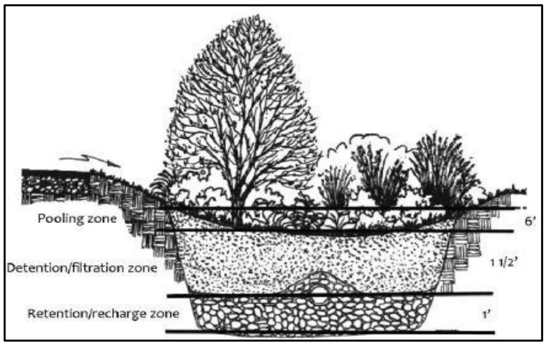


Figure 55. Typical cross section of a rain garden.
Source: George’s County, Md.

Bioswale/Enhanced Swale

How does it work? A bioswale is a vegetated, mulched, or xeriscaped channel designed to capture and treat runoff within cells formed by check dams or other structures (see Figure 56). It slows, infiltrates, and filters runoff, providing treatment and retention as it moves stormwater from one place to another.

Where is it used? A bioswale or vegetated swale’s linear design makes it particularly suitable for streets and parking lots. It is not suitable for steep slopes.

Figure 56. A bioswale.
Source: U.S. Environmental Protection Agency.

VARIATIONS ON RAIN GARDENS AND BIOSWALES

Planter Box

A planter box is an urban rain garden with vertical walls. Used on impervious surfaces, it collects and detains or infiltrates rainfall and runoff. The box contains a growing medium, plants, and a reservoir. The bottom collects and absorbs runoff from streets, parking lots, and sidewalks. The reservoir decreases peak flow rates. Although data on pollutant removal effectiveness is limited, a planter box may provide some pollutant filtration.

It is ideal for space-limited sites in dense urban areas and for use as a streetscaping element.

Stormwater Bumpout

A stormwater bumpout is a vegetated curb extension. A bumpout is made from a layer of stone aggregate topped with soil and plants. An inlet or curb cut directs runoff into the structure where it can be stored, infiltrated, and absorbed by the vegetation. Excess runoff is permitted to exit the system and flow to an existing inlet. The bumpout’s plants should be short to allow for open sight lines.

A bumpout protrudes into the street either at an intersection or midblock. When located at crosswalks, they may increase pedestrian safety by reducing the street crossing distance. Bumpouts can also help calm traffic.

Grass Channel

A grass channel provides biofiltration of runoff as the water flows across the surface (see Figure 57). With low flow rates and pervious soils, it can partially infiltrate runoff from small storm events. As a channel alone generally cannot meet the total suspended solids (TSS) removal performance goal, it should be used as either a pretreatment measure or a part of a treatment train.


Figure 57. Grass channel example. Source: iSWM Technical Manual, 2010.

A grass channel can be used as part of the runoff conveyance system to provide pretreatment. It is recommended for use on very slight slopes to avoid either standing water or bottom erosion and pollutant resuspension.

Filter Strip

A filter strip provides biofiltration of runoff as the water flows across the surface (see Figure 58). A filter strip alone generally cannot meet the TSS removal performance goal, so it should be used as either a pretreatment measure or as part of a treatment train. It may also help recharge groundwater.


Figure 58. A filter strip example. Source: iSWM Technical Manual, 2010.

A filter strip can be used as part of the runoff conveyance system to provide pretreatment. It should be designed so runoff from the adjacent impervious area is evenly distributed as sheet flow across the strip.

Infiltration Trench

An infiltration trench is a belowground repository filled with stone aggregate (see Figure 59). The trench is designed to capture runoff, then let it seep to the bottom of the trench and infiltrate into the surrounding soil, potentially recharging groundwater. It can also be used to slow the flow of stormwater into a conveyance system. A sediment forebay and grass channel or equivalent pretreatment is required.

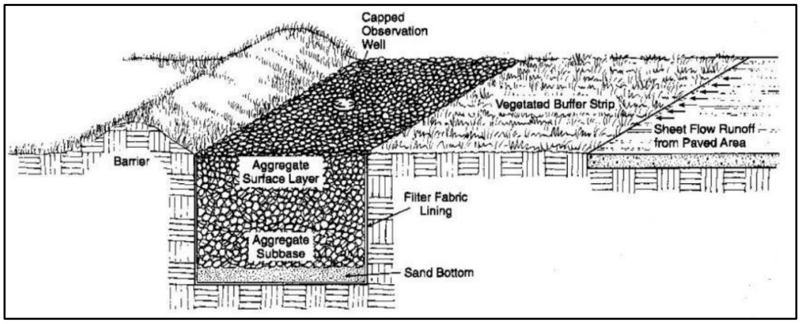


Figure 59. Infiltration trench example. Source: iSWM Technical Manual, 2010.

Infiltration trenches can be put under sidewalks, parking lots, lawns, or recreational areas such as basketball courts and athletic fields. They can also be connected to other features like stormwater bumpouts to receive stormwater overflow. An infiltration trench is good for small sites with porous soils. However, there is some potential for groundwater contamination. It should not be used on sites that collect fine-particle soils. There are significant setback requirements and restrictions in karst areas. Geotechnical testing is required where groundwater may be impacted.

Stormwater Pond

A stormwater pond is a constructed stormwater retention basin. Detention ponds can be either wet (containing a permanent pool of water, as seen in Figure 60) or dry (holding water only during and right after storms). There are also variations, such as the Texas A&M AgriLife pilot project's pond, which is similar to a wet detention pond with an elevated outflow but without a sealed bottom. The wet pond offers additional water quality benefits because it allows for reactions with vegetated benches and sediment settlement. Runoff from each rain event is detained and treated in the pool. It provides a moderate to high removal rate of urban pollutants. A sediment forebay and grass channel or equivalent pretreatment is required.

Figure 60. Stormwater pond at Timber Creek High School, Fort Worth, Texas.
Source: Teague Nall & Perkins.

A stormwater pond should have a minimum contributing drainage area of 25 acres (10 acres for an extended-detention micropool pond), according to the iSWM manual. It can provide wildlife habitat.

F.1.3 Examples of Costs from Case Studies

The information below supplements the case study costs provided in Section 5.2.4. When looking at the costs, the reader should be aware that information provided by each case study varied. For example, one estimate did not provide planting or soil costs while other estimates did not include excavation or grading costs because those could not be accurately calculated for a specific green element when the costs available were for the entire project.

Perot Museum of Nature and Science – Dallas, Texas – 2012 [CS 8]

The Perot Museum of Nature and Science in Dallas, Texas, incorporated a planted bioswale (3,500 ft^2) that extends the length of the parking lot and captures runoff water for the cistern system (see Figure 61). It cost approximately \$12/ft^2.

Figure 61. Perot Museum's parking lot bioswales.

St. Stephen's Pedestrian Green - Austin, Texas – 2012 [CS 18]

Four acres in the campus center were transformed from a ragged, eroded hillside surrounded by a circular drive into a sustainable terraced landscape connecting different parts of campus. A separate visitor turnaround and parking area provides a safe, efficient drop-off for the pedestrian campus. Under previous site conditions, heavy rains sheet drained over rocky slopes, creating hazards to pedestrians and increasing erosion. The Pedestrian Green project's terraced landscape (see Figure 62) slows water runoff during heavy rains, allowing the rainfall to hydrate plants and soak into the porous limestone.

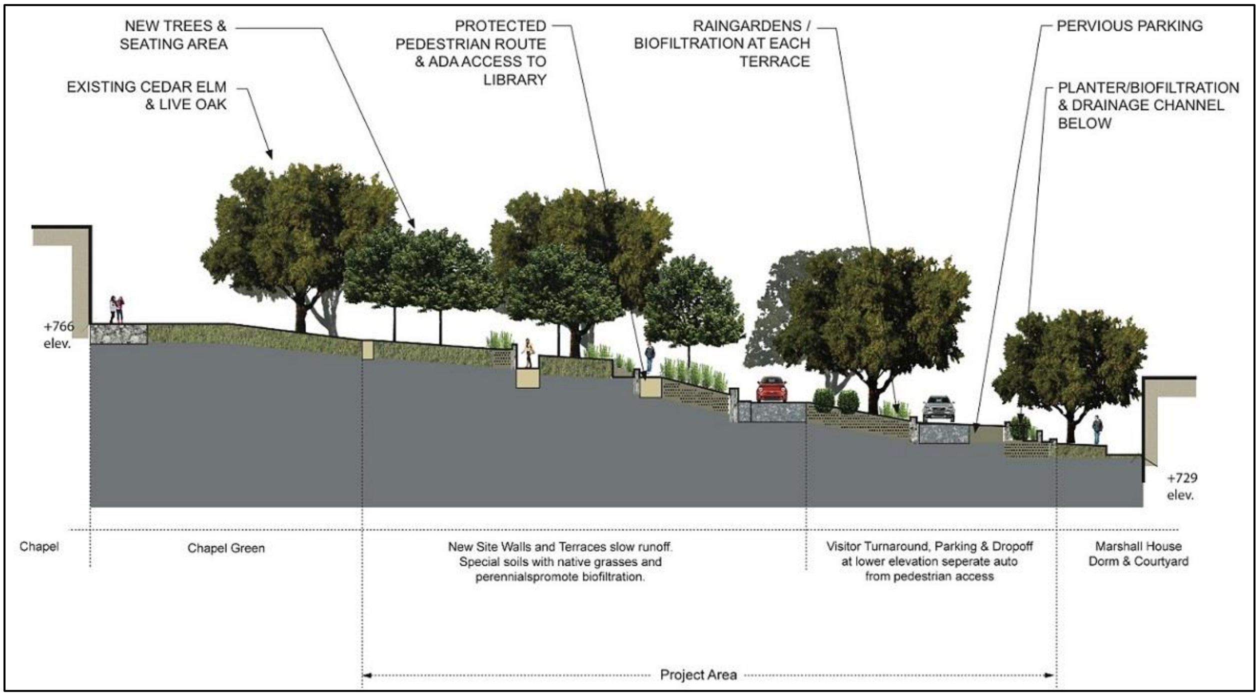


Figure 62. Section drawing for St. Stephen’s Pedestrian Green.
Source: Resource Design, 2014.

Water trapped behind walls soak into the land where native xeric plantings naturally filter pollutants through bio-infiltration. The green elements work together to reduce erosion, recharge groundwater supplies, and decrease sedimentation in the creeks that feed Lake Austin downstream. Other expected benefits mentioned in the case study include reduced costs of gray infrastructure, a more comfortable walking environment, shaded open spaces, and reduced irrigation and maintenance needs. A grant from a private foundation for the purpose of environmental remediation funded the project.

- Five stone terrace walls: $10/ft.
- Bioretention beds behind terrace walls: $10/ft^2
  Includes high-quality soil (18-inch depth), native Texas hardwood mulch (3-inch layer), and native plant species
  Combined bioretention beds and terrace walls: $40/ft^2
- Filter strip (lawn/sheet drainage): $0.83/ft^2
- 30 native shade trees: $20,000
- Pervious pavers at parking lot: $12.22/ft^2

Bioretention for Stormwater Quality Improvement in Texas – Bryan, Texas – 2012 [CS 19]

This was a 670 ft^2 pilot demonstration cell on a highway roadside, managing 2 acres of impervious area (see Figure 63). TxDOT wanted to see how bioretention worked in Texas and built the bioretention cell with Texas A&M Transportation Institute's assistance. The cost was originally estimated at $5,888, but the time for the TxDOT personnel was extended due to lack of previous experience. The total cost was increased to $8,978, or $13.40/$ft^2$ (including labor, equipment, and materials). See Table 17 for a breakdown of costs.


Figure 63. Bioretention pilot in Bryan, Texas.
Source: Texas A&M University/Texas A&M Transportation Institute.

Table 17. Bioretention for Stormwater Quality Improvement Costs.

Elements	Unit	Qty.	Unit Price	Total
Construction sand	CY	35	$11.00	$385.00
Compost	CY	15	$25.00	$375.00
3/8" pea gravel	CY	10	$40.00	$400.00
1.5" gravel	CY	18	$40.00	$720.00
4" perforated PVC	LF	120	$1.00	$120.00
Rock rip rap	CY	5	$250.00	$1,250.00
Texas sage	EA	25	$10.00	$250.00
Equipment and operator	HR	16	$75.60	$1,209.60
Manpower (2 people)	HR	24	$43.27	$1,038.48
Material delivery	Load	7	$20.00	$140.00
Additional labor time				$3,090.00
Total				**$8,978.08**

Bagby Street Reconstruction – Houston, Texas – 2013 [CS 20]

Figure 64. Two sections of the Bagby Street reconstruction.
© Shau Lin Hon - Slyworks Photography/Walter P Moore.

Prompted by a 2008 drainage study to address flooding issues in the area, the Bagby Street Project was included as part of the City of Houston's Midtown Tax Increment Reinvestment Zone Capital Improvement Program. To the design team, Bagby Street was much more than a drainage improvement and street reconstruction project. Beyond basic improvements (new storm sewers, water lines, wastewater lines, pavement, landscape, sidewalks, and traffic signals), the project presented an opportunity to redevelop the Bagby corridor to better serve its diverse and mixed-use community.

The Bagby team focused on contextual design and the changing demographics of the area, providing a streetscape sensitive to the unique needs of each block. The use of rain gardens in the rights-of-way of a walkable urban environment (see Figure 64) is unique in the area. The rain gardens filter and remove oil and grease, total suspended solids, bacteria, and phosphorus from stormwater before it enters the storm sewers, bayous, and ultimately Galveston Bay.

This case study highlights the fact that not all rain gardens are created the same. The Bagby team's rain garden design took into account previous lessons learned to improve flow dissipation, incorporating appropriate engineered soils and bridge aggregates. A presentation on its rain garden design also advised using the largest trees the project can afford and to spend as much as possible on soils within the rain garden, especially if you have an impervious liner at the bottom of the feature. The project also used Focal Point, a high performance biofiltration system (see Figure 65 for a diagram of the Focal Point system layers). See Table 18 for a breakdown of costs for the project's rain gardens.

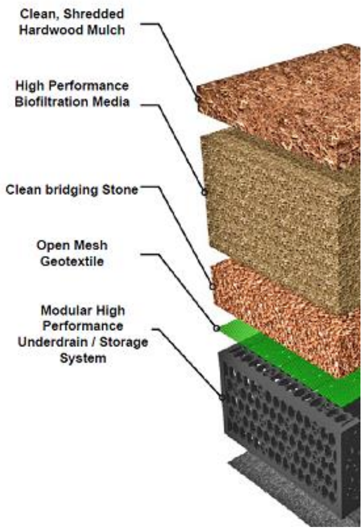


Figure 65. FocalPoint Biofiltration System layers. Source: FocalPoint presentation. (n.d.)

Table 18. Rain garden costs provided for Bagby Street Reconstruction, Houston, Texas.

Elements	Unit	Qty.	Unit Price	Price
Rain garden crossing *Complete, supply and install per detail* ◦ Welded steel grating ◦ Flat bar ◦ Angle edge protector	EA	12	$2 ,700.00	$32,400.00
Rain garden platform *Complete, supply and install per detail* ◦ Welded steel grating ◦ Angle edge protector	EA	2	$6,300.00	$12,600.00
Rain garden splash block *Complete, supply and install per detail* ◦ Basalt cobbles	EA	19	$740.00	$14,060.00
Rain gardens – Hard (includes all hard elements of rain garden) *Complete, supply and install per plans* ◦ Concrete walls ◦ Curb ◦ Weir support beams ◦ Weirs ◦ Firestone membrane (along rain garden – roadway side from top of dirt to bottom of media)	SY	1,125	$166.80	$187,650.00
Rain gardens – FocalPoint (includes all elements of High Performance Modular Drain System) *Complete, supply and install per plans* ◦ 6" underdrain ◦ High Performance Modular Drain System	SF	1,070	$19.60	$20,972.00
Rain gardens – Concrete flumes *Complete, supply and install per plans* ◦ Concrete flume between curb and rain garden	EA	21	$1 ,300.00	$27,300.00
Total				**$294,982.00**

Note: Does not include plantings.

Surface area of FocalPoint	1,045 ft^2	0.024 acres
Area of Rain gardens	9,828 ft^2	0.226 acres
Total right-of-way	288,886	6.63 acres

This equates to \$30/ft^2 without plantings but with a high-performance modular drain system. (See Figure 65 for the layers included in the bioinfiltration system.) The case study asserts that the project further demonstrates that low-impact development (LID) can be implemented within a highly urbanized area, improving quality of life and yielding positive economic impacts. It backs up that assertion with numbers: in 2013, a \$25 million increase in private development had occurred since the announcement of the project and a 25% increase in rental market rates (\$1.40 to \$1.75 average per square foot per month).

Birnamwood Drive – Houston (North Harris County), Texas – 2012 [CS 21]

Figure 66. Green stormwater infrastructure at Birnamwood Road.
Source: Construction EcoServices.

In February 2010, the Houston Land/Water Sustainability Forum completed its Low Impact Development Design Competition. In that competition's Green Roadway Design Challenge, the subject property was a Harris County roadway slated for expansion from a two-lane roadway to a four-lane boulevard. This project aimed to:

- Keep post-development discharge curves below predevelopment rates and manage the 100-year storm (keeping in mind 50-plus inches of annual rainfall, clay soils that offer minimal infiltration potential, and flat terrain)
- Exceed current water quality standards
- Make the implementation less expensive than that of conventional designs

Birnamwood Drive was the first opportunity for Harris County to move forward with the implementation. As this was an initial LID project, one decision was to not stray too far from traditional designs. The techniques included in the Birnamwood Drive depressed center median were native landscaping, check dams, bioswales, and a High Performance Modular Biofiltration System next to each extreme-event outfall (see Figure 66).

The first design consideration was traditional slow-flow-rate biofiltration media that would require a system to be installed throughout the entire ¾-mile center median, which would mean both increased excavation and substantial underdrain piping. It would also mean that the County maintenance crews could not use their typical machinery and established protocols on the entire bioswale to avoid media compaction. What was chosen instead was a High Performance Modular Biofiltration System that lessens the system's footprint more than 20 times while still allowing for the same flood control benefits.

With its GSI elements, the project did not require a traditional detention pond, saving the County more than $350,000 on land and excavation costs. The system also increased their savings for the LID design to 7% versus traditional pipe and pond. (According to the case study contact, subsequent LID-based Harris County roadways have reduced costs even further.) See Table 19 for the case study's comparison of costs, looking at estimated traditional versus actual LID costs.

Table 19. Estimated cost comparison provided by the Birnamwood case study.

1-Mile Long 4 lane Concrete Boulevard with Median		
	Traditional (estimated)	**LID (actual)**
Site Prep & Earthwork	$391,634.00	$449,060.00
Drainage	$400,000.00	$288,432.00
SWPPP	$69,600.00	$87,000.00
Landscape Planting	$30,000.00	$66,140.00
Landscpe warranty/Maint	$0.00	$34,630.00
Bridge	$208,517.00	$208,517.00
Subgrade & Paving	$1,139,791.00	$1,139,791.00
Traffic	$9,000.00	$9,000.00
Signing & Striping	$25,461.00	$25,461.00
Traffic Signal	$128,010.00	$128,010.00
Utilities	$16,140.00	$16,140.00
Extra Work Items	$15,650.00	$36,650.00
Biofiltration System	$0.00	$132,931.00
SWQ System	$30,000.00	$0.00
Detention Basin	$350,000.00	$0.00
Total	$2,813,803.00	**$2,621,762.00**
estimated cost benefit:	**$192,041.00**	**7% Cost Reduction Per Mile**

The cost estimate for the green feature, including the high-performance biofiltration system and landscape planting, is approximately $100/ft^2. This estimate does not include the erosion control ("SWPPP" in the table above) or the landscape warranty/maintenance. The case study also noted the following:

- Extensive vs. intensive planting would have saved $36,140 on landscaping.
- No required offsite detention maintenance equates to $2,000 savings per year.
- There was a 50% reduction in mowing; no irrigation was required beyond establishment.

The expected lifetime is 20-50 years, depending on plant selection and pollutant loading.

SE Clay Green Street – Portland, Ore. – **2014** [CS 27]

Residents of Portland's inner eastside have long sought improved and safer connections to the Willamette River from the outlying neighborhoods. SE Clay Street is a primary Route to the River for inner eastside neighborhoods. The 10-block SE Clay Green Street Project enhances the corridor and complements existing green amenities along the Eastbank Esplanade. A key part of this project is constructing 20 green street facilities along the route, mostly vegetated curb extensions with Filterra Stormwater Bioretention Filtration System units and some parking strip planters. See Figure 67 for a simplified map and example of the stormwater curb extensions.

The green street facilities are expected to remove 1.6 million gallons of stormwater runoff annually from combined storm sewer systems.

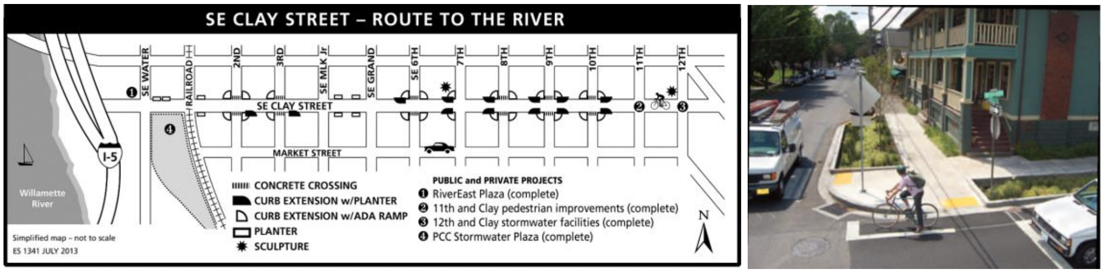


Figure 67. SE Clay Street. Left: Simplified map. Right: Stormwater curb extension.
Source: City of Portland.

The costs for the entire project are below.

- Pre-design: $69,000
- Design: $508,000
- Advertisement: $4,000
- Construction: $1,383,000
- Closeout: $34,000
- Total: $1,998,000

The cost estimate for the 20 green street facility portion of the project is $322,250, which includes associated materials but excludes plants.

Area-wide Right-of-Way Bioswale – New York City, N.Y. – Ongoing [CS 32]

In 2010, the New York City (NYC) Department of Environmental Protection (DEP) released the NYC Green Infrastructure Plan, which outlined a hybrid green/grey approach to reducing combined sewer overflows (CSOs) in New York City. The Plan shows that this approach to CSO mitigation is more cost-effective than traditional gray projects alone, and also provides benefits such as improved air quality and neighborhood beautification. Under an amended Consent Order that DEP signed in 2012, DEP must manage 1 inch of stormwater runoff from 10% of the impervious area of the combined sewer areas of the City by 2030. To meet the first of multiple incremental milestones under the Consent Order, an "Area-wide Approach" was developed. This includes building GSI such as right-of-way bioswales on city streets and sidewalks.

Figure 68. Isometric view of a New York City right-of-way bioswale.
Source: NYC Department of Environmental Protection.

DEP uses several types of bioswales, ranging from 10 ft. x5 ft. to 20 ft. x 5 ft. (See Figure 68 for an isometric view of a New York City right-of-way bioswales.) A typical 20 ft. x 5 ft. right-of-way bioswale, which is calculated to manage 360 cubic feet of stormwater for an area of 4,320 square feet, cost approximately $25,000 in 2013.

- Design, survey, and geotechnical investigation - $6,000
- Construction - $17,000
- Construction management - $2,000
- Total - $25,000

According to the "NYC Green Infrastructure 2013 Annual Report," the site selection costs can represent a higher percentage of the total cost per location than typical construction projects. DEP requires geotechnical investigations at most proposed locations but will update these requirements as well as design and construction practices as the Green Infrastructure Program progresses.

The city constructs approximately 150-200 right-of-way bioswales in each construction contract. DEP is working to ensure that costs stay competitive and that economies of scale are realized for contracts. The report notes that its estimated costs as of 2013 are nearly $10,000 less than the previous year's reported costs.

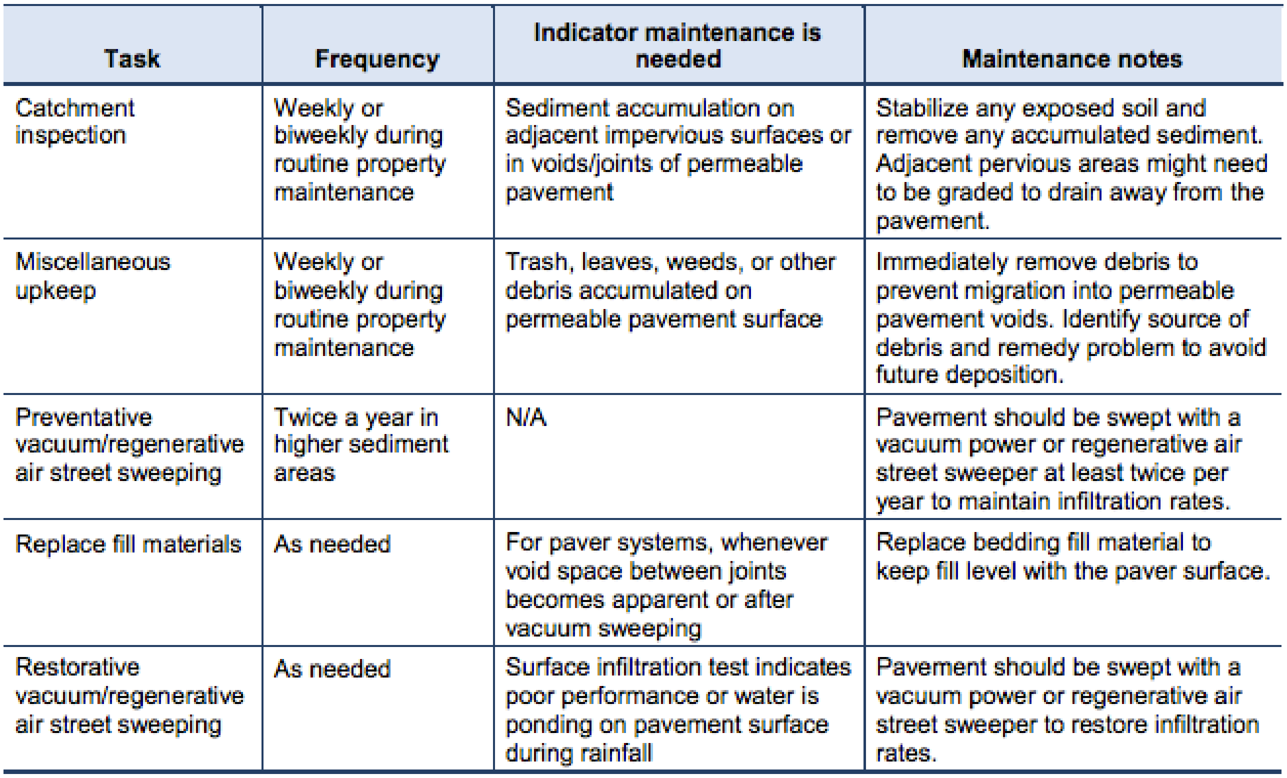
Clark Park Infiltration Bed (Basketball Court) – Philadelphia, Pa. – **2011** [CS 33]

A subsurface infiltration bed beneath a new basketball court at Clark Park manages stormwater runoff from the basketball court as well as from an adjacent street and parking lot (see Figure 69). With a storage volume of 3,080 cubic feet, the system has been designed to capture about 1.5 inches of rainfall from the contributing drainage area. However, with well-drained soil, the project owners anticipate that actual stormwater capture will be much greater. Its cost is estimated at $50,000 for design and $250,000 for construction.

Figure 69. A subsurface infiltration bed under construction at Clark Park, Philadelphia, Pa. Source: Philadelphia Water Department.

F.1.4 Example Operation and Maintenance Task Lists for Green Stormwater Infrastructure

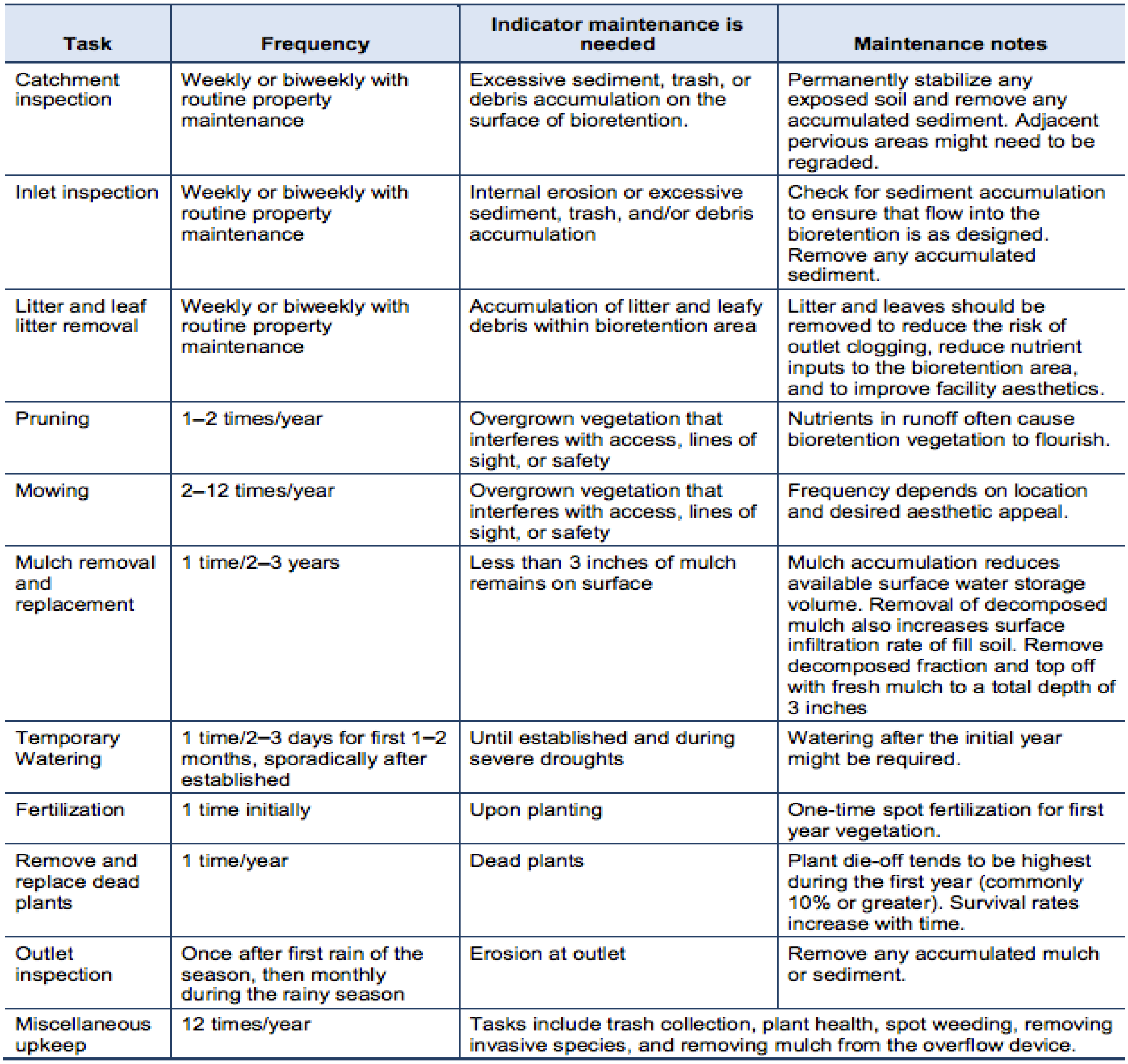
List of Permeable Pavement Operation and Maintenance Tasks (Example)



Task	Frequency	Indicator maintenance is needed	Maintenance notes
Catchment inspection	Weekly or biweekly during routine property maintenance	Sediment accumulation on adjacent impervious surfaces or in voids/joints of permeable pavement	Stabilize any exposed soil and remove any accumulated sediment. Adjacent pervious areas might need to be graded to drain away from the pavement.
Miscellaneous upkeep	Weekly or biweekly during routine property maintenance	Trash, leaves, weeds, or other debris accumulated on permeable pavement surface	Immediately remove debris to prevent migration into permeable pavement voids. Identify source of debris and remedy problem to avoid future deposition.
Preventative vacuum/regenerative air street sweeping	Twice a year in higher sediment areas	N/A	Pavement should be swept with a vacuum power or regenerative air street sweeper at least twice per year to maintain infiltration rates.
Replace fill materials	As needed	For paver systems, whenever void space between joints becomes apparent or after vacuum sweeping	Replace bedding fill material to keep fill level with the paver surface.
Restorative vacuum/regenerative air street sweeping	As needed	Surface infiltration test indicates poor performance or water is ponding on pavement surface during rainfall	Pavement should be swept with a vacuum power or regenerative air street sweeper to restore infiltration rates.

Source: *San Antonio River Basin Low Impact Development Technical Design Guidance Manual*, 2013.

List of Bioretention Inspection and Maintenance Tasks (Example)



Task	Frequency	Indicator maintenance is needed	Maintenance notes
Catchment inspection	Weekly or biweekly with routine property maintenance	Excessive sediment, trash, or debris accumulation on the surface of bioretention.	Permanently stabilize any exposed soil and remove any accumulated sediment. Adjacent pervious areas might need to be regraded.
Inlet inspection	Weekly or biweekly with routine property maintenance	Internal erosion or excessive sediment, trash, and/or debris accumulation	Check for sediment accumulation to ensure that flow into the bioretention is as designed. Remove any accumulated sediment.
Litter and leaf litter removal	Weekly or biweekly with routine property maintenance	Accumulation of litter and leafy debris within bioretention area	Litter and leaves should be removed to reduce the risk of outlet clogging, reduce nutrient inputs to the bioretention area, and to improve facility aesthetics.
Pruning	1–2 times/year	Overgrown vegetation that interferes with access, lines of sight, or safety	Nutrients in runoff often cause bioretention vegetation to flourish.
Mowing	2–12 times/year	Overgrown vegetation that interferes with access, lines of sight, or safety	Frequency depends on location and desired aesthetic appeal.
Mulch removal and replacement	1 time/2–3 years	Less than 3 inches of mulch remains on surface	Mulch accumulation reduces available surface water storage volume. Removal of decomposed mulch also increases surface infiltration rate of fill soil. Remove decomposed fraction and top off with fresh mulch to a total depth of 3 inches
Temporary Watering	1 time/2–3 days for first 1–2 months, sporadically after established	Until established and during severe droughts	Watering after the initial year might be required.
Fertilization	1 time initially	Upon planting	One-time spot fertilization for first year vegetation.
Remove and replace dead plants	1 time/year	Dead plants	Plant die-off tends to be highest during the first year (commonly 10% or greater). Survival rates increase with time.
Outlet inspection	Once after first rain of the season, then monthly during the rainy season	Erosion at outlet	Remove any accumulated mulch or sediment.
Miscellaneous upkeep	12 times/year	Tasks include trash collection, plant health, spot weeding, removing invasive species, and removing mulch from the overflow device.	

Source: *San Antonio River Basin Low Impact Development Technical Design Guidance Manual,* 2013.

F.2 Vegetation

F.2.1 An Example of Tree Ecosystem Service Benefits

An example of quantified ecosystem service benefits is provided in the Texas Trees Foundation's report on Southern Methodist University's campus tree inventory. The organization analyzed the benefits using the peer-reviewed software suite i-Tree Streets model (www.itreetools.org/streets/), which was developed by the USDA Forest Service, Northern Research Station.

An overview of the campus tree inventory and the trees' benefits follow.

- Number of trees: 2,236 (with about 20 trees remaining to be inventoried due to construction at the time of the report); 2,075 are in fair to good condition
- 25% canopy cover
- Most common species: Live oak, Crape myrtle, Shumard red oak
- Carbon absorption: 793,251 pounds per year (value: $6,283 per year)
- Carbon storage: 12,278,716 pounds stored (value: $92,000)
- Energy savings: $24,417 per year
- Rainfall interception: 8.1 million cubic feet per year (value $80,472 per year, or about $35 per tree). Value based on fees assessed for moving, storing, and cleaning stormwater.
- Does not include aesthetics, stress relief, or property values.

i-TREE STREETS MODEL

The i-Tree Streets model is one of several urban forest analysis tools and utility programs offered for free. Other models include i-Tree Eco, i-Tree Hydro, i-Tree Design, and i-Tree Species.

Table 20 is a sampling from the report, showing the average annual benefits of the campus trees by species.(Negative values in the air quality column relate to the release of volatile organic compounds. Matt Grubisich, director of operations at Texas Trees Foundation, pointed out that other benefits, such as urban heat island mitigation, far outweigh that negative. This table reveals that the benefits can vary widely by species, but they all provide a net benefit.

Table 20. Average Annual Benefits of All Trees by Species ($/Tree).

Species	Energy	CO_2	Air Quality	Storm-water	Aesthetic/ Other	Total
Live oak	$19.08	$4.93	-$9.85	$71.00	$88.54	$173.70
Crape myrtle	$3.50	$0.40	$1.29	$4.38	$7.35	$16.92
Shumard red oak	$11.19	$2.73	-$7.62	$39.37	$54.57	$100.24
Rough-leaf dogwood	$1.25	$0.13	$0.48	$1.41	$3.11	$6.39
Osage orange	$20.52	$13.45	$8.29	$71.89	$89.44	$203.58

Source: Texas Trees Foundation, Southern Methodist University campus inventory, 2013.

SMART IRRIGATION

While this guidebook does not cover irrigation, it is an important aspect for the Texas SmartScape program. The project's choices for irrigation could be key to conserving water and saving money. After all, if the area is watered more frequently or heavily than necessary, the choice of a water-sipping plant is almost meaningless.

The Green at College Park (University of Texas – Arlington) uses advanced irrigation technologies with a smart controller that relies on a weather station and evapotranspiration rates to determine irrigation scheduling and times. As a direct result of this project, the university decided to upgrade the entire campus with the recommended central control system, with the long-term goal of water conservation. Potable water use has been reduced by 76%.

For more information on watering and conservation, visit www.txsmartscape.com/design_tools/water_conservation.asp.

The species of the tree is not the only factor to consider. Size also plays an important role, according to Houston's Regional Forest report. It found that large trees are disproportionately important; less than 30% of the region's trees are five inches in diameter or greater, but they provide more than 60% of the environmental benefits.

The report emphasizes the importance of protecting the region's large trees, citing land use change, non-native tree species, and insect pests as the most significant threats. For more information about native plants, see the Native and Adapted Species section.

F.2.2 Native and Adapted Species

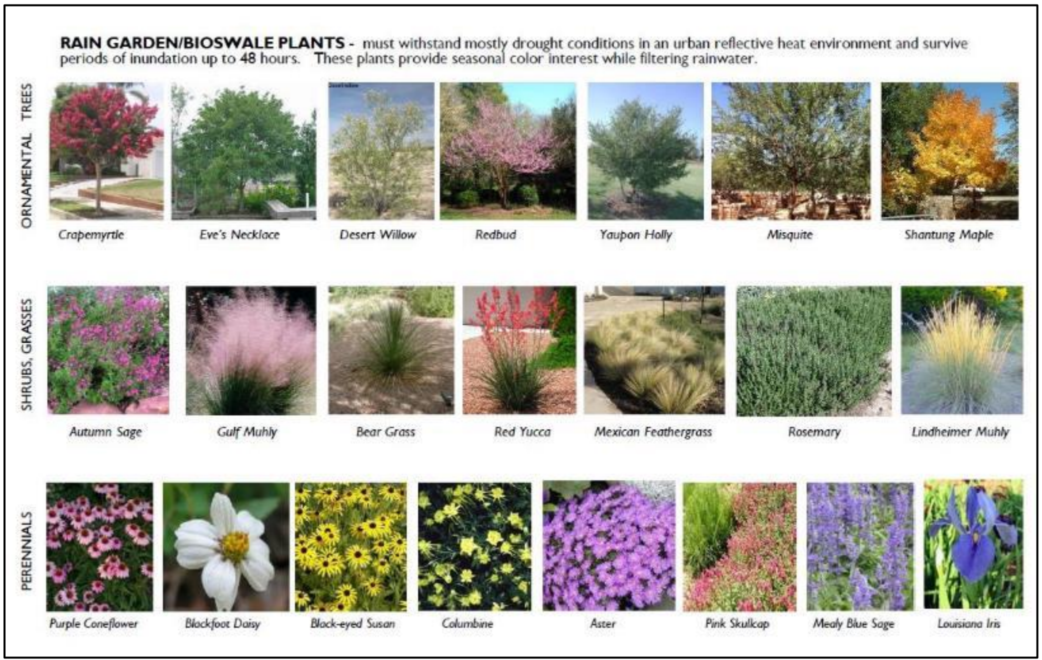
According to Wildflower Program information provided by the Texas Department of Transportation (TxDOT), more than 5,000 species of wildflowers and native grasses flourish along our state's roadsides, reducing maintenance and labor costs by promoting the growth of native species that require less mowing and care. These plants can reduce the amount of money spent on water bills because they require up to 80% less water than nonadapted plants, typically need little or no fertilizer and pesticides (which has the added benefit of reducing these pollutants in runoff as well as reducing related water pollution treatment costs), and are not likely to die due to watering restrictions. Selecting drought-tolerant plants also conserves water, a precious resource. With booming growth a certainty for the region, conservation is a necessary tool to support ourselves, pets, wildlife, plant life, and industry.

One program that includes a curated selection of native plants and plants adapted to our region's climate and local conditions is Texas SmartScape™, a program supported by the North Central Texas Council of Governments in partnership with the Regional Stormwater Management Program. The goal of Texas SmartScape is to conserve local water supplies by reducing the amount of water needed to maintain landscapes and to improve stormwater runoff quality by decreasing the amount of pesticides and fertilizer needed in landscaping practices.

Many of the Texas SmartScape plants also provide habitat or food to attract and sustain butterflies, bees, birds, and other wildlife. As our region continues to develop, open spaces and natural areas are becoming increasingly rare, so a choice of native plants in bioretention or landscaping can act as a critical patch in a hostile landscape matrix.

Several projects in the region have highlighted the use of native and adapted plants, emphasizing several benefits. These include reduced water use, reduced erosion, improved filtration, beautification, and wildlife habitat.

- The design team for the Congo Street project in Dallas, Texas, [CS 4] leveraged native and hardy plants to improve the natural filtration in their stormwater bumpouts.
- Cedar Hill's Red Oak Creek Trail [CS 3] features Texas SmartScape plants.
- Timber Creek High School in Fort Worth [CS 15] uses native and adapted plants that both conserve water and act as an educational tool.
- The consultants for the Elm Street streetscape improvements in Dallas, Texas, [CS 6] chose plants for its rain gardens that can both withstand mostly drought conditions in an urban reflective heat environment and survive up to 48 hours of inundation. (See Figure 70 for the selection of plants.) The plants also provide seasonal color interest, habitat for butterflies and hummingbirds, and increased biodiversity, all while filtering rainwater. To change the soil structure to increase permeability, the landscape architect used amended soils in the rain gardens with deep-rooted native plants.



RAIN GARDEN/BIOSWALE PLANTS - must withstand mostly drought conditions in an urban reflective heat environment and survive periods of inundation up to 48 hours. These plants provide seasonal color interest while filtering rainwater.

Figure 70. The selection of rain garden/bioswale plants for the Elm Street Streetscape improvements. Source: CCA Landscape Architects.

- The planting plan for the Green at College Park (University of Texas – Arlington) [CS 1] creates more than 50% wildlife habitat and uses more than 75% plants native to North Central Texas. It includes a hummingbird and butterfly garden.

- The site design for the Perot Museum in Dallas, Texas, [CS 8] reflects a cross-section of the Texas landscape from west to east, highlighting different regions of the Texas environment. The project uses native and drought-resistant perennials, grasses, and shrubs. Figure 71 shows a sample of these plants used in a parking lot bioswale. This representation of the indigenous landscape was intended to demonstrate a living system that will evolve naturally over time.

Figure 71. The Perot Museum parking lot bioswales uses native and drought-tolerant plants.

- St. Stephen's Pedestrian Green in Austin, Texas, [CS 18] features native xeric species with filamentous leaf structure to promote transpiration and pollutant uptake (see Figure 72). Species include native bunch grasses such as Lindheimer Muhly and Gulf Muhly and perennials such as Mexican Petunia and Texas Betony.

Figure 72. Native plants used at St. Stephen's pedestrian green. Source: Reese Hyde.

- Blue Hole Regional Park in Wimberley, Texas, [CS 22] amended soils and added 5,300 square feet of native cover vegetation, mostly grasses, to stabilize 365 linear feet (85% of total length) of the Cypress Creek streambank. For the entire project, 100% of the new plantings are native to the region, including seven species of hardwood trees and custom seed mixes of prairie grasses and forbs. To ensure resiliency against flash floods, soil composition and species were selected for quick plant material establishment.

- The City of Fort Worth's Stormwater Management Division launched a pilot program in August 2013, planting native prairie grasses in drainage channels to improve neighborhood safety and reduce costs. According to a City of Fort Worth article on the program, sediment is one of the top causes of blocked storm drains and channels in Fort Worth. Blockages can result in the flooding of streets and properties as well as the risking of lives in flooded roadways. The pilot is using the native grasses in the hope that they are hardy enough to prevent significant erosion. Less erosion should result in improved water quality. Other benefits include reduced maintenance and water needs and, of course, natural beauty.

Similar to the consideration noted in the Bioretention and Infiltration section, plants are not a "one size fits all" approach. Plant selection requires a deep understanding of plants, the site, and the BMP's function and goals. A different plant may work better or use less water. This may be true for the Dallas Urban Reserve case study [CS 5], which noted that love grass or buffalo grass might be a better, less water-intensive option than its original choice of horsetail reed. The Fort Worth Nature Center and Refuge case study [CS 12] mentioned that the project owners were working to find the best plant materials for the parking lot bioswales. However, this was not seen as a negative, but rather a learning experience.

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Ravinia Festival South Parking Lot, Highland Park, Ill.
St. Stephen's Pedestrian Green, Austin, Texas
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Blue Hole Regional Park, Wimberley, Texas
Clark Park Infiltration Bed (Basketball Court), Philadelphia, Pa.
The Dallas Urban Reserve, Dallas, Texas
Deaderick Street, Nashville, Tenn.
Elmer Paseo Stormwater Improvement Project, Los Angeles, Calif.
Elm Street Streetscape Improvements, Dallas, Texas
Fort Worth Nature Center and Refuge Green Parking Lot, Fort Worth, Texas
The Green at College Park, Arlington, Texas
Green Tracks Pilot Project, Baltimore, Md.
Historic Handley Urban Village Streetscape Project, Fort Worth, Texas
Merritt Road, Rowlett, Texas
Mill Creek Tree Trench, Philadelphia, Pa.
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Vegetation: Trees and Native and Adapted Species

Trees

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Native and Adapted Species

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The Dallas Urban Reserve, Dallas, Texas
Elm Street Streetscape Improvements, Dallas, Texas
The Green at College Park, Arlington, Texas
Perot Museum of Nature and Science, Dallas, Texas
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