Smart Cities Applications for Green Infrastructure on Vítězné Náměstí in Prague

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Master’s Program in Engineering

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Declaration

This thesis/report is an output of the International Dual Master Degrees Program in Smart Cities Science and Engineering, a collaboration between Czech Technical University, Czech Republic, and The University of Texas At El Paso, United Sates of America

SMART CITIES APPLICATIONS FOR GREEN INFRASTRUCTURE ON VÍTĚZNÉ NÁMĚSTÍ IN PRAGUE

by

LUISA ANDREA CASTREJON, Bc.

THESIS

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MASTER'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Luisa Castrejon, B.S.CE

Study programme (field/specialization) of the student:

master's degree – SC – Smart Cities

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Theme title (in English): **Smart Cities applications for Green Infrastructure on Vítězné Náměstí in Prague**

Guidelines for elaboration

During the elaboration of the master's thesis follow the outline below:

- Perform a literature review on stormwater management conditions in the city of Prague with a focus on green infrastructure (GI) applications.
- Quantify the benefits of GI such as stormwater management, surface temperature, pavement condition index, air and water quality.
- Develop a method of tracking benefits.
- A case study will be developed for Vítězné náměstí in Prague.
- The case study conducted in El Paso for prioritizing GI sites will be included in this research to reference important site selection methods that can be useful to any GI project.

Graphical work range:	---
Accompanying report length:	At least 55 pages.
Bibliography:	National, Association of City Transportation Officials. Urban Street Stormwater Guide, Island Press, 2017 Kaluarachchi, Y. (2020). Potential advantages in combining smart and green infrastructure over silo approaches for future cities. Frontiers of Engineering Management, 8(1), 98–108

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L.S.

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I confirm assumption of master's thesis assignment.

Luisa Castrejon

Luisa Castrejon
Student's name and signature

Prague ....June 30, 2022

I declare that this Master's thesis is my own work and that I list all references in compliance with ethical guidelines on elaboration of Master's thesis.

I have no relevant reason against using this work in the sense of § 60 of Act No. 121/2000, on the copyright law.

Prague, Czech Republic
May 8, 2022

Luisa A. Castrejon

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Abstract

The impact that climate change has left on communities around the world have ranged from minimal to extreme. Countless catastrophic events lead the way to resilient designs with respect to architecture, energy consumption, building, life style, and resource conservation habits that provide environmental, social, and economic improvements. Smart cities is an idea of designing to increase quality of life and sustainability with the help of technology. Necessity for change inspired countless innovative projects in the sustainability field to design resilient infrastructure. This research will develop a method of Green Infrastructure (GI) implementation in a Smart Cities project for the city of Prague in the Czech Republic. GI offers many benefits such as increasing property value, promoting walkability, decreasing Heat Island Effect, managing and treating storm water, and improving air quality which certify it for one of the best sustainable projects. An initial literature review is conducted to understand the details of existing GI in Prague. Then, a modelling software, used for old or new GI sites, can determine the beneficial impacts of GI on a small scale. Using Information and Communication Technology (ICT), such as sensors, improves the functionality of GI by aiding in decision making and obtaining on site information. Furthermore, this data is useful to city planners or officials to determine what kind of GI benefits better suit the local environment and/or the community's needs.

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Chapter 1: Introduction

Climate change has become a major concern worldwide, prompting a reevaluation of the quality of life engineering has historically provided to society. With the potential impact of individuals' actions on the environment becoming increasingly evident to society, the need for sustainable resource management has grown in importance. Over the past few decades, technological advancements have enabled us to analyze infrastructure planning and design using a data oriented or a ”smart cities” lens. One sustainable infrastructure solution that has gained widespread popularity is Green Infrastructure (GI), which provides a variety of benefits, such as decentralized water treatment, increased property values, and a sense of community well-being.

This thesis explores the implementation of GI in a smart cities framework. The framework includes quantitative approaches to identifying locations for GI implementation based on open data sources and estimating potential benefits to GI implementation for a given site. Though the framework is a continuous process, it is presented piece-wise through two case studies. The first portion of the framework is demonstrated through a case study focused on El Paso, TX. The second portion of the framework is demonstrated through a case study on a roundabout in Prague, Czech Republic. The reason for this approach is because the author had the opportunity to study abroad in Prague. The discrepancies between the two cities allows for interesting comparisons of the role and potential of GI to improve cities. The potential for GI as a component of a Smart City is analyzed and discussed as well.

Thesis Outline

Chapter 2 of this thesis provides an overview of the literature surrounding green infrastructure, smart cities, and other topics related to this research.

Chapter 3 presents the unified methodology to site selection and benefit quantification of GI through a data-driven, smart cities lens.

Chapter 4 presents the case study of the first part of the proposed framework including identifying and comparing potential GI sites using open data.

Chapter 5 presents a similar case study focused on the second portion of the framework including assessing potential improvement to indices of concern that stem from a proposed GI installation.

Chapter 6 includes discussion of the case studies, including benefits and limitations, and how the proposed framework operates within a Smart City.

Chapter 7 presents conclusions and future research directions.

Chapter 2: Literature Review

Definition of Green Infrastructure

Green infrastructure (GI) is a network of decentralized storm water management practices, such as green roofs, trees, rain gardens and permeable pavement, that can capture and infiltrate rain where it falls, thus reducing storm water runoff and improving the health of surrounding waterways. GI practices can also positively impact energy consumption, air quality, carbon reduction and sequestration, property prices, recreation and other elements of community health and vitality that have monetary or other social value (Gallet, 2011). There are several forms of GI such as, permeable pavement, bio-retention swales or planters, bio-filtration gardens, and green roofs (of City Transportation Officials, 2017). GI is meant to promote the growth of the native vegetation that strengthens current infrastructure's resiliency while contributing benefits to the community. Furthermore, it contributes to all principles of sustainability – environmental, economic, and social. While GI decentralizes gray infrastructure by managing storm water on an independent level, it also recharges ground water and partially returns an urban zones to its pre-development conditions (cen, 2020). However, underground gray infrastructure pipes connected to GI is a potential improvement to treating and managing storm water (Kaluarachchi, 2020). The evapotranspiration it causes offers air temperature reductions (Jarden et al., 2015), (cen, 2020), and vegetation improves air quality (Currie and Bass, 2008) and (Baldauf, 2016). The type of storm water management GI implements, controls runoff non-point source pollution (MacAdam et al., 2012). Green spaces encourage the initiation of walkable cities and lessens the dependency on cars or automobiles to gain access to basic necessities, in addition to the sense of mental and physical well-being of the community (of City Transportation Officials, 2017). Furthermore, GI increases property value by 2 percent to 5 percent annually (cen, 2020) . This article also mentions an EPA study found that $63 to $136 million could be saved from flood damage losses per year if GI practices were expanded. Runoff absorption expands the life expectancy of pavement conditions for the roads by draining nuisance flooding that can cause cracking or potholes, which saves money on road maintenance. Similarly, it also complements the life cycle of gray infrastructure (Mingjiang and Mallick, 2019).

Green Infrastructure in Prague

Prague has advanced much in resilient infrastructure by adapting to the fluctuating demands that come with population increase. They have developed strategic documents to achieve certain sustainable goals, one of them known as the Prague Riverfront Concept, where they seek to bring public spaces to areas around the Vltava river within Prague's city limits. Thus, creating more green spaces or implementing GI. Other strategies that have undertaken developing Nature Based Solutions (NBS) are known as Climate Adaptation Strategy of the Capital City of Prague (2016), Strategic Plan of the City of Prague (2016) and Implementation Program (2018). Lastly, the representative of the city of Prague are so invested in implementing sustainable rainwater management and other adaptive measures that City Hall has approved the initiation of a brand new department of Blue-Green Infrastructure, according to the Local Press Report in 2021 (Report, 2021).

The Climate Adaptation Strategy gave way to a project known as Periurban Park - A Tool for Reducing the Impacts of Climate Change. The projects main goal is to ensure adaptation to climate change by addressing flooding hazards, slowing down surface water runoff, floodplain revitalization, and increasing solar radiation absorption. Other smaller projects have focused on creating green areas around the city. For example, renovations on Seifertova Street are aimed at generating a public space for pedestrians.

Definition of Smart Cities

According to The Welding Institute (TWI), a research and technology organisation, a Smart City uses information and communication technology to improve operational efficiency of services. TWI offers a set of characteristics most smart cities consist of: infrastructure based technology; environmental initiatives; effective and highly functional public transportation; residents who are able to live and work within the city who can use the city's resources; and confident and progressive city plans. They also note ”The main goal of a smart city is to optimise city functions and promote economic growth while also improving the quality of life for citizens by using smart technologies and data analysis. The value lies in how this technology is used rather than simply how much technology is available" (Institute, 2020).

Other sources like a European IT company, Thales, describes a smart city as a framework composed of information and communication technology (ICT) to develop sustainable practices to address growing urbanization challenges. Making smart decisions and involving the community in important governmental decisions, while improving quality of life is facilitated through the utilization of the Internet Of Things (IoT). Based on these two definitions, it is apparent that the concept of smart cities varies slightly. The European commission offers a much shorter and general definition as cities that use technology to improve management and efficiency of an urban environment. They also go into detail about different applications of smart technologies in a conventional city: governance, storm water and waste management, transportation networks, safety, and meeting the needs of an ageing population (Thales, 2020).

Green Infrastructure in Smart Cities

In Kaluarachchi's 2020 report "Potential advantages in combining smart and green infrastructure for future cities", they describe the combination of GI with gray water infrastructure to increase the system's efficiency and effectiveness. This harmonious combination was referred to as "smart green infrastructure (SGI)". Furthermore, they explain that integrating gray infrastructure with natural based solutions and smart technology can potentially transition to next-generation infrastructure. The combination of new infrastructure such as SGI with novel technological systems supported by data, is a way to attain a sustainable city. They suggest obtaining data to understand green-gray analysis. They suggest: "the concept of“smart”,which incorporates sensor, databases, and wireless access to sense, adapt, and provide services for users within the city environment collaboratively, has inspired possible“smart city”solutions for urban challenges." Other examples of smart technology that can be combined with GI: utility service management, citizen engagement in decision making processes, and online activities. Continuous Monitoring and Adaptive Control systems can provide efficiency increase and value to storm water management infrastructure. Other interesting applications include flood risk management, coastal infrastructure management, urban waste management, transportation management, recreational space management, and asset management (Kaluarachchi, 2020).

The importance of including Nature Based Solutions in Smart Cities

Kaluarachchi also states that concerns have been growing when it comes to incorporating too much technology. ”Too much of a good thing is bad”. This is due to sense of isolating communities rather than improve unity and harmony. There are several examples of cities around the world that have advance in technology and infrastructure, but seem to have a lack of the sense of community: Masadar city in Abu Dhabi, Songdo in South Korea, Eko-Atlantic in Nigeria. These cities are mostly unpopulated or only use a small fraction of the resources and services provided. Furthermore, these highly developed cities have neglected the social aspect of a smart sustainable city due to their main focus on economic wealth. It seems like the more smart technology implemented in a city, the more susceptible it is to marginalize ethnic groups. Therefore, creating a toxic environment for the resident’s mental health.

Data and methods used to model GI

Several studies have been conducted around the world to determine the relationship that vegetation has to atmospheric conditions. These conditions range from temperature to atmospheric CO2 fluctuations. For example, the article ”Air pollution removal by trees in public green spaces in Strasbourg city,France” published under the Urban Forestry and Urban Greening journal, showed they’re finding of reduced air pollution thanks to urban forests by using the i-Tree Eco software. The program allowed them to determine the amount of carbon sequestration by trees per year (Selmi et al., 2016).

Another article named ”Information Integration in a Smart City System—A Case Study on Air Pollution Removal by Green Infrastructure through a Vehicle Smart Routing System”, studied the importance of having urban forests and their efficiency in pollution sequestration by having close proximity to road environments. Therefore, they developed a method of ”smart routing” for local transportation movement, which depended on a routing program that suggested the greener roads to the driver, while considering the travel time (Muvuna et al., 2020).

while other studies, such as the article ”Green Infrastructure Planning for Climate Smart and “Green” Cities”, developed a methodology for GI planning using Geographic Information Systems (GIS). Data collected included zoning area, flood plains, industrial parks, land uses, trees and green spaces to analyze and determine ways to assist in urban planning. This article also mentions a smart city project where the application of sensors is suggested to monitor the behavior of a selected GI site in Chicago. This project was called the ”City Digital’s Smart Green Infrastructure Project”, where said sensors would track the quantity and flow of storm water runoff, along with humidity levels, air pressure, and chemical absorption rates. This data would be available to the public and city planners would be able to use the information for improved GI planning (Crncevic et al., 2017).

Chapter 3: Methodology

Selecting a location for a GI site is critical since the effectiveness of GI is highly dependent on site characteristics. Equally important to the success of GI is site-specific design consideration. The proposed methodology is comprised of two distinct phases. Phase 1 is focused on site selection and Phase 2 is focused on comparing GI designs for a given site.

Figure 3.1 shows the work flow of the proposed methodology. Notice that while Figure 3.1 shows a single process, the process is divided into two phases, with each phase demonstrated in a unique case study. The reason that the study was split into independent case studies was that the author pursued a dual degree, splitting their time between El Paso, TX, USA and Prague, CR. This provided an opportunity to explore GI in two very different climates, urban settings, and regulatory environments.

Phase 1 - Selection of Sites for GI

The first phase of the proposed methodology is focused on site selection for GI sites. Phase 1 consists of four primary steps. The first step is focused on data collection. Step 2 is focused on leveraging the collected data to identify potential sites. The third step is to define measurable goals for the sites based on stakeholder input and other concerns. Finally, Step 4 leverages the Analytic Hierarchical Process to select the site with most potential benefits.

Data collection - Step 1

A variety of data can be collected to understand existing conditions of potential GI sites. Such data can include but is not limited to surface temperatures, pollution conditions, flood risks, underlying utilities and the city's building code, and considering pavement conditions along with topography, slopes, and available space. There are several open data sites provided by municipalities where much this data can be obtained. The Copernicus website developed by the European Unions' space program offers in-depth atmospheric information and data available to the general public. The Copernicus Atmospheric Monitoring Systems (CAMS) monitors the fluctuation of anthropogenic CO2 along with other emissions (Copernicus, 2014).

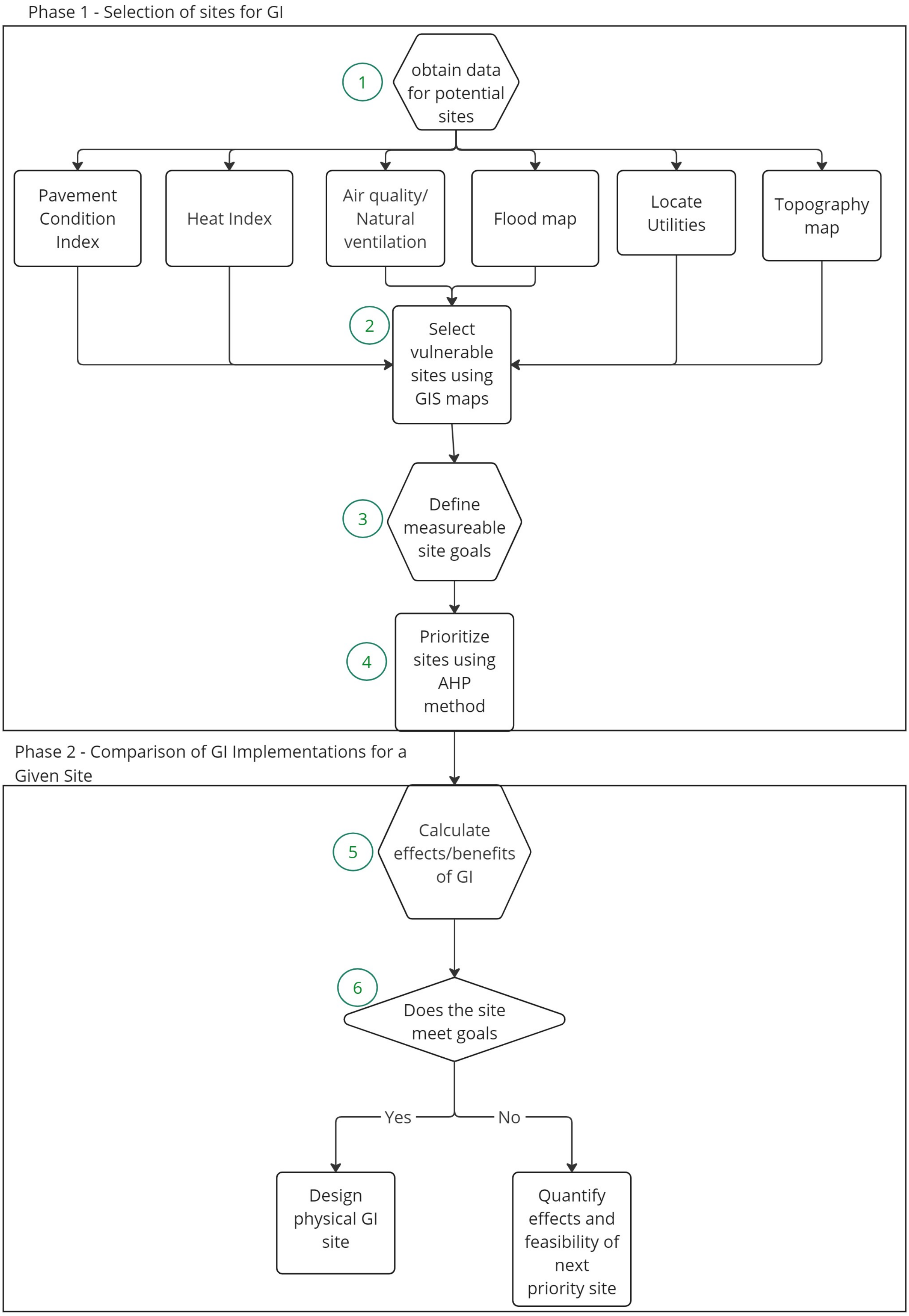


Figure 3.1: Proposed Methodology for Selection of GI sites and Quantification of Benefits

Atmospheric/Pollution Conditions

Determining pollution condition at a potential site is a viable approach to understand the scale of potential air quality improvements. Vegetation has air purifying properties that can combat pollution generated by human activity in urban environments. In addition, urban environments tend to have variation natural atmospheric ventilation due to different heights and shapes of buildings or the general layout of the city. Ventilation can greatly impact the health of the population if stagnant air pollution remains in the poorly ventilated regions. Both of these data sets indicate the areas which may benefit the most with GI.

Surface Temperature

Impervious pavement absorbs heat throughout the day causing a phenomenon known as the Heat Island Effect. Significant areas of impervious pavement are correlated with clusters of high heat measurements in cities. High temperatures also negatively affect the health of the community an causes discomfort.

Flood Maps

The presence of extensive impervious pavement brings higher risks of floods. Nuisance flooding, where a large puddle of water is accumulated in an undesirable location, is a wasted resource in arid climates and a nuisance . Identifying the areas of a city that are prone to flooding in storm events is beneficial to the design of a GI site and it ensures irrigation for the vegetation during a storm event. Of course, intense flooding can not be prevented by GI, but it can be subdued by collecting surface water runoff in upstream zones.

Pavement Conditions

Nuisance flooding or floods in general have negative impacts on the integrity of concrete or road infrastructure, which is already subject to deterioration due to loading. This means that identifying areas with poor pavement condition and nuisance flooding can provide opportunities to improve pavement condition through GI. Flood maps and pavement condition indices complement each other in identifying potential GI sites.

Topography

Site topography has substantial influence on the suitability of a site for GI applications. Understanding the topography of the site and how storm water runoff flows through the site informs locating storm water inlets and curb cuts, for example. Furthermore, in case of a larger storm event an outlet would be recommended to allow an overflow to reach existing storm water inlets.

Underlying Utilities Network

Underlying utilities provide an impediment to GI implementation because they can be affected by new vegetation. The effect of a retrofitting project such as this one could pose a potential risk for existing infrastructure, and therefore inform the feasibility of the GI project. Other parameters to take into consideration are regulations or codes set by city standards. For example, the maximum distance between the right of way and any obstacle that may interrupt the line of sight of drivers, such as trees or shrubs. Data on location of existing utilities is useful in the design of what vegetation and topography of GI is feasible for a given site.

Select Vulnerable Sites - Step 2

The data discussed in the previous sections are best used by displaying them on a GIS map to help visualize vulnerable areas. Vulnerable areas or zones are characterized by being prone to floods, high surface temperatures, poor pavement conditions, and/or poor air quality. Finding a correlation between data sources where vulnerable zones overlap leads into identifying potential beneficial sites for GI.

Defining Goals for GI site - Step 3

Understanding the existing conditions, obtained from data, in which a GI site is to be implemented is helpful in defining what goals we wish to obtain. Furthermore, it indicates whether the site is effective or not. These goals can change to better fit the needs or requirements of the environment and the community. These goals usually include air quality improvement, surface temperature reductions, and/or creating recreational areas for the community to enjoy.

Prioritizing Sites - Step 4

Determining where to develop a GI site can seem daunting due to a wide range of sites experiencing some issues, especially in large cities. However, starting somewhere is important to increase a city's resilience. One method to integrate in the prioritizing process is the Analytical Hierarchy Process (AHP) (Vargas, 2010). The AHP method is a mathematical model used to make decisions based on priorities of the interested parties. This method is initiated by defining the issue and its respective solution, which ever is most adequate. Parameters, with weighted importance, are determined depending on the favorable characteristics that one wishes to see in the end results of the product/project. These parameters are compared to each site project depending on data collected or human judgement. Site project comparisons are one to one, using scores shown in Table 3.1, and then combined resulting in site rankings.

The report for the El Paso case study explains in greater detail how AHP can be used, but a general explanation is provided here (Weidner et al., 2022). The basic concept of AHP scoring is to assign scores to the gap between each of the calculated averages for several parameters of GI which are normalized. The parameters used herein consist of storm water management, pavement condition, traffic safety, Heat Index, recreational area, project cost, Air Quality Index, water recharge, and construction duration. For the case study, some parameters were replaced with surrogates because data was unavailable. These instances will be noted in the case study, but it should be noted that the methodology allows for this flexibility. Comparisons are conducted between options two at a time. For example, if we were to initiate by comparing the importance of street A with respect to street B, and a parameter average difference between street A and street B is 10 units (degrees, vehicles, etc.), then an AHP score of 9 will be assigned to street A. The reciprocal score will be assigned to the other street. The AHP method can be easily performed in a spreadsheet where formulas and weights are integrated in the selection process.

Parameter average difference	Equivalent AHP score	Reciprocal	Description
10	9	1/9	Extremely important
9	8	1/8	Very strongly to extremely important
8	7	1/7	Very strongly important
7	6	1/6	Strongly to very strongly important
6	5	1/5	Strongly important
5	4	1/4	Moderately to strongly important
4	3	1/3	Moderately important
3	2	1/2	Equal to moderately important
2	1	1	Equally important
1	1	1	Equally important
0	1	1	Equally important

Table 3.1: AHP method scores and their meaning.

Phase 2 - Comparison of GI Implementations for a Given Site

The second phase of the proposed methodology focuses on comparing the potential benefits of GI for a given site. This phase differs from Phase 1 in the depth of detail that is used to calculate benefits of GI. Step 5, the first step in Phase 2, focuses on calculating with more accuracy the benefits of GI for a given site using available analytical tools. The final step is focused on assessing the goals of the project and whether they can be achieved.

Calculating Effects and Benefits of a GI Site - Step 5

Once sites have been prioritized, the quantification of GI benefits can encourage stakeholder involvement. Understanding how to improve the GI site design ensures a successful sustainability project. There is a variety of programs and guides that provide insight for GI outcomes. Some provide data on particular parts of the world, and are limited in functionality. Choosing a program or guide that best fits the project's goals is key. There are a many tools and models available online, for example (Environmental Protection Agency, 2022).

Determining if The Site Meets Predetermined Goals - Step 6 and 7

Finally, stakeholders must ask themselves a very important question - does the site meet the predetermined goals and is it prove to be a feasible project? If the outcomes prove to be efficient and favorable, then GI implementation is encouraged and the construction or design process can begin. On the other hand, it is probably most beneficial to select other priority sites.

Integration of Smart Cities Ideology

Smart City projects tend to handle and manage large files of data and information to obtain possible solutions. This method or technique can be applied to both phase 1 and phase 2 of GI projects where data collection is required and must be analyzed for conclusions and the same data can be used in a modeling program that quantifies impacts. These techniques are reliable to city planners or stakeholders for integrating more natural based solutions in urban zones.

Chapter 4: Case Study: Site Selection in El Paso, TX

Case Study in El Paso, Texas

The city of El Paso is located in west Texas, directly on the border with Mexico. The region is an arid, desert climate. The city struggles to obtain enough water year round to provide to its citizens. To combat this challenge, many water conservation methods have been set in place to ensure a sustainable future. However, droughts are becoming longer and more pronounced and there has been a rise in per capita water demands. In addition, there are nearby farm lands that highly depend on the bordering Rio Grande for flood irrigation purposes. A case study was conducted in the city of El Paso to determine sites vulnerable to localized flooding that pose great potential to maximize the benefits of GI. Five streets were selected as examples for priority GI sites to be compared, based primarily on anecdotal observations of nuisance flooding. The AHP method was used to weigh each street with respect to flooding vulnerability, high surface temperature, pavement condition, and traffic safety.

Using the El Paso case study as a comparison to the needs of Prague is an important aspect of this research due to the different climate zones or environments they are found in. Two different cities with a very different population and demand for water resources gives perspective to the adaptation flexibility of GI for different environments. El Paso has a higher need for water conservation projects., while Prague doesn't experience the same drought events. Temperatures also differ significantly with Prague's temperatures being much colder than El Paso's. Describing this case study is important to the methods of selecting an optimum GI site, which is scalable to other regions with their own unique challenges.

The upcoming sections will briefly discuss the goals and findings of the El Paso case study.

Identifying Flood Locations

The following Figure 4.1, represent the locations of severe nuisance flooding identified by El Paso Water, the water utility company of El Paso. In addition, a driving survey using a dash camera was conducted to identify nuisance flooding in the eastern part of El Paso, shown in Figure **??**.

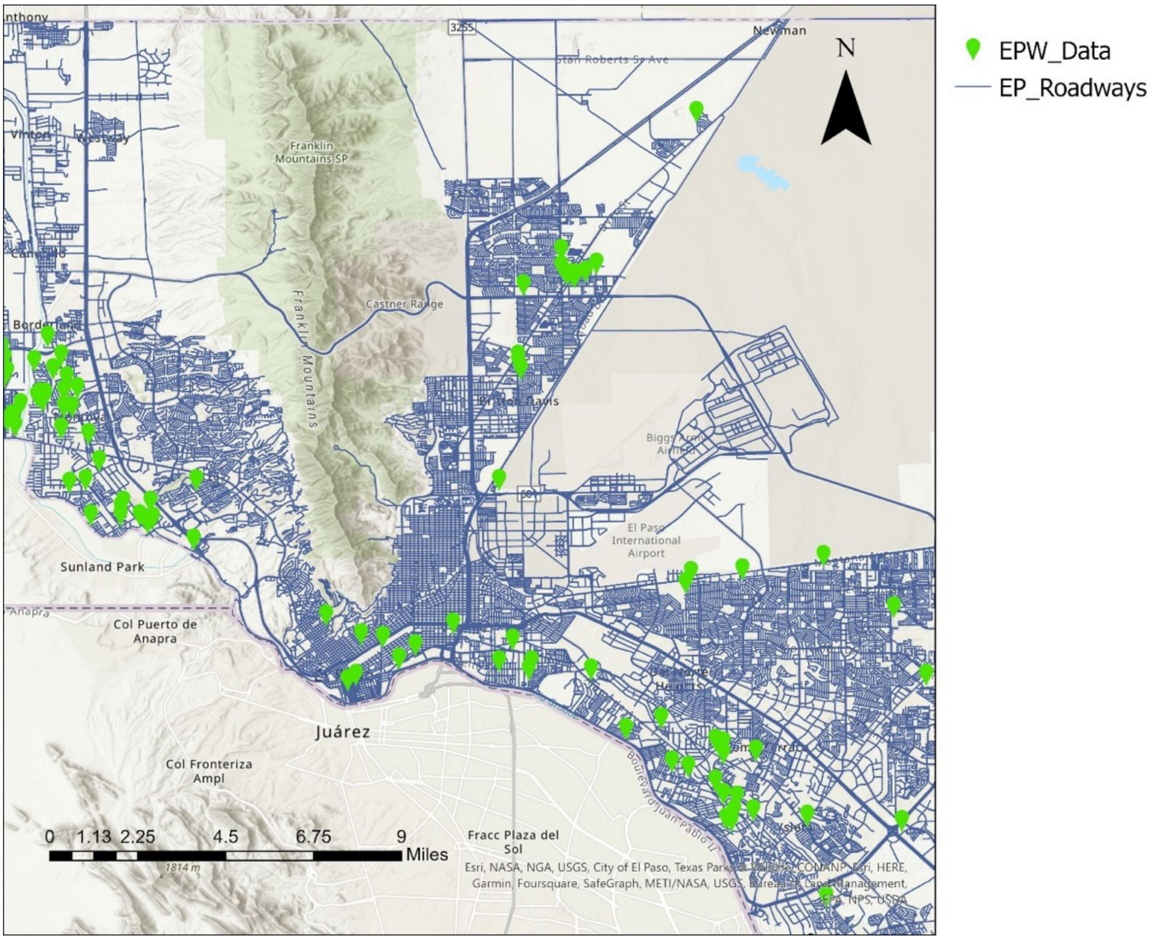


Figure 4.1: El Paso Water nuisance flooding locations

Data Collected

After flooding locations were identifies, further data research was required to determine any correlations between floods and surface temperatures, pavement conditions, and traffic safety hazards. Traffic safety hazards or crashes was considered in this case due to the possibility of reducing the width of roads to slow down vehicles.

Alameda Avenue

Figure 4.4 shows a highlighted section of one of the five streets that showed the most potential. An intersection image is shown in Figure 4.3, where significant nuisance flooding is expected during rainstorms. As seen, Alameda avenue exhibits many issues with respect

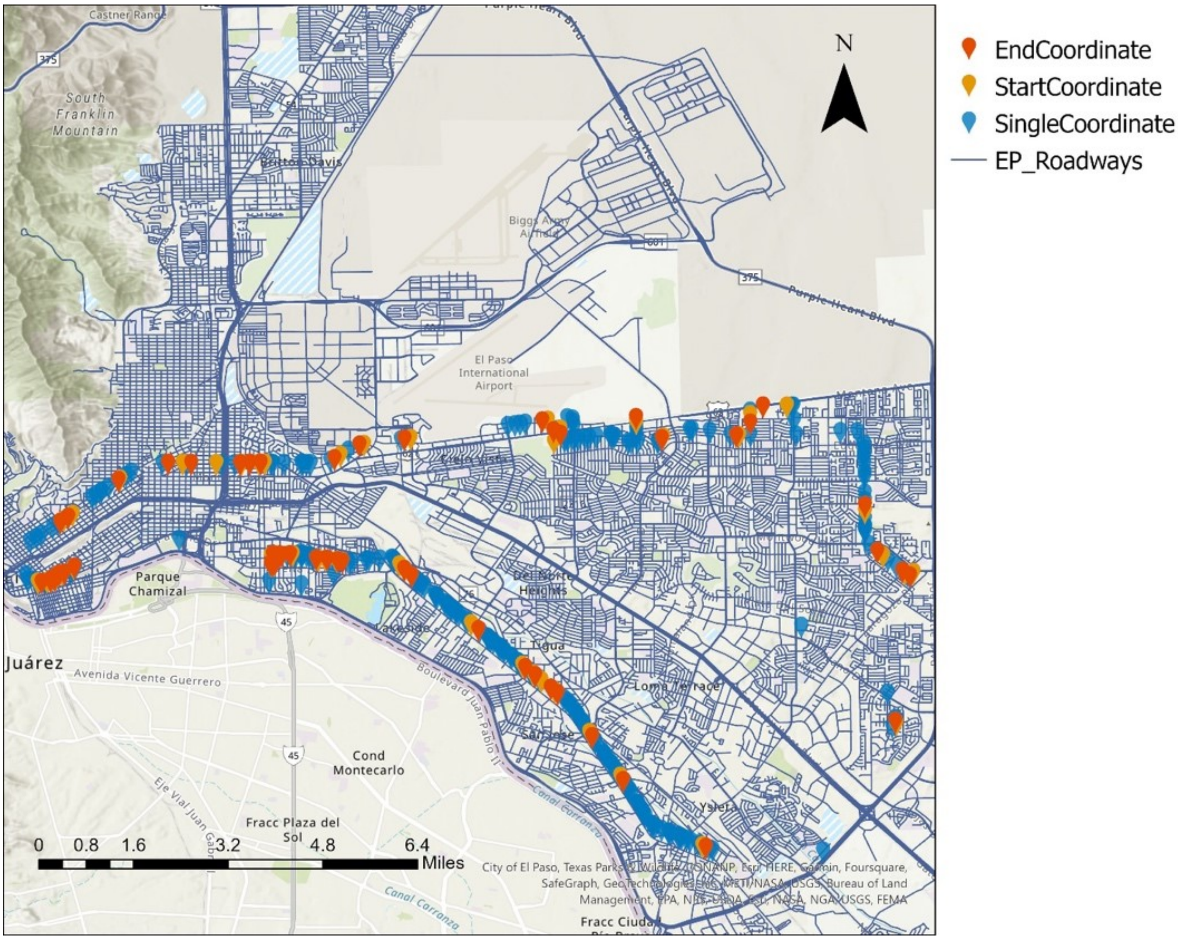


Figure 4.2: El Paso nuisance flooding locations per driving survey

to poor pavement quality (Figure 4.5), high surface temperatures (Figure 4.6), and commonly reported crashes (Figure 4.7).

Figure 4.3: Alameda Avenue in El Paso

Rutherglen Street

Rutherglen Street is a neighborhood road (Figure 4.8) that consistently experiences floods. Although, pavement conditions are rated as satisfactory (Figure 4.10), residents have reported plenty of issues caused by floods. Some of these issues have to do with damages to peoples vehicles. This area has had a few crashes reported as of 2021 (figure 4.12). In addition, Rutherglen experiences relatively high temperatures, especially in the intersection with Montana Avenue (Figure 4.11)

Saul Kleinfeld

Saul Kleinfeld is a collector road that connects two important arterial roads (Zaragoza Rd. and Montana Ave.). Figure 4.13 depicts the nuisance flooding this road experiences during rain storms. Pavement conditions are mostly good or satisfactory (Figure 4.15). On the other had, there are high temperatures recorded along Saul Kleinfeld (Figure 4.16). Lastly, Figure 4.17 shows that there have been several crashes, especially at two parallel intersections.

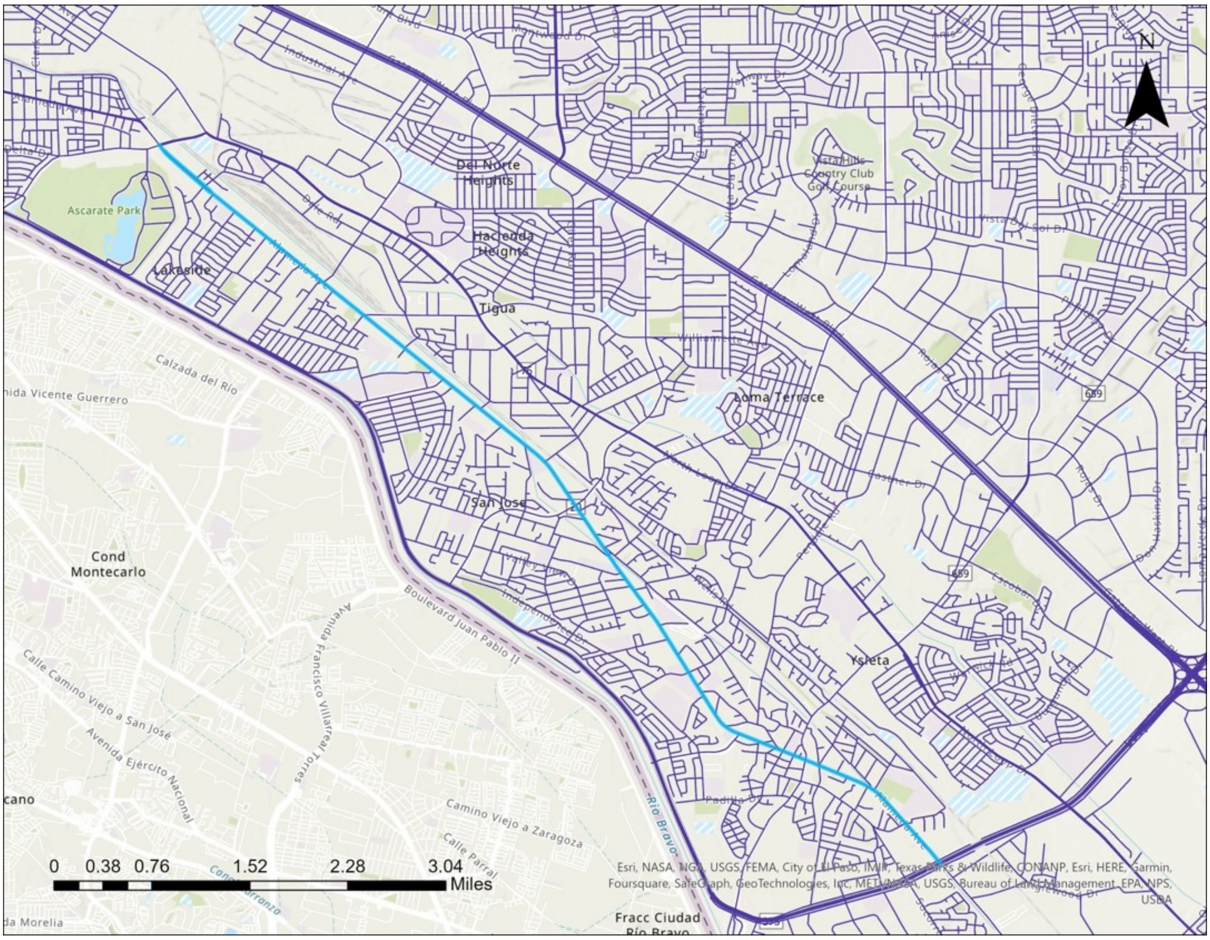


Figure 4.4: Alameda Avenue Studied Section

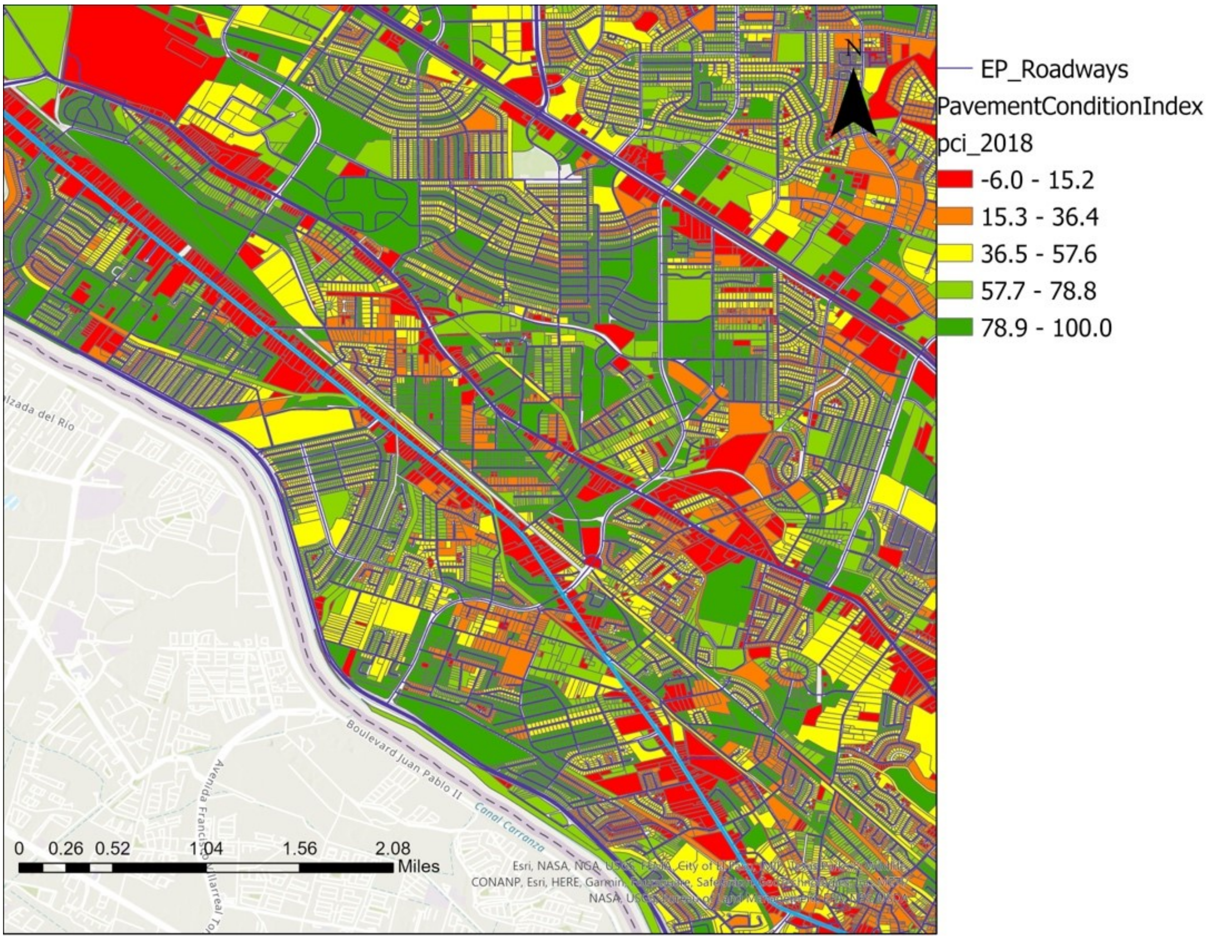


Figure 4.5: Alameda Avenue Pavement Condition

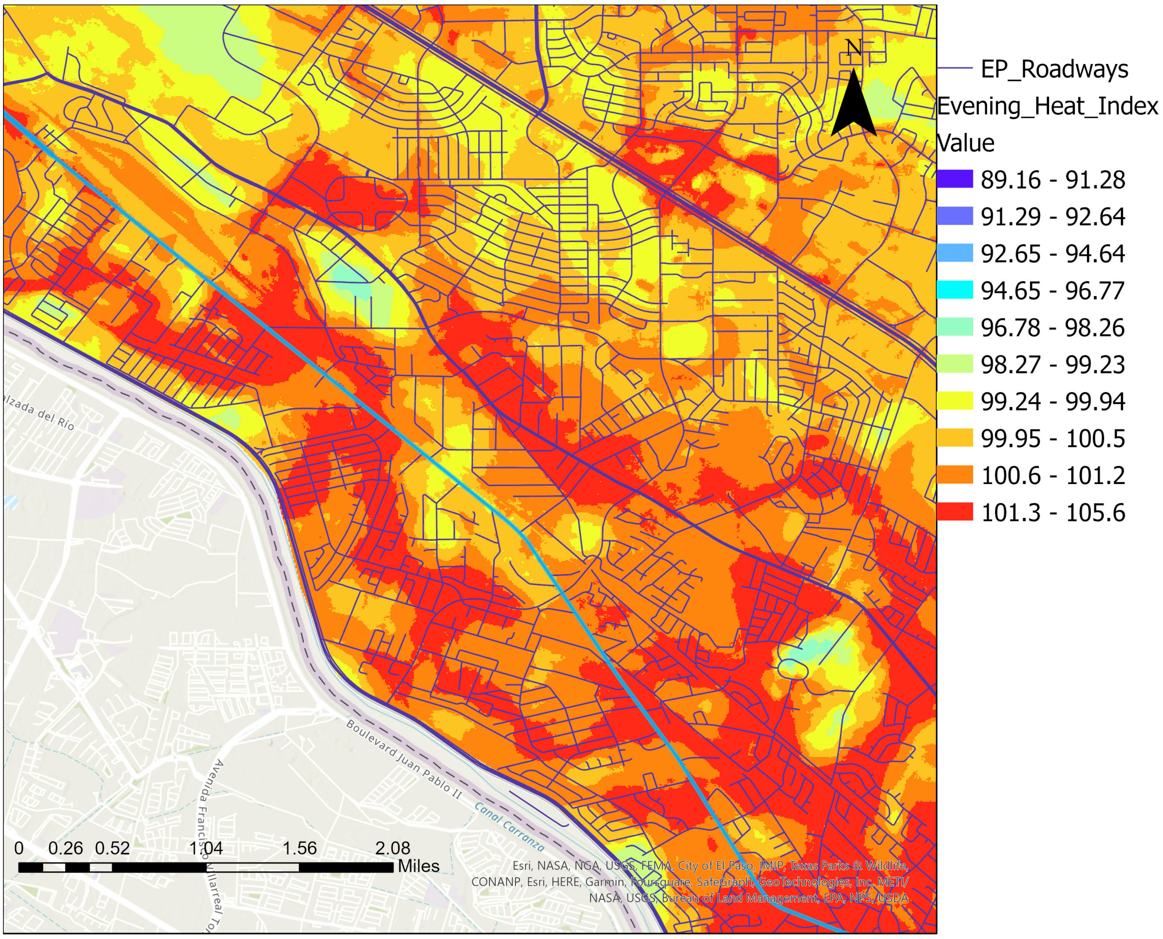


Figure 4.6: Alameda Avenue Heat Index

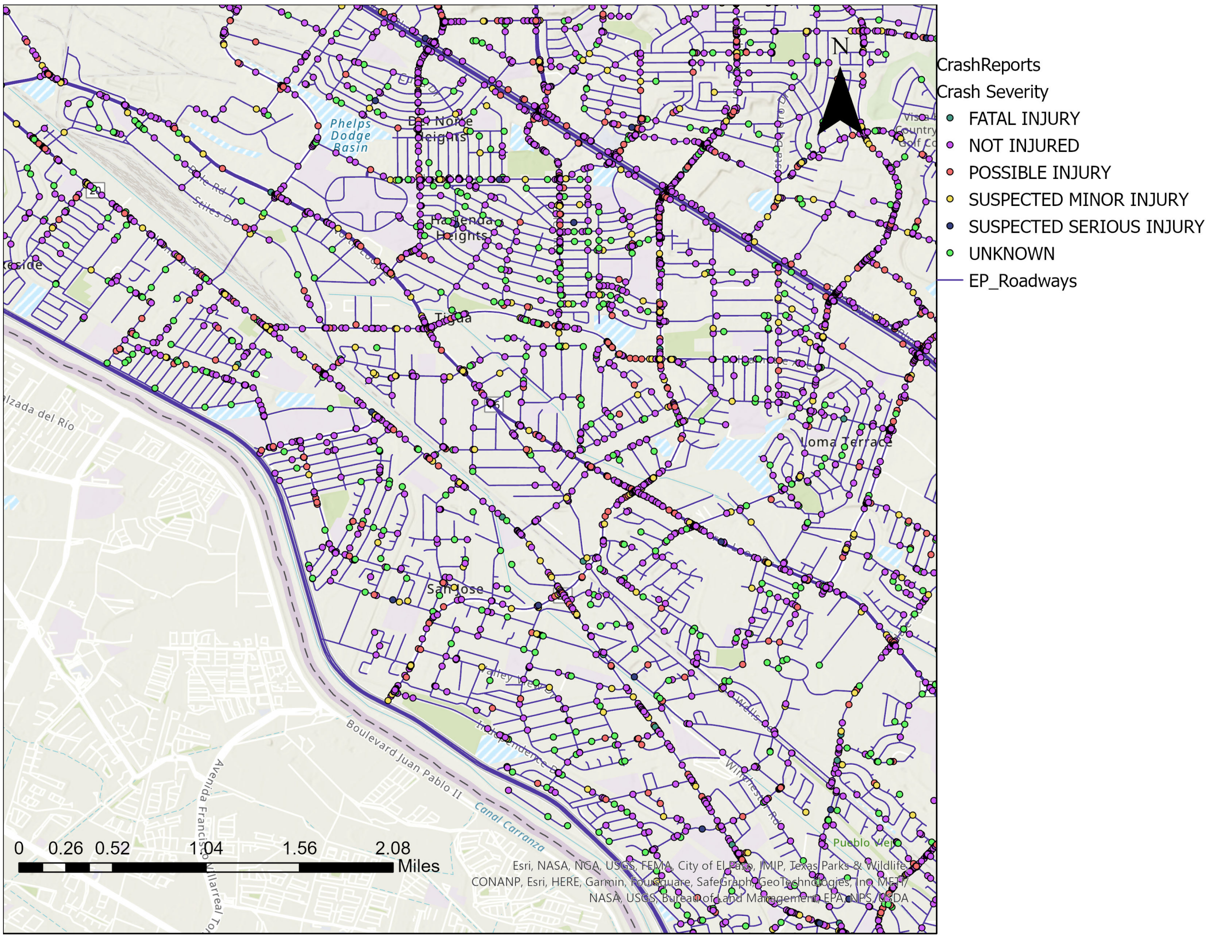
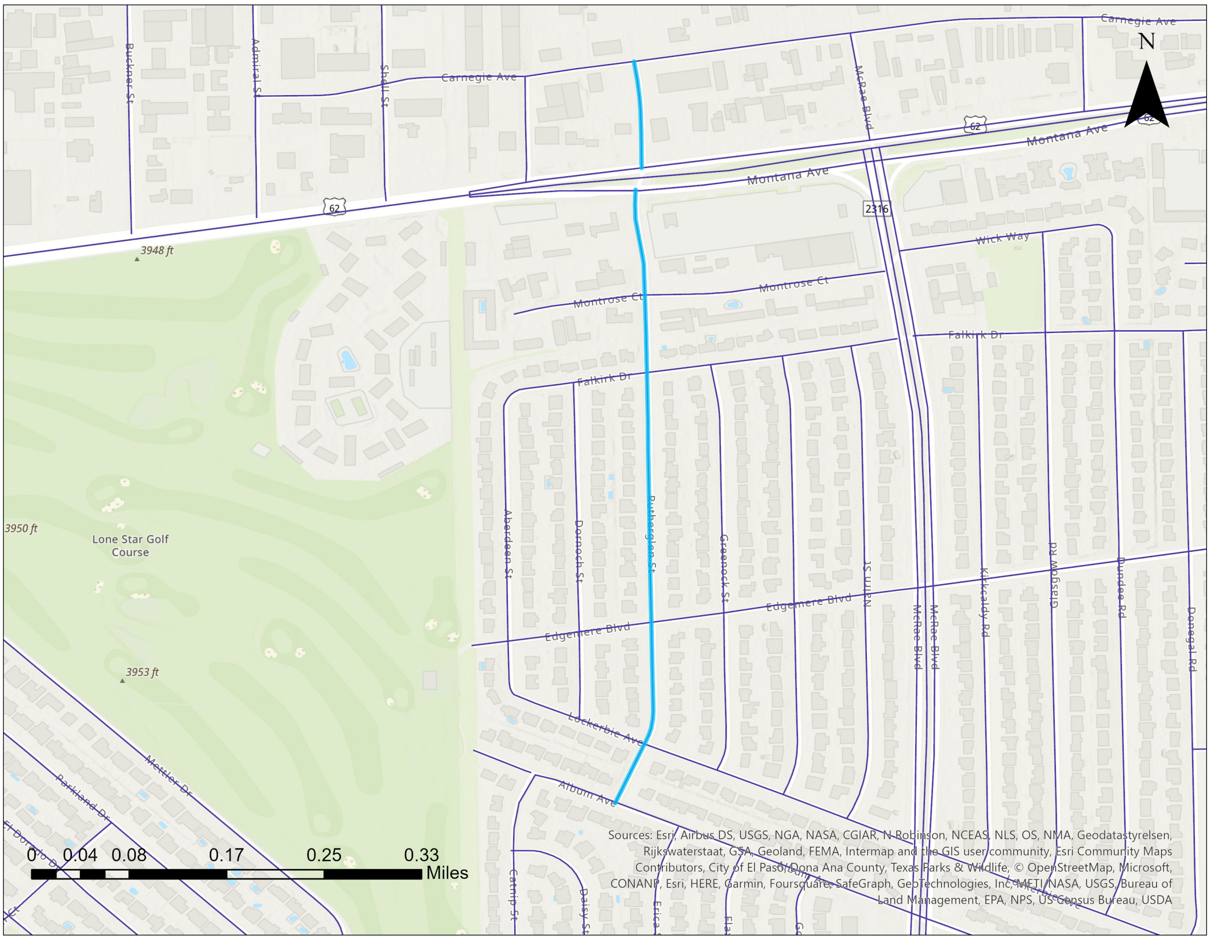


Figure 4.7: Alameda Avenue Crashes

Figure 4.8: Rutherglen Street

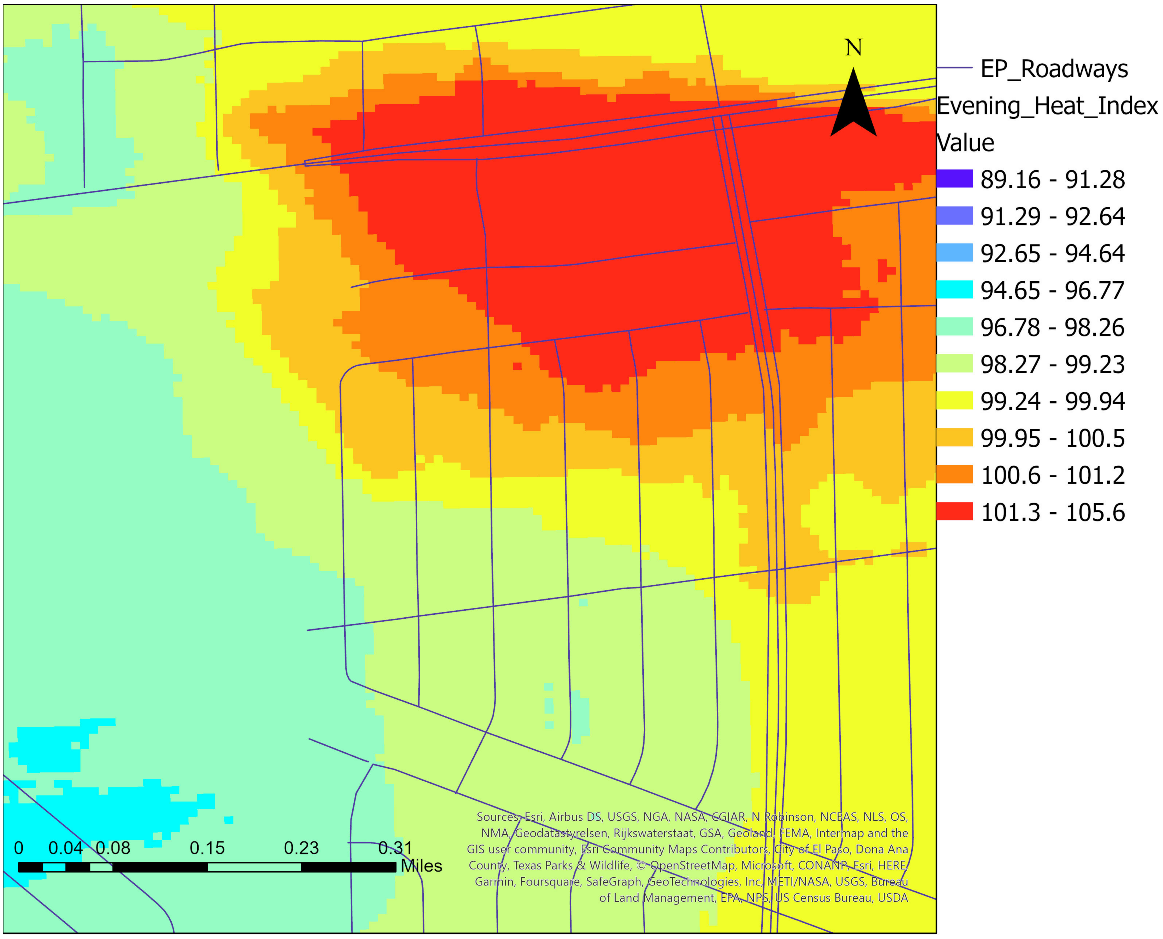


Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, City of El Paso, Dona Ana County, Texas Parks & Wildlife, © OpenStreetMap, Microsoft, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA

Figure 4.9: Rutherglen Street Studied Section

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, City of El Paso, Dona Ana County, Texas Parks & Wildlife, © OpenStreetMap, Microsoft, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA

Figure 4.10: Rutherglen Street Pavement Condition



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, City of El Paso, Dona Ana County, Texas Parks & Wildlife, © OpenStreetMap, Microsoft, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA

Figure 4.11: Rutherglen Street Heat Index

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, City of El Paso, Dona Ana County, Texas Parks & Wildlife, © OpenStreetMap, Microsoft, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA

Figure 4.12: Rutherglen Street Crashes

Figure 4.13: Saul Kleinfeld

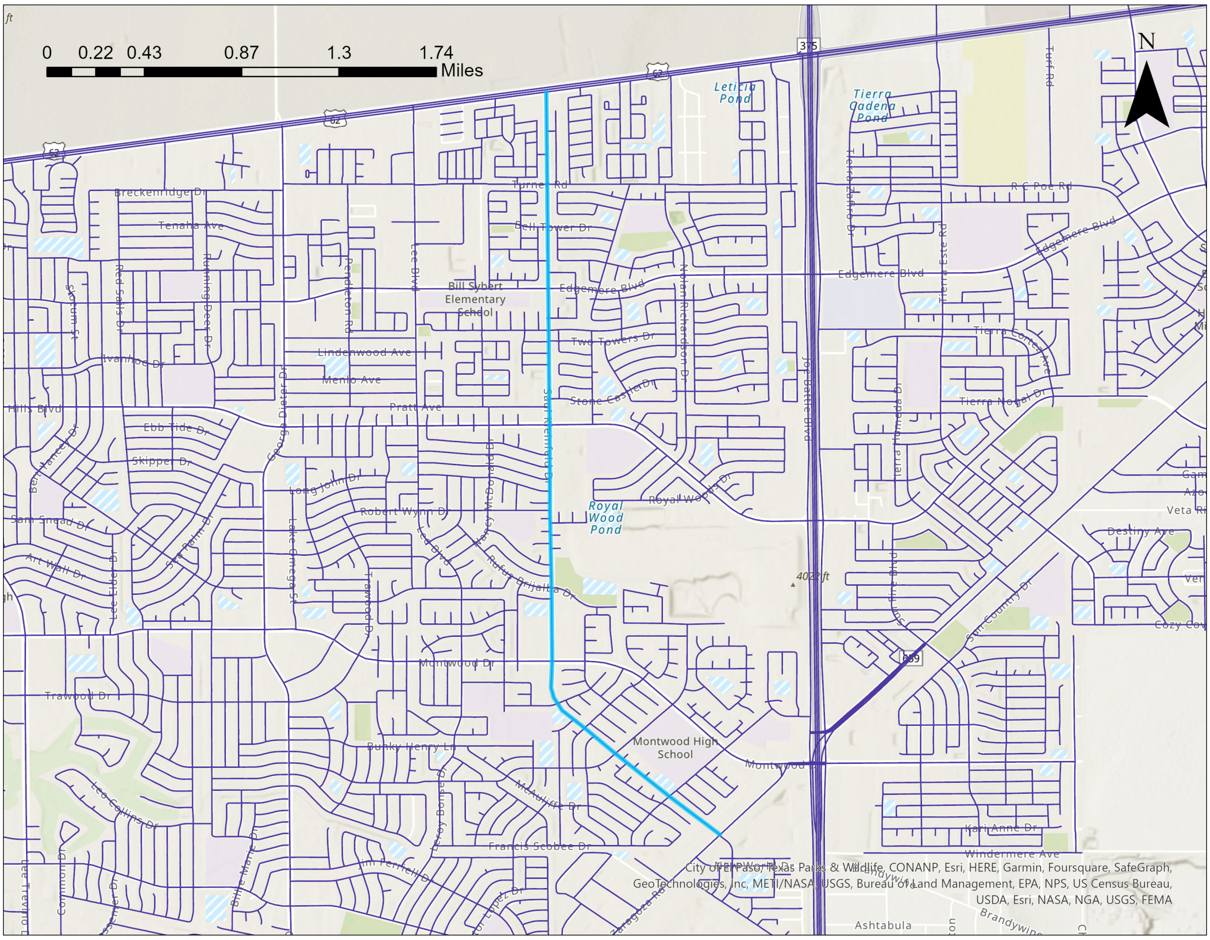


Figure 4.14: Saul Kleinfeld Studied Section

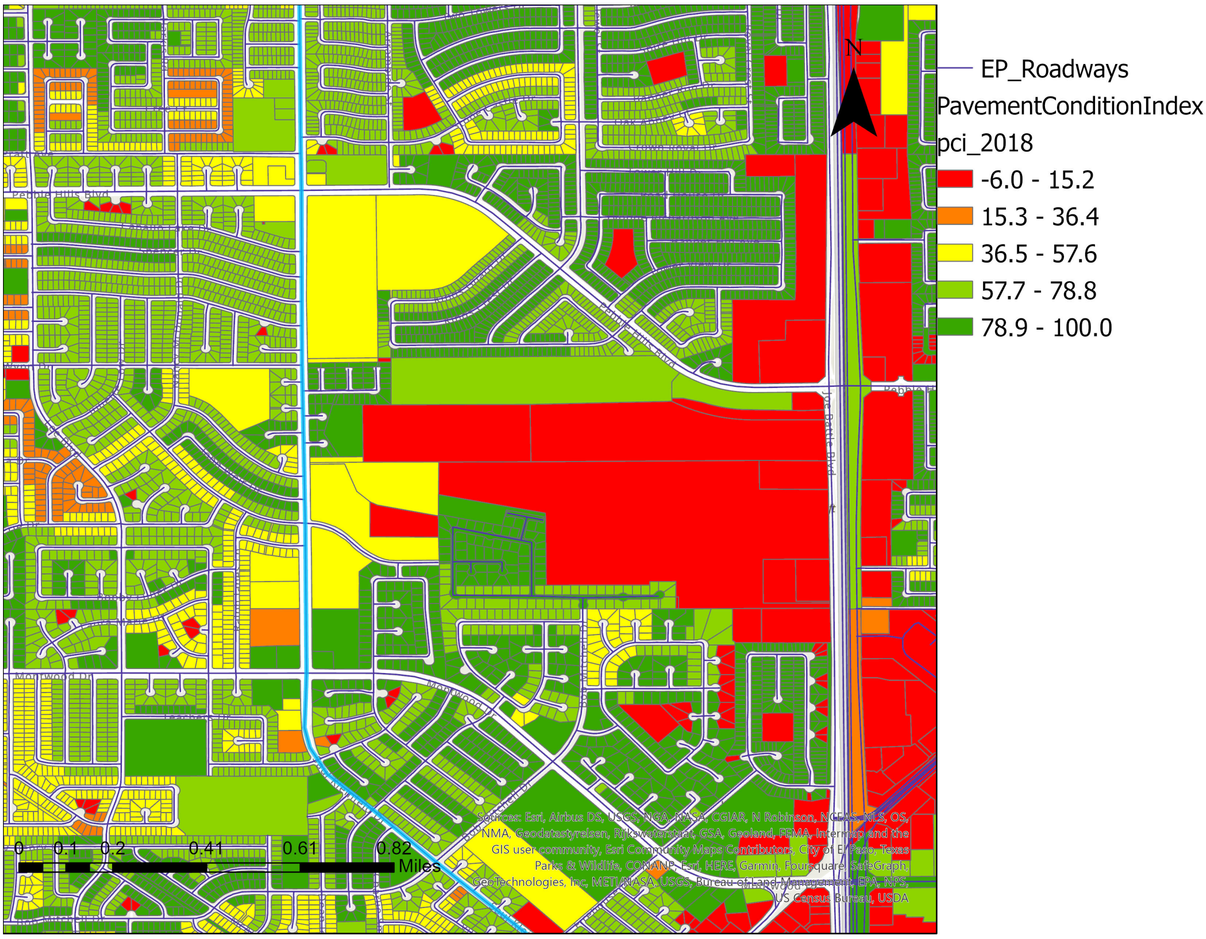
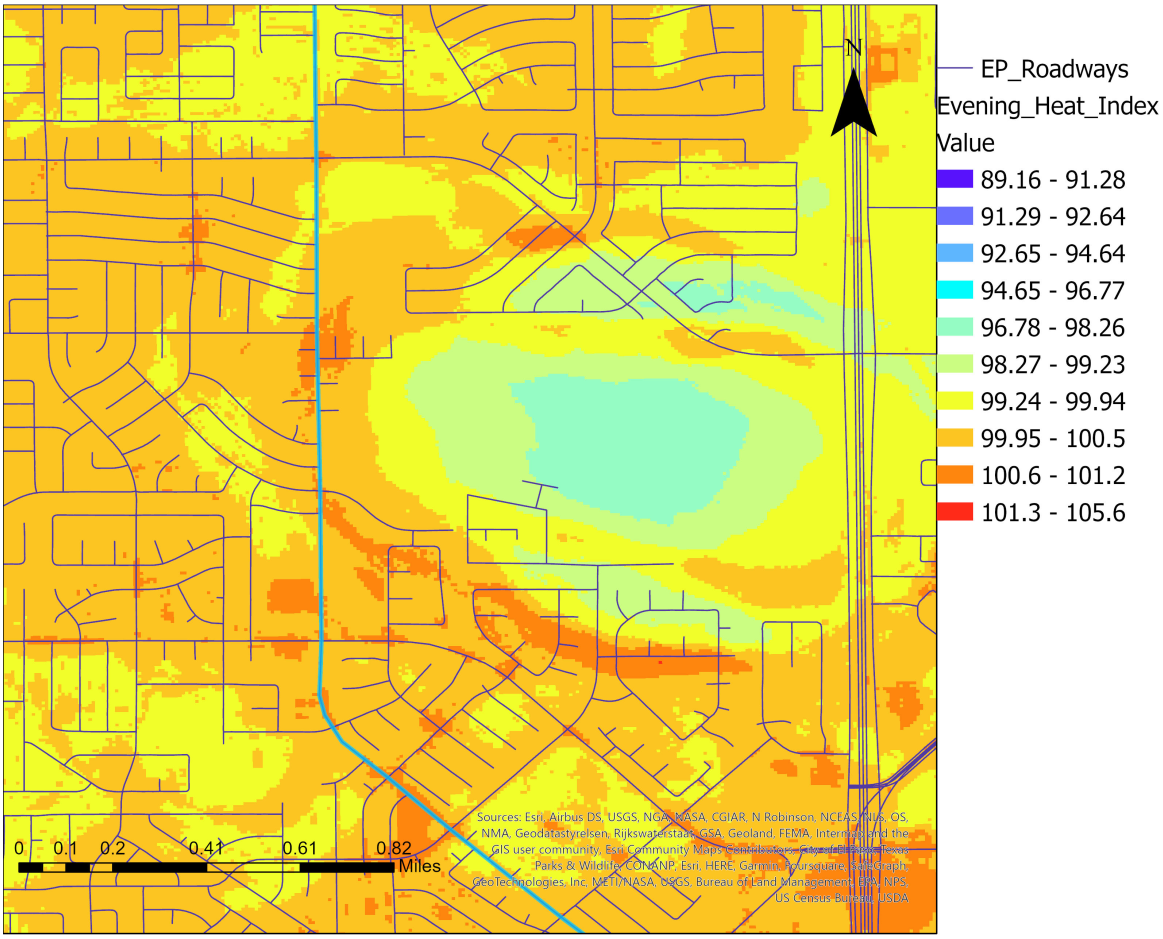


Figure 4.15: Saul Kleinfeld Pavement Condition



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, City of El Paso, Texas Parks & Wildlife, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA

Figure 4.16: Saul Kleinfeld Heat Index

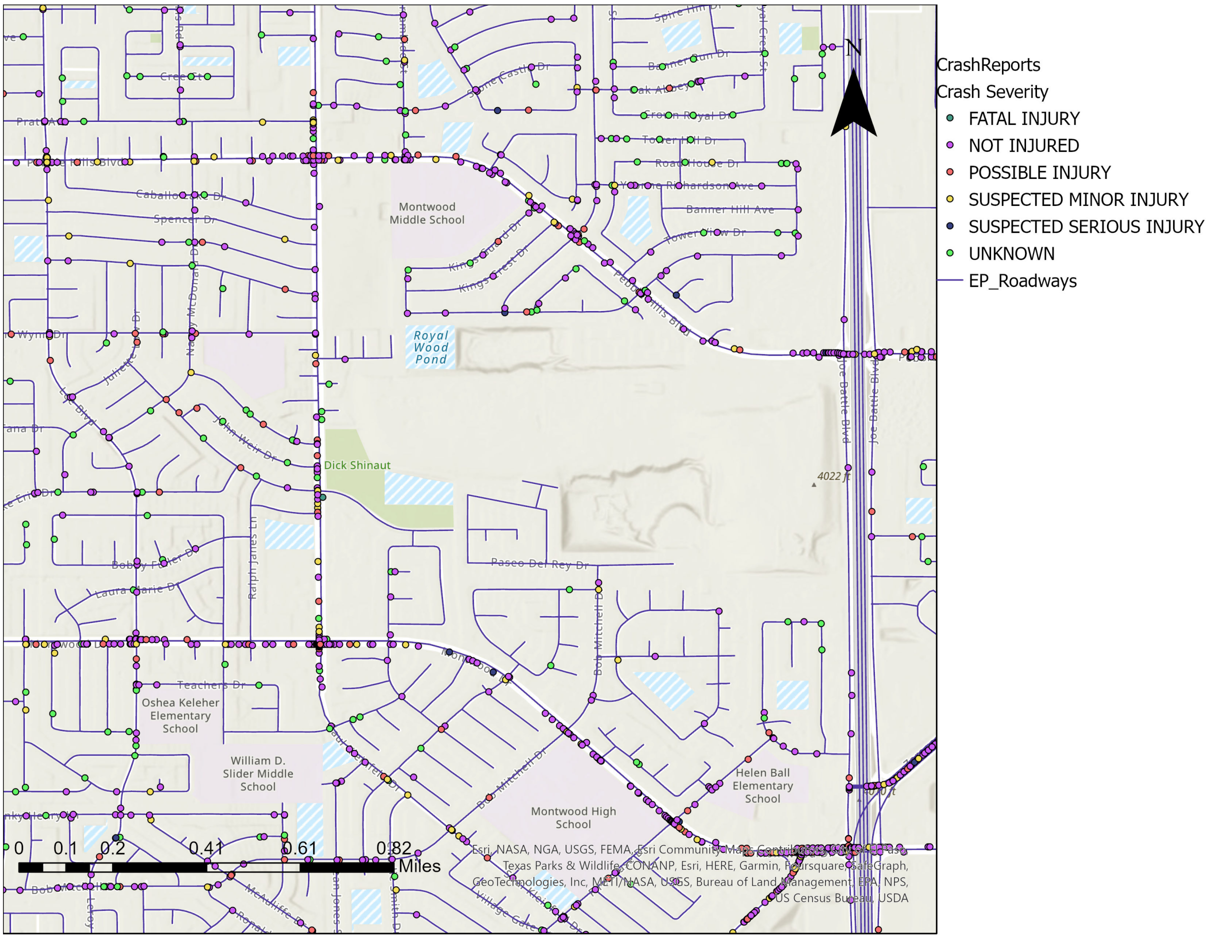


Figure 4.17: Saul Kleinfeld Crashes

Montana Avenue

Montana Avenue is one of the most important arterial roads in the city. It consists of many businesses, much like Alameda, and high traffic volumes. Figure 4.18 shows one out of many nuisance flooding locations found along the road. Only a small section near the historical part of the city was considered for this research (figure 4.19). Pavement conditions in this street range from poor to good, as shown in Figure 4.20. This section is also part of a region that experiences high temperatures and many crash reports (Figure 4.21 and Figure 4.22).

Figure 4.18: Montana Avenue

Dyer Street

Dyer street is also another important arterial road near the Franklin Mountains in El Paso. During big rainstorms this street is heavily impacted by floods, as shown in Figure 4.23. Only a section of Dyer was considered for this study which is shown in Figure 4.24. A large portion of the road has a failed category for pavement condition (Figure 4.25). Similarly, this zone experiences high surface temperatures and numerous crash reports (Figure 4.26 and Figure 4.27).

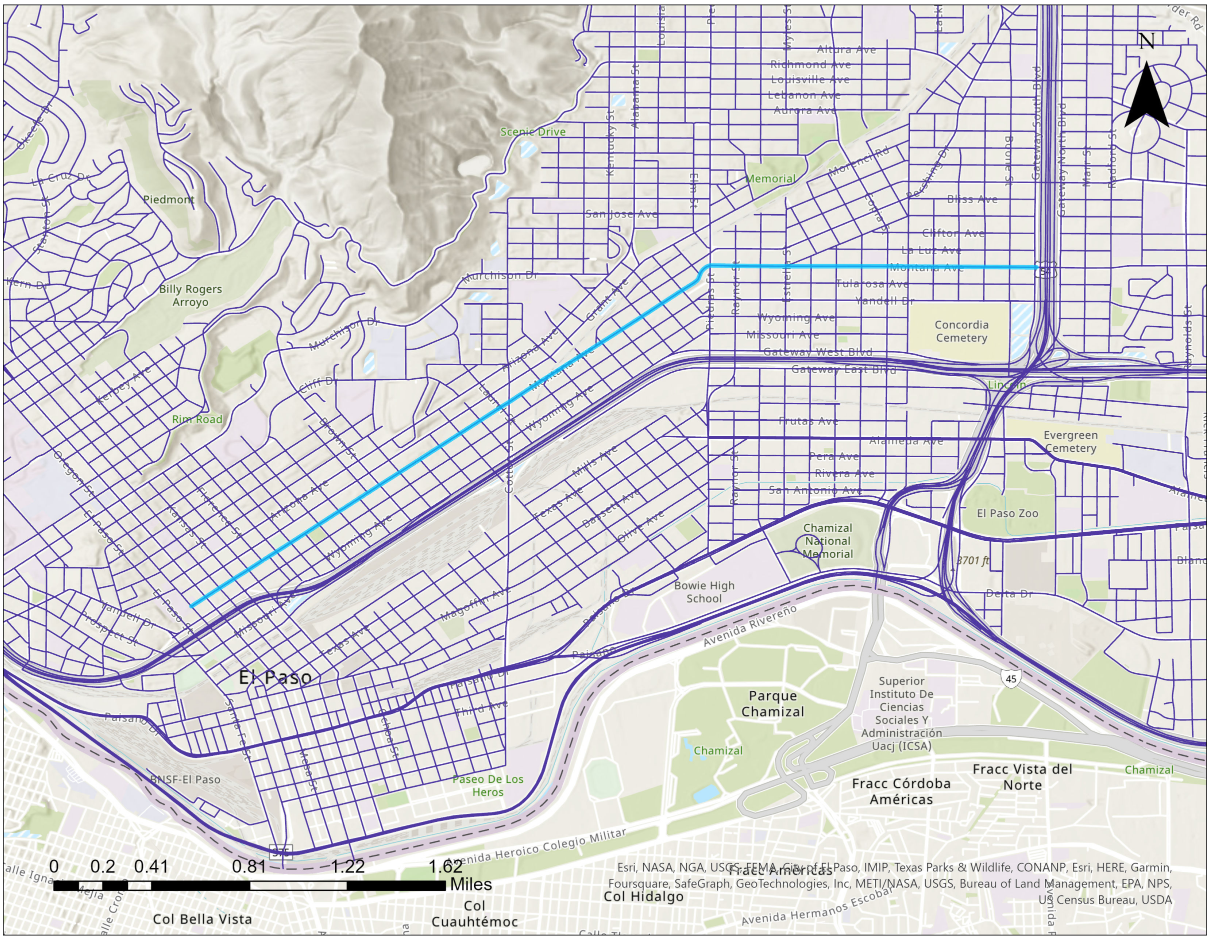


Figure 4.19: Montana Avenue Studied Section

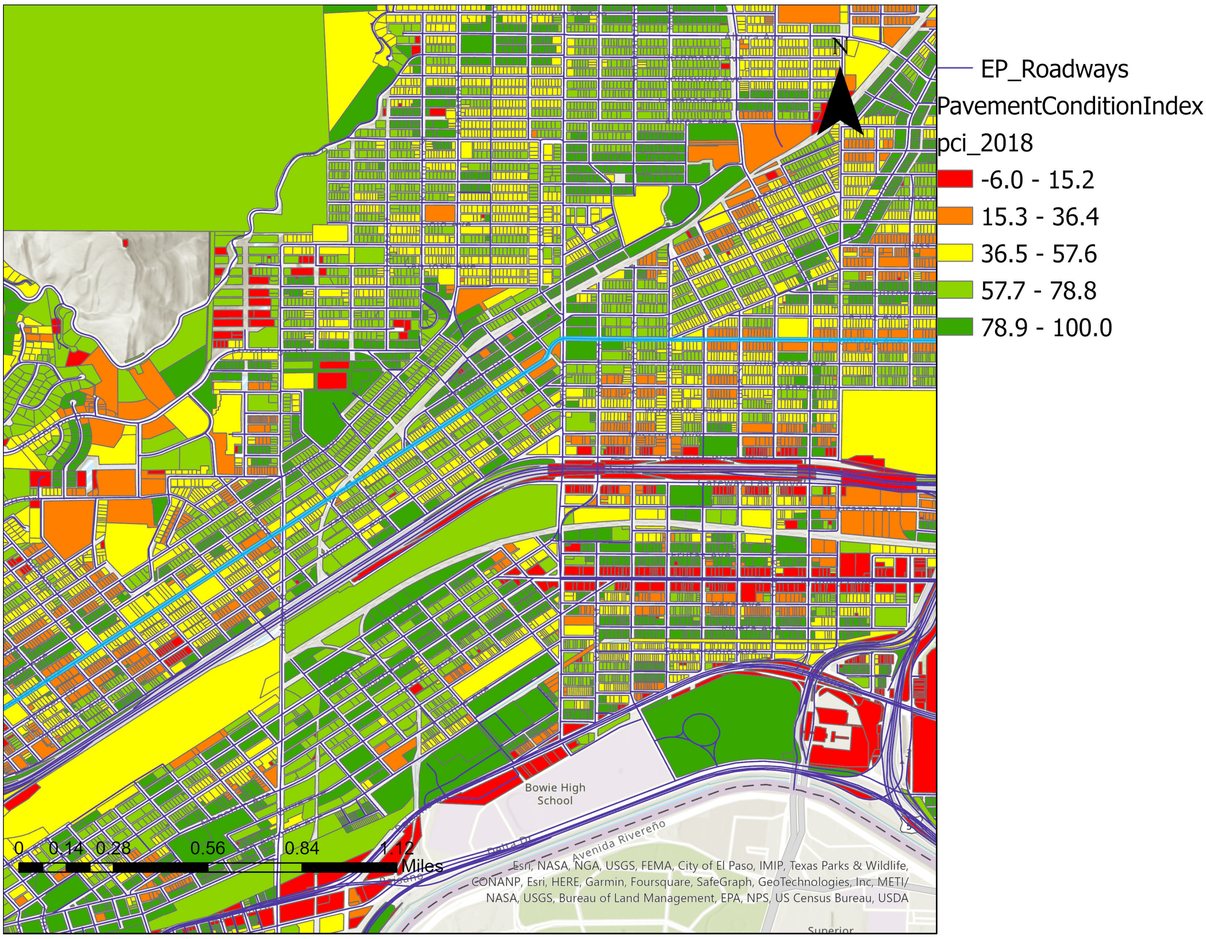


Figure 4.20: Montana Avenue Pavement Condition

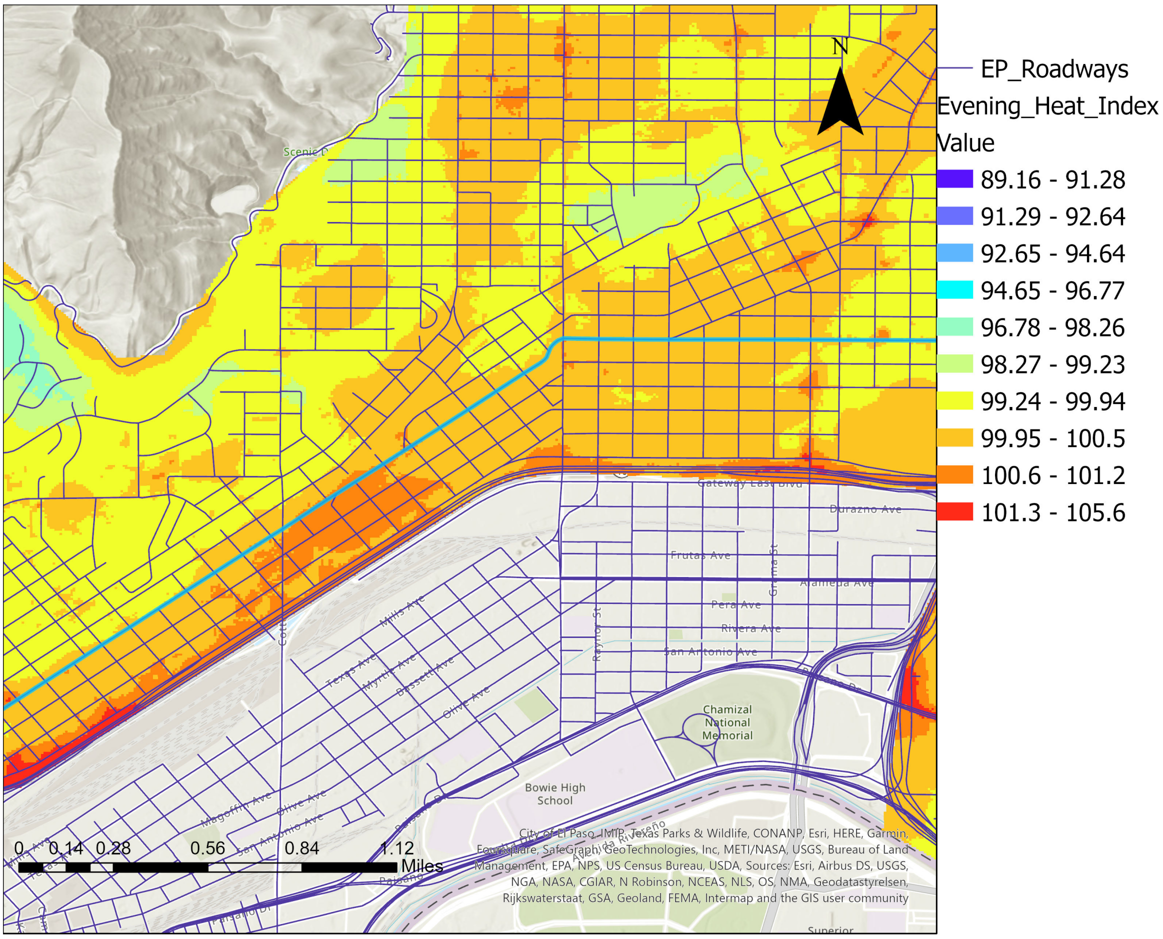


Figure 4.21: Montana Avenue Heat Index

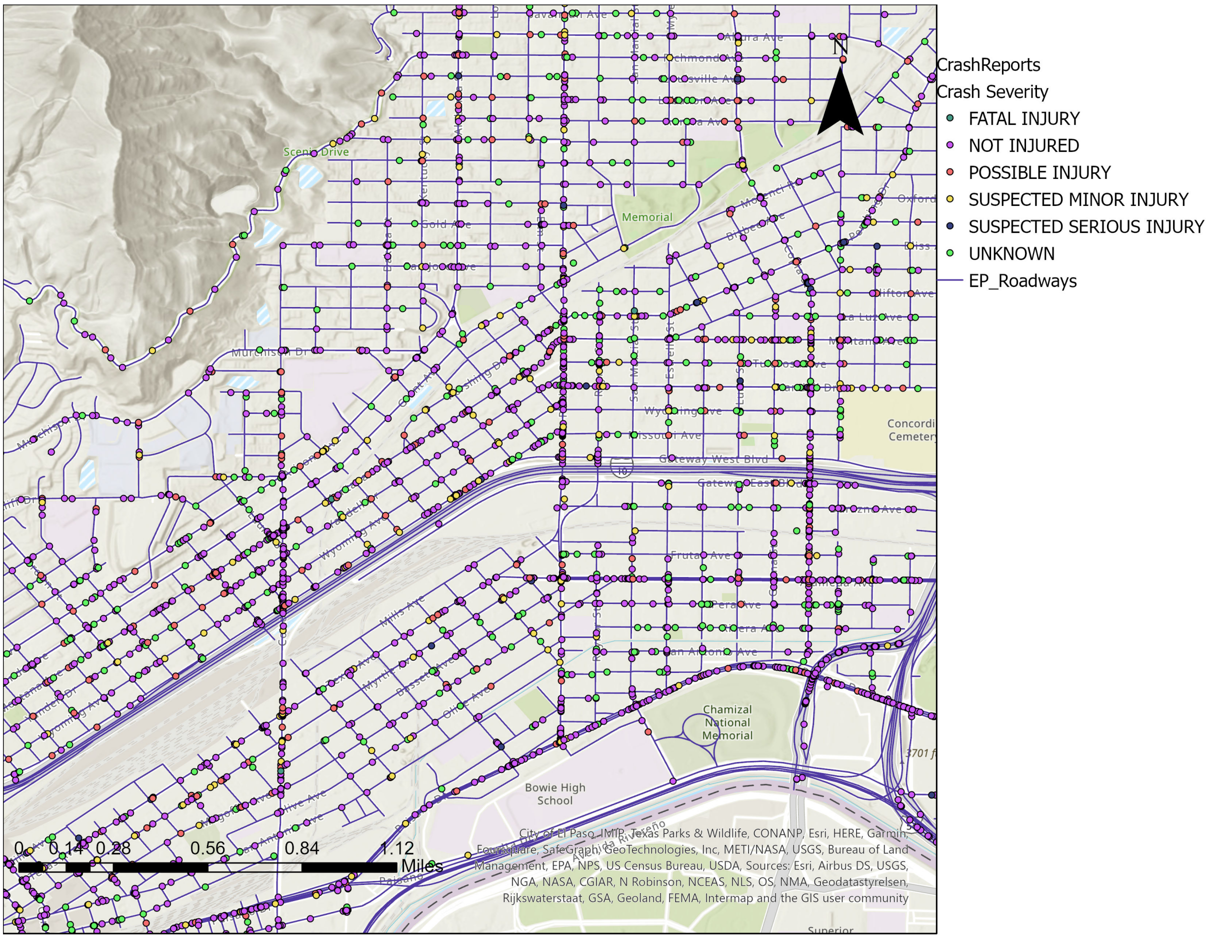


Figure 4.22: Montana Avenue Crashes

Figure 4.23: Dyer Street

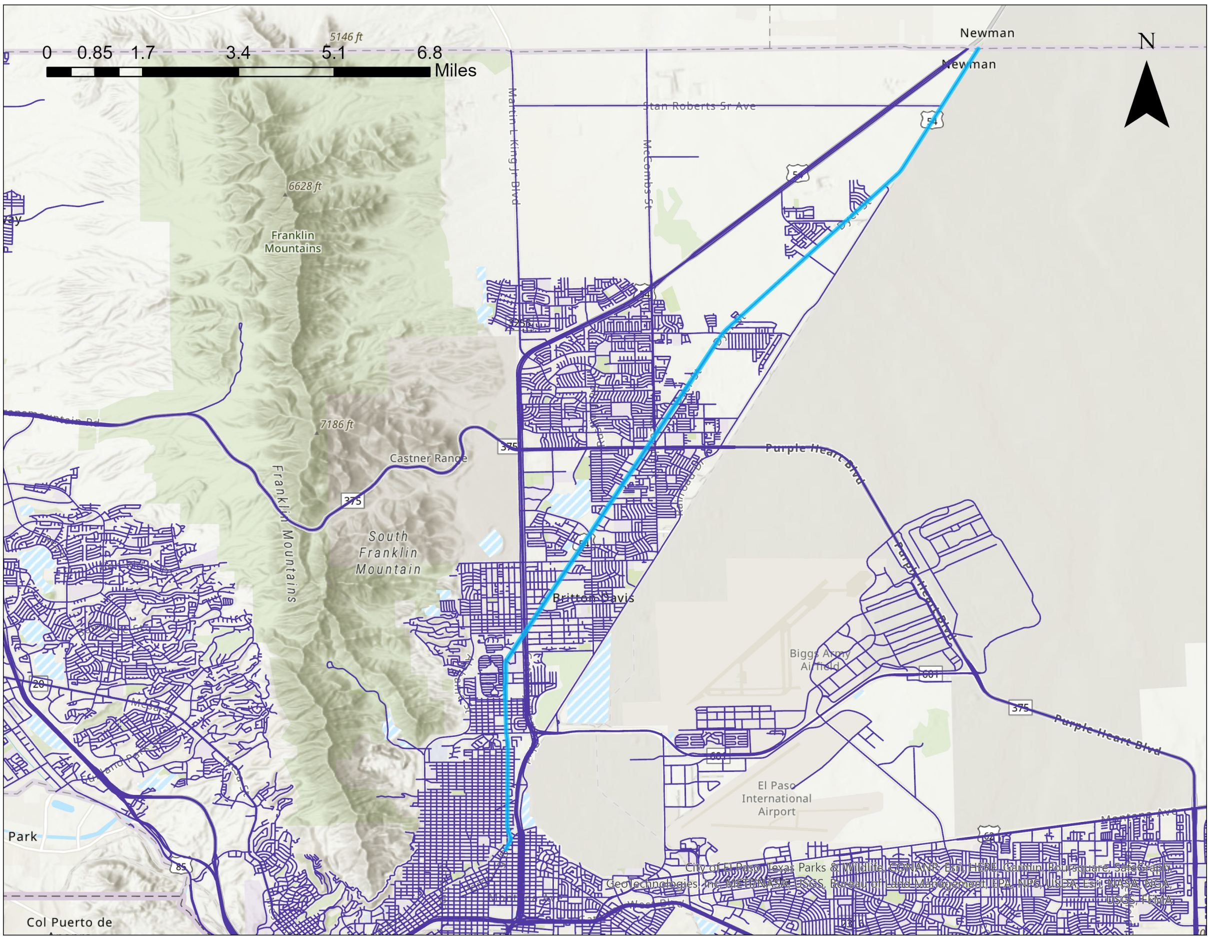


Figure 4.24: Dyer Street Studied Section

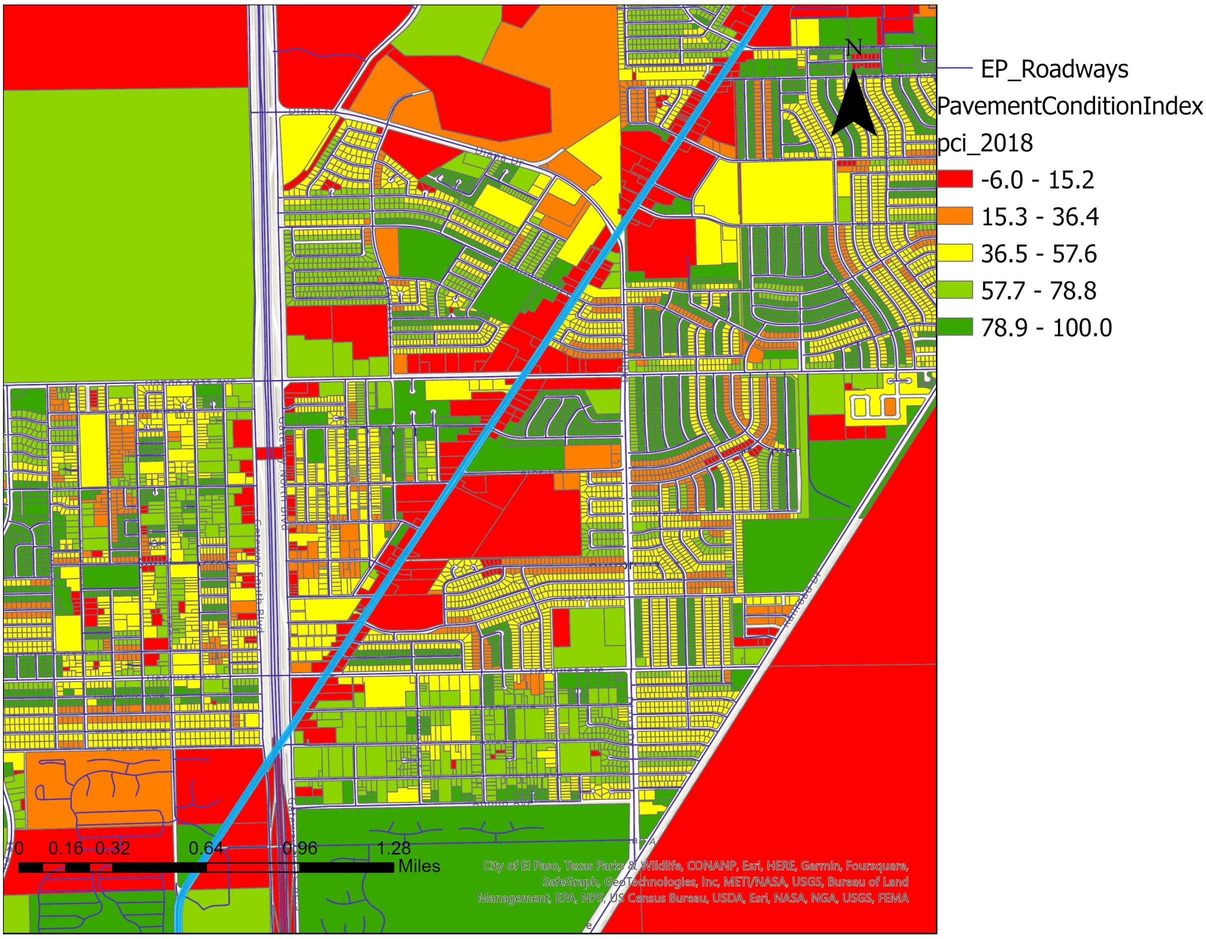
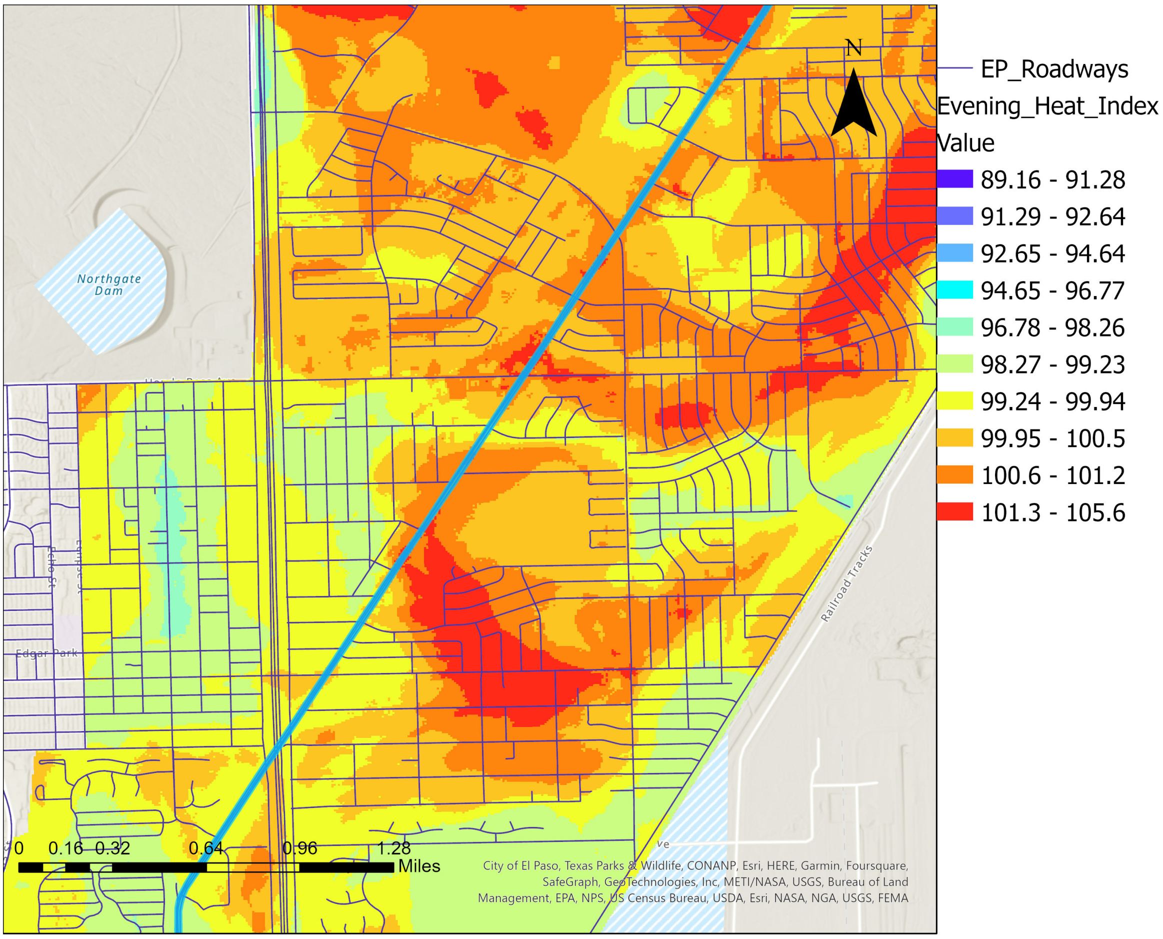


Figure 4.25: Dyer Street Pavement Condition



City of El Paso, Texas Parks & Wildlife, CONANP, Esri, HERE, Garmin, Foursquare, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, US Census Bureau, USDA, Esri, NASA, NGA, USGS, FEMA

Figure 4.26: Dyer Street Heat Index

Figure 4.27: Dyer Street Crashes

Data Processing Approach

The data discussed in this chapter was collected through several sources and analyzed using GIS maps. Pavement Condition Index was accessed through the municipalities archives, where the capital improvements department conducted surveys in identifying the state or condition of roads on a city wide scale. This data is best visualized using a color scheme to represent failed, poor, fair, satisfactory, and good pavement conditions. Heat index is another important set of data that was collected during a Mapping Urban Heat Islands study conducted by the University of Texas at El Paso. Several students volunteered to drive designated routes around the city and collect temperature/humidity measurements. Analyzing heat index was managed through the use of GIS maps as well, where a different color scheme is selected to visualize the heat intensity during the evening. Lastly, car crash data was collected from the Crash Report Information System (CRIS) managed by the Department of Transportation in Texas (TxDOT). The data in this system is filled out by the police department when reporting the incident. The location of the incidents was identified and categorized by severity of injury.

Using the AHP Method to Prioritize Sites

After analysing all of the previous data discussed, a prioritizing process was conducted using the Analytical Hierarchy Process (AHP). The following, Table 4.1, represents the ranks of the selected parameters, characteristics or goals set for the GI sites: storm water management, traffic safety, ground water recharge, Heat index and Air quality impacts, pavement condition, improvement of quality of life through the availability of recreational area, impact on the duration of the site's construction, and affordability of the project. The scores assigned to both parameters and streets were determined by the method explained in Table 3.1. These parameters were weighted by importance of the sites common vulnerability factor, in this case sites were mostly vulnerable when it came to flooding.

Results from El Paso Case Study on Site Selection

After weights are designated to each parameter, the sites can be ranked by importance and priority according to the parameters (Table 4.1). Finally, the five selected sites were ranked using the AHP method as seen on Table 4.2.

Ranking	Parameter
1st	Storm water management
2nd	Traffic safety
3rd	Water recharge
4th	Heat index and Air quality
5th	Pavement condition
6th	Recreational area
7th	Construction duration
8th	Project cost

Table 4.1: GI Parameter Ranks.

Ranking	Street
1st	Alameda Ave.
2nd	Montana Ave.
3rd	Dyer St.
4th	Rutherglen St.
5th	Saul Kleinfeld Dr.

Table 4.2: Sites Ranked by Potential Benefits of GI.

Chapter 5: Case Study: Quantification of Site Improvement with GI in Prague, CZ

For this second phase of research on GI implementation, we will focus on an area in central Europe, known as Czechia or the Czech Republic. The map in Figure 5.1, shows the Czech Republic highlighted in green, where Prague is the beautiful capital of this country.

Figure 5.1: Czech Republic in Central Europe

Case Study in Prague

The case study carried out in this research for the city of Prague will consist of applying GI within a smart cities ideology. The GI site has been predetermined, which will be discussed in further detail in the following sections. It is also important to take into consideration the current state of water resources and their usage, along with the city's current storm water management infrastructure. However, for this case we will mostly focus on air pollution effects and intercepted storm water runoff. The GI analysis software, i-Tree Eco, is used to provide an assessment of the impacts on GI deployment at the site.

The Vítězné náměstí roundabout was the selected for this research due to it's potential impact on recreational area for the community and available space within the inner circle of the roundabout for GI. The site is located directly adjacent to part of the Czech Technical University campus. The total green area within the site was surveyed along with the number of existing trees. The figure below, figure 5.2, shows which green spaces are included in the scope of work. Notice that the inner circle of the roundabout is technically green space but unreachable to the public due to its location and heavy traffic. The roundabout carries traffic from four directions in a typical counterclockwise pattern, with varying numbers of lanes depending on dedicated exit and entrance lanes. The unique characteristic of the roundabout at the site is the presence of the tram lines which can travel in all directions into and out of the roundabout except to the east.

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, CUZK, GUGiK, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Figure 5.2: Green Spaces in Vítězné Náměstí

Data Collected

Background Information

According to the climate zones, the Czech Republic is in a temperate zone with high humidity levels year round. The river crossing through the center of Prague, known as the Vltava River, provides about 10 percent of the water resources to the city. About 30 percent is pumped from ground water and the other 60 percent comes from the Zelivka Dam, (Noll, 2015). According to news articles and the Czech Statistics Agency, water consumption has increased while farmers claim that crop yields will decrease due to drought covering about 30 percent of the country, (McEnchroe, 2020). Weather reports claim that Prague has an annual precipitation level of about 20 inches with the wettest periods being in the late spring and summer. Floods and thunderstorms are known weather hazards in Central Europe. In addition, the Vltava River is prone to flooding in the southern or southeastern parts of the city.

The Prague Environment Yearbook of 2006, (Prostredi, 2006) provides an analysis on the current wastewater treatment system. It is noted that the newer sections of Prague have a Separate Sewage System, which do not mix rainwater and sewage in under ground pipeline systems. This offers better control of rainwater volumes in case of an overflow. On the other hand, the central and older parts of Prague still rely on a Combined Sewage System, which consists of pipelines that combine both rainwater and sewage that lead to the wastewater treatment plants (WWTP). This system can cause environmental issues if there are high volumes of rainwater causing sewage overflow to spill into the Vltava River, which serves as a precautionary method to protect the pipeline system from bursting and therefore preserve the integrity of the WWTP and/or wastewater and sewer system. The Prague Environment yearbook clearly states: ”At present the Central Wastewater Treatment Plant (CWWTP) does not comply with the very strict requirements for discharged pollution in indicators of total nitrogen and total phosphorus...” This could negatively impact the surrounding ecosystem and the health of nearby residents. In addition, the contaminated discharge can create negative set backs for the current efforts in the Prague Riverfront Concept projects which are encouraging to develop more public or green spaces on the river bank.

Atmospheric/Pollution Conditions

According to historic air quality reports conducted in the Czech Republic, (Baránek and Kurzok, 2023), the country has had high levels of contamination in their atmosphere. The European Commission has gone as far as issuing a warning in 2015 stating that the country would be fined if the problem didn't improve significantly. These high levels of contaminants were due to the methods in household heating, industrial machinery, and transportation. According to the Prague Environment Yearbook of 2019, (životního prostředí, 2019), air quality conditions have improved, yet a significant amount of greenhouse gases are still being produced by individual vehicles. Another contaminant that rose great concern was ground level ozone (O3), which is known to be a contributing factor to many cases of Heat Island Effect. Meteorological reports show that the summer of 2022 has been the fifth hottest since 1775 in Prague's history. The hottest summer recorded was in 2019 with an average temperature of 22.9 degrees Celsius. CAMS is a useful resource to further understand the existing conditions of air quality. Figure 5.3 shows a map of a recent carbon dioxide flux forecast from central Europe. These fluctuations were one of the highest measurements observed during the day of April 16th of 2023. Here, we can notice the fluctuations in the Czech Republic, specifically near the Prague area.

Figure 5.4 provides a map with data for determining what the natural ventilation conditions are like at the site. According to the metadata from the Geoportal Praha website, a scale from zero to five was designated to the wind flow categories (of Planning and of Prague, 2022). Zero is designated to the worst conditions and five represents the most favorable. This map was developed by considering topographic obstacles and wind frequencies. From this information we can conclude that the roundabout is located in an area with a ventilation grade of about 1 or 2, which is not favorable.

Topography

The topography of the region is shown in Figure 5.5. This data provides information on which direction surface storm water runoff will flow. Hydrology studies are necessary to confirm these results, however. Figure 5.5 below shows the topography map created using ArcGIS Pro. The topography generally slopes southwest to northeast, towards the river. There

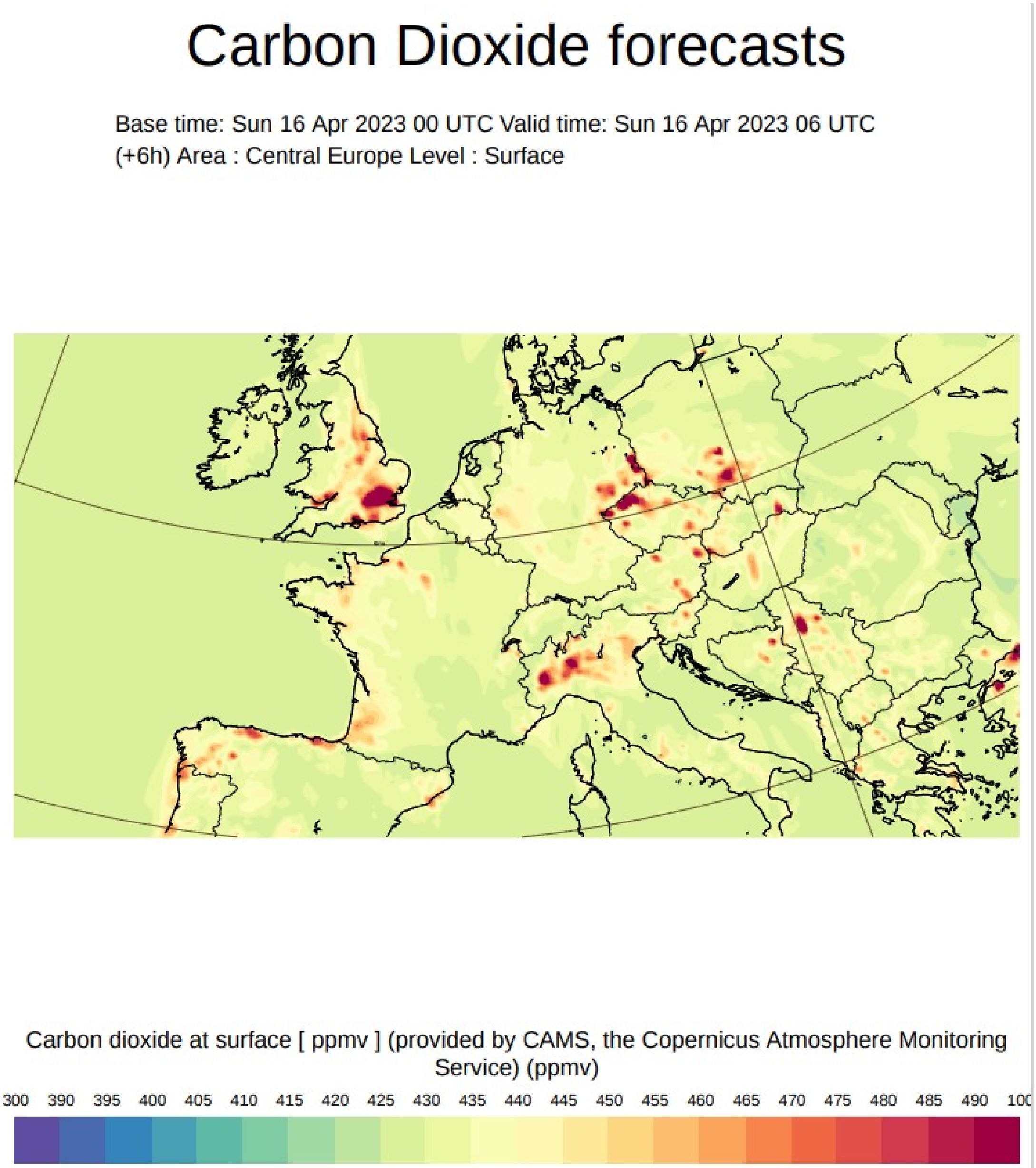
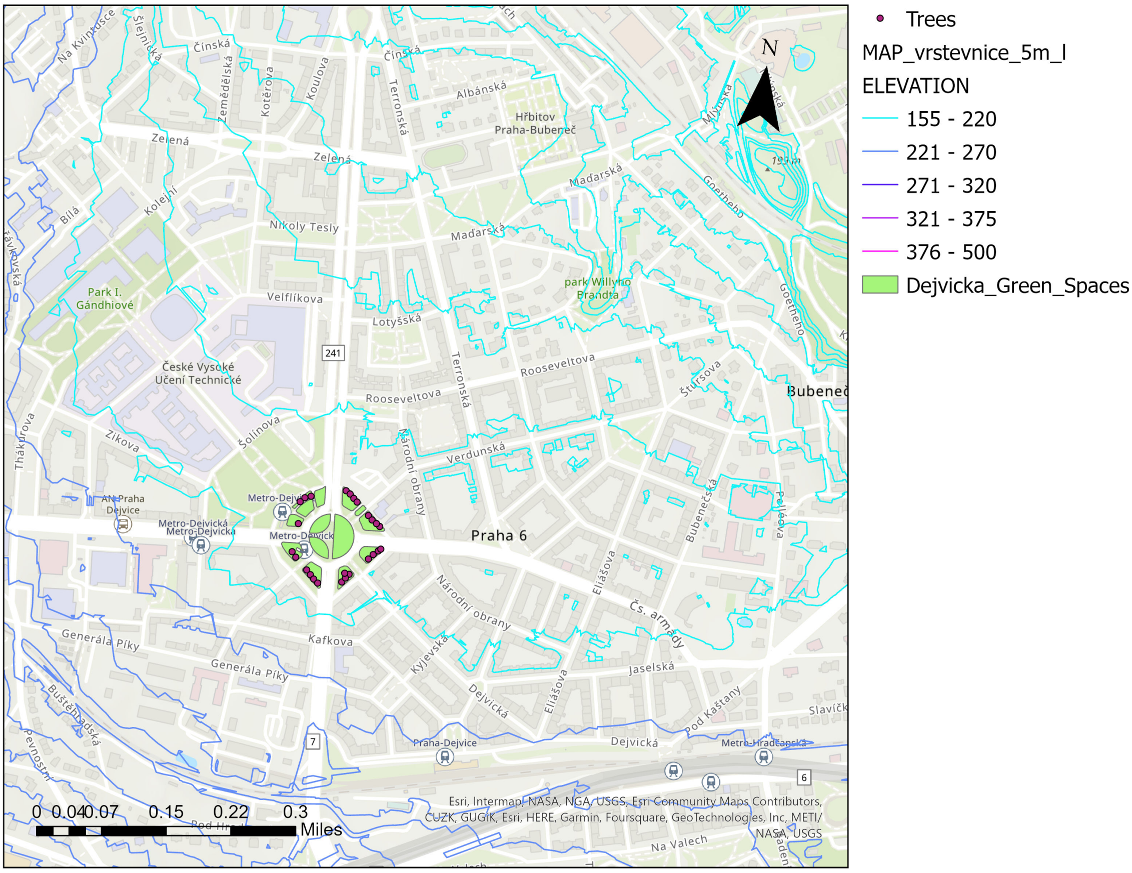


Figure 5.3: Surface Carbon Dioxide by CAMS for Europe

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, CUZK, GUGiK, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/ NASA, USGS

Figure 5.4: Natural Ventilation in the Vicinity of the Site

is little elevation change located at the site.



Esri, Intermap, NASA, NGA, USGS, Esri Community Maps Contributors, ČÚZK, GUGiK, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Figure 5.5: Topography Map

Utilities Network

A map of the underground utilities network was derived from the IPR Praha website in their Digital Technical Map of Prague site (Praha, 2020). This information helps to determine the feasibility of implementing infrastructure changes to the site. As seen below in Figure 5.6, there are some sections of the quadrants that contain a variety of utilities, which may complicate changes. This illustrative map is included to demonstrate the challenges related to existing utilities. Explicit consideration of specific utilities is beyond the scope of this work. A list or legend of the vast number of utilities shown can be attained from the Digital Technical Map of Prague website.

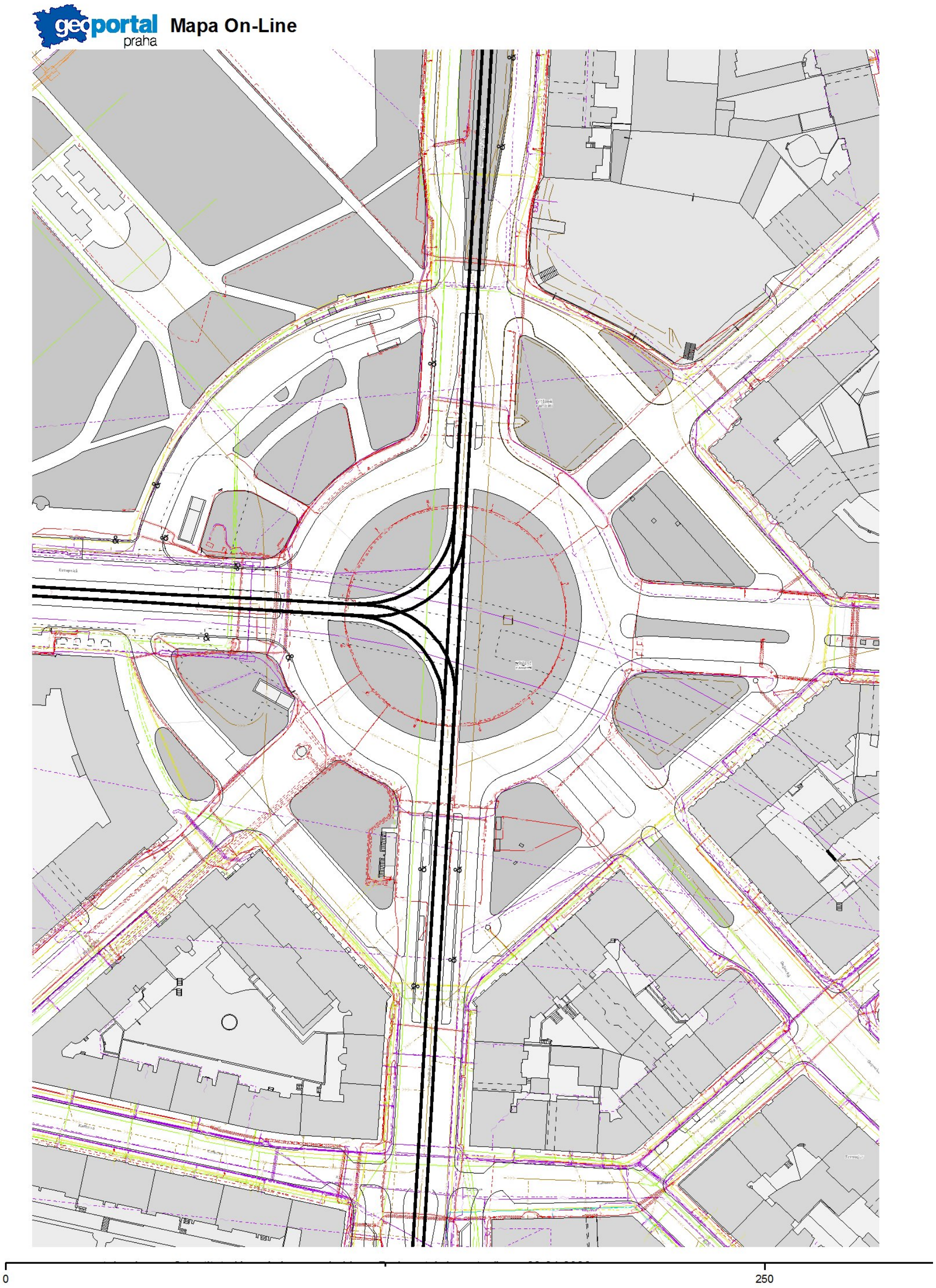


Figure 5.6: Underlying Utilities

Flood Map

The flood map shown below, Figure 5.7, reveals the intensity of a large scale flood in 2013. The GI site would be located in the area labeled as Praha 6. According to the topography map in Figure 5.5, the GI site is possibly upstream from where the flood looks most intense in Bubeneč. On that account, we can assume that the Vítězné náměstí roundabout is a good location for GI since it can reduce runoff upstream from areas where flooding occurs.

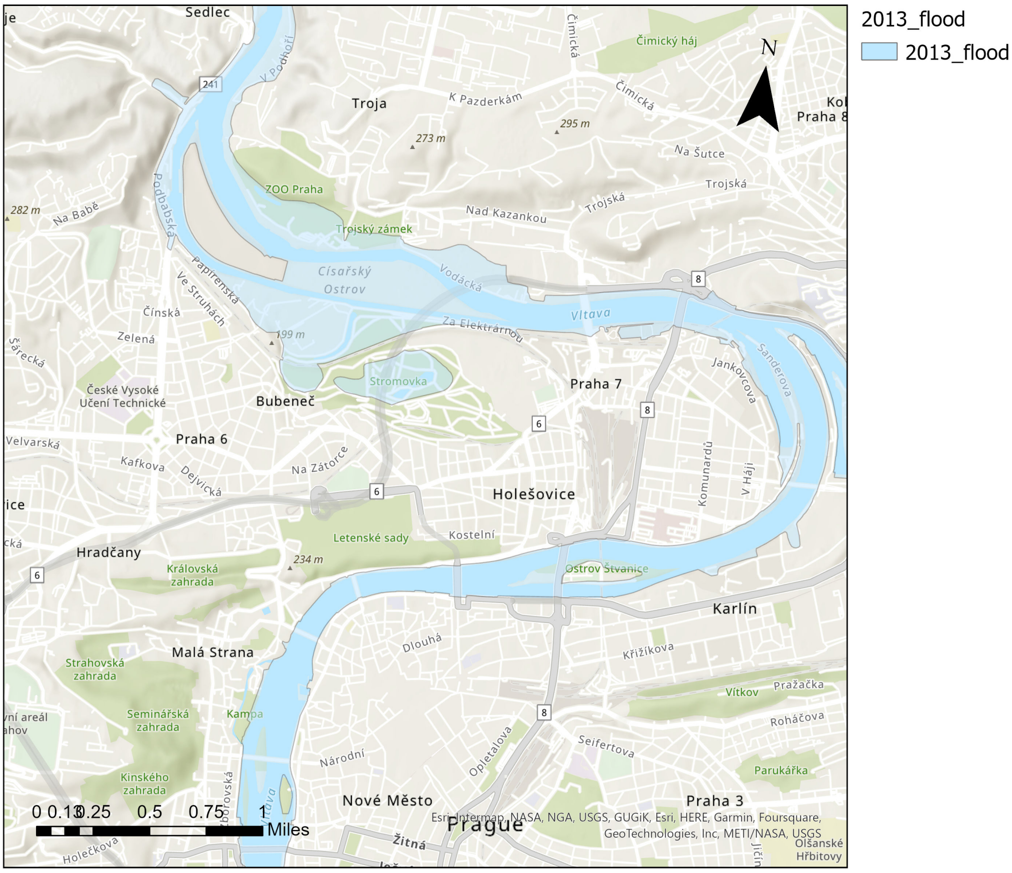


Figure 5.7: Flood Map showing Prague 6 and the Proposed Site

Summary of Data Collection

The proceeding sections describe data collection in the vicinity of the Vítězné náměstí roundabout. Data collection focused on understanding the current conditions of the roundabout (green areas, air quality, natural ventilation) and the potential demand related to stormwater (flooding, topography). As an integral part of the urban fabric in Prague 6, the roundabout receives considerable attention as an area of improvement. Three potential improvement scenarios are described and analyzed below.

Analysis Approach using i-Tree Eco

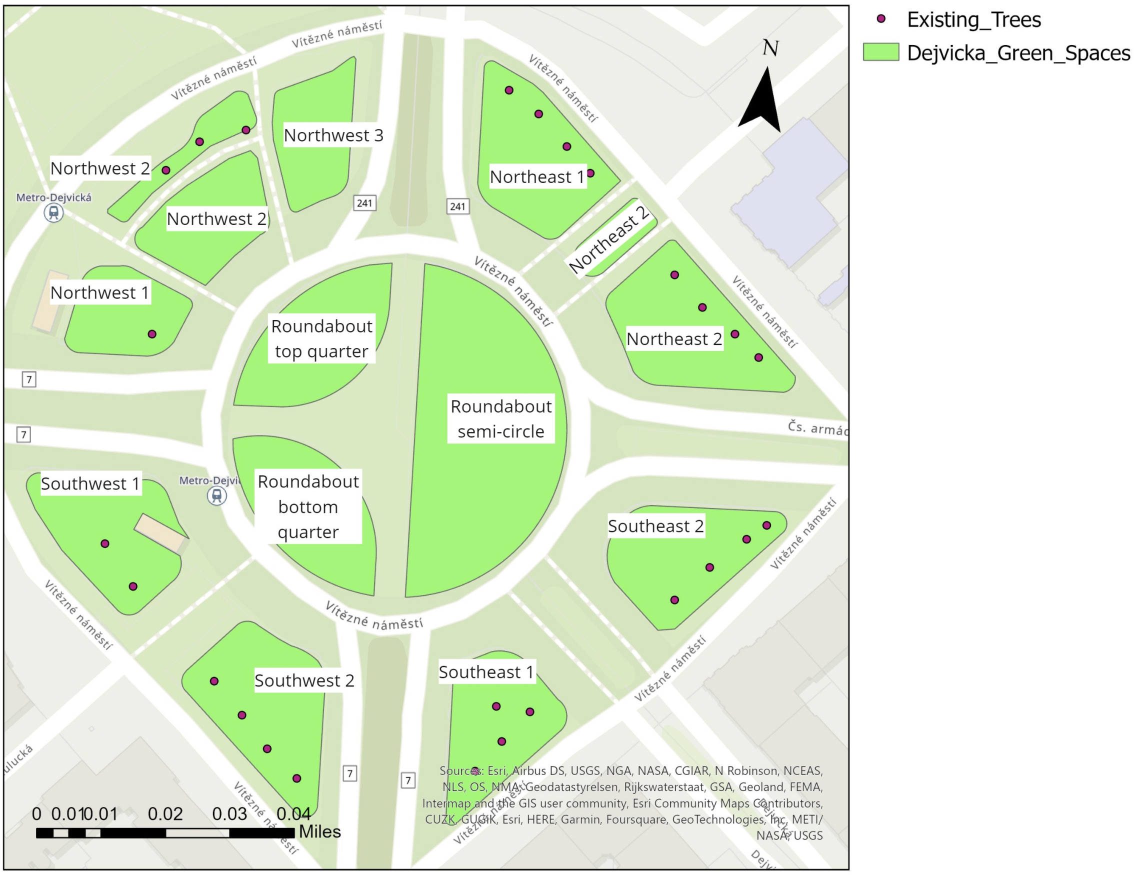
Three probable scenarios were created, which will be discussed in detail in the upcoming sections. Each scenario was modeled using i-Tree Eco, a free software tool developed by a public-private partnership alliance. There were several restrictions with respect to retrofitting the site that were consistent across the three scenarios. One of these restrictions, as previously mentioned, included underlying utilities and available spaces for change. Additionally, the scope of the site excluded the four quadrants surrounding the roundabout because they are frequently used by the community as lounging areas or to host events from local businesses.

i-Tree is a very useful tool for understanding the impact that trees have on a selected site with respect to pollution removal, carbon sequestration, precipitation interception, transpiration, potential evapotranspiration, among many other parameters.

Project setup in i-Tree Eco includes defining the location, pollution, and weather data year for the site. For this study, the most recent data available for pollution and weather was for 2015. Prices were also adjusted to the April 2023 exchange rate of Czech Crowns (CZK or Kc) to U.S. Dollars of 1 USD = 22 CZK.

A single tree inventory was conducted to obtain the height, width, diameter at breast height (DBH), percent dieback, species, and an estimation on how many sides of the tree receives sunlight. The green space plots, shown in Figure 5.8, were designated a number and an abbreviation describing their orientation such as northwest 1 (NW1), northwest 2 (NW2) and so on. The inner circle of the roundabout was separated into sections: semi-circle; top quarter; bottom quarter. Each tree was then assigned to its respective plot number. In addition, land use information was implemented in this model, such as a park or transportation site. In this model, a combination of both was included, parks being designated to the green spaces accessible by the public and transportation site to the spaces unreachable or undesirable as recreational area by the public.

The results derived from the i-Tree Eco program showed a variety of impacts and benefits.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, CUZK, GUGiK, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

Figure 5.8: Labeled Green Spaces at the Proposed Site

For example, the program offers a forecast option which predicts the effects of site changes over a 30 year period. However, an annual cost report on costs and benefits is sufficient for this research. The model outputs that were leveraged were carbon sequestration, storm water runoff reduction, and pollution removal. The reliability of the results is contingent on the accurate identification of species of the existing trees, which was completed to the best of the author's abilities.

Scenario 1 - Existing Site

Scenario 1 will represent the existing roundabout site, which includes 26 trees, a total area of about 12,600 squared feet or 1.17 hectares, and grass and bare soil ground covers. The following subsections will display the results obtained from i-Tree Eco.

Annual Net Carbon Sequestration

The following, Figure 5.9, describes the annual net carbon sequestration of the existing site by stratum or plot. As seen on Figure 5.8, plot Northeast 1 (NE 1) contains 4 trees. Plot Northeast 2 (NE 2) has the same amount of trees but there is a difference is carbon sequestration due to different factors such as species type and tree height. The plots with little to no trees (e.g., NW3, Roundabout bottom-quarter, top-quarter, and semi-circle) have no significant carbon sequestration. Based on the i-Tree report and the graph in Figure 5.9, the annual net carbon sequestration for scenario 1 is about 0.4 tons or 806 pounds. This amount correlates to approximately 1.63 thousand CZK.

Hydrology Effects

Figure 5.10 shows the gallons per year of various hydrology effects of trees only. The effects of any grass cover or shrubs is included in the i-Tree output. There is a clear difference in gallons per year between similar plots. According to i-Tree reports, water interception is defined by water absorbed by leaves, branches, and forest floor. Whatever isn't intercepted is free to flow through the ground soil or may eventually become runoff. While trees intercept precipitation, their roots systems promote infiltration and storage in soil. The avoided runoff

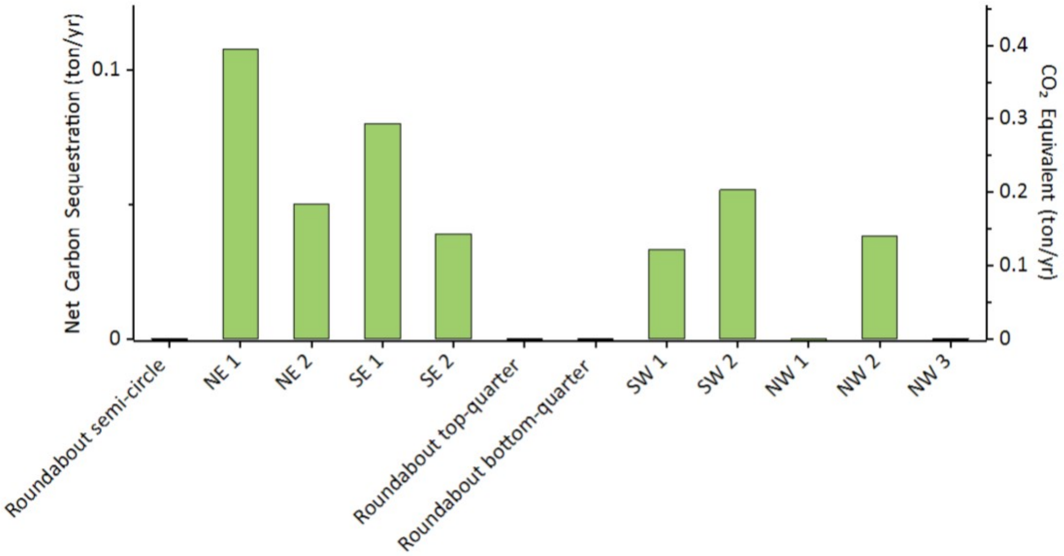
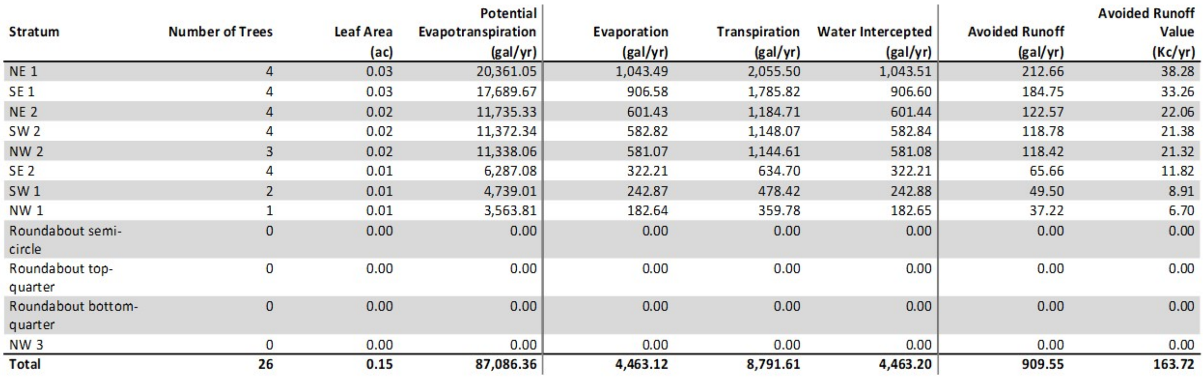


Figure 5.9: Scenario 1 - Annual Net Carbon Sequestration

is the difference between the water intercepted by the trees in this site (scenario 1) from a site with no trees or vegetation, leaving as a result a reduction of surface water runoff. Evapotranspiration is a combined process of both evaporation and transpiration. Note that transpiration and evaporation happen at different rates depending on leaf area, humidity, and sun exposure. During 2015, the annual precipitation was about 15 inches, according to i-Tree Eco. Currently, the annual absorption in storm water runoff of trees is about 909.6 gallons with an associated monetary value of 163 CZK.



Stratum	Number of Trees	Leaf Area (ac)	Potential Evapotranspiration (gal/yr)	Evaporation (gal/yr)	Transpiration (gal/yr)	Water Intercepted (gal/yr)	Avoided Runoff (gal/yr)	Avoided Runoff Value (Kc/yr)
NE 1	4	0.03	20,361.05	1,043.49	2,055.50	1,043.51	212.66	38.28
SE 1	4	0.03	17,689.67	906.58	1,785.82	906.60	184.75	33.26
NE 2	4	0.02	11,735.33	601.43	1,184.71	601.44	122.57	22.06
SW 2	4	0.02	11,372.34	582.82	1,148.07	582.84	118.78	21.38
NW 2	3	0.02	11,338.06	581.07	1,144.61	581.08	118.42	21.32
SE 2	4	0.01	6,287.08	322.21	634.70	322.21	65.66	11.82
SW 1	2	0.01	4,739.01	242.87	478.42	242.88	49.50	8.91
NW 1	1	0.01	3,563.81	182.64	359.78	182.65	37.22	6.70
Roundabout semi-circle	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roundabout top-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roundabout bottom-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NW 3	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**26**	**0.15**	**87,086.36**	**4,463.12**	**8,791.61**	**4,463.20**	**909.55**	**163.72**

Figure 5.10: Scenario 1 - Hydrological Effects

Pollution Removal

Figure 5.11 shows pollution removal within the first year. The current amount of pollution removal is about 9 pounds per year, with an associated value of 1.47 thousand CZK.

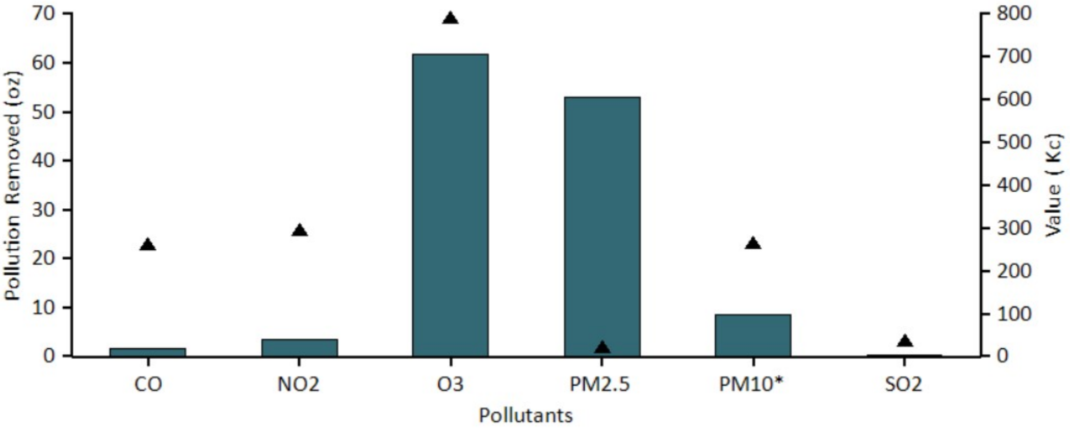


Figure 5.11: Scenario 1 - Pollution Removal over the First Year

Scenario 1 serves as a baseline scenario which is compared to Scenarios 2 and 3.

Scenario 2 - GI Site and Same Number of Trees

Scenario 2 consists of the same number of trees due to the limitation or restrictions previously mentioned with utility lines, and concerns with driver visibility. Besides grass and bare soil ground cover, this scenario also contains herbs and duff/mulch. Changes will be mostly applied to the roundabout semi-circle, top quarter and bottom quarter. Shrubs are a viable option to increase biomass without adversely impacting driver visibility. Therefore, a total of 16 shrubs are considered in this scenario. Integrating native vegetation is preferable due to their adaptation. However, resilient species to adverse conditions, such as high salinity levels in runoff, are viable. For example, there are native species to Europe that are adapted to chemicals or salts spread on roadways. A variety of these species were identified in previous studies (Hasan Chowdhury and Sujoun Lasker, 2018). The specific grass species were not available as inputs for i-Tree Eco, however.

Annual Net Carbon Sequestration

Figure 5.12 shows a similar carbon sequestration magnitude to scenario 1. This is expected because scenario 1 and scenario 2 have similar numbers of trees which drive this metric. Shrubs will have only a small impact on air pollution impacts because they have significantly less biomass. The total amount of carbon sequestration in one year is about 0.4 tons or 806 pounds. Its equivalent monetary value 1.63 thousand CZK.

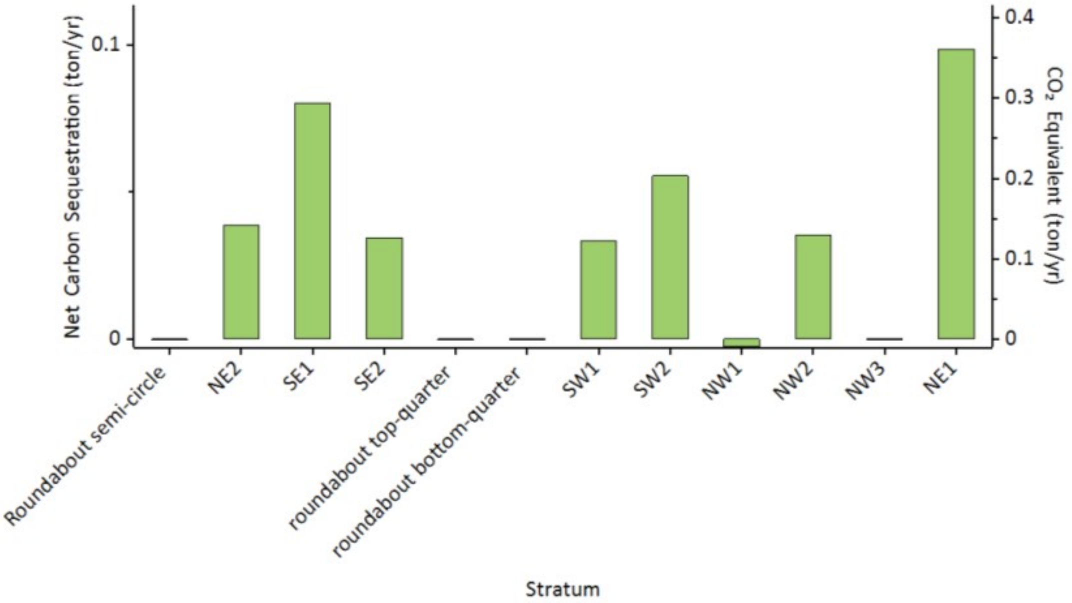
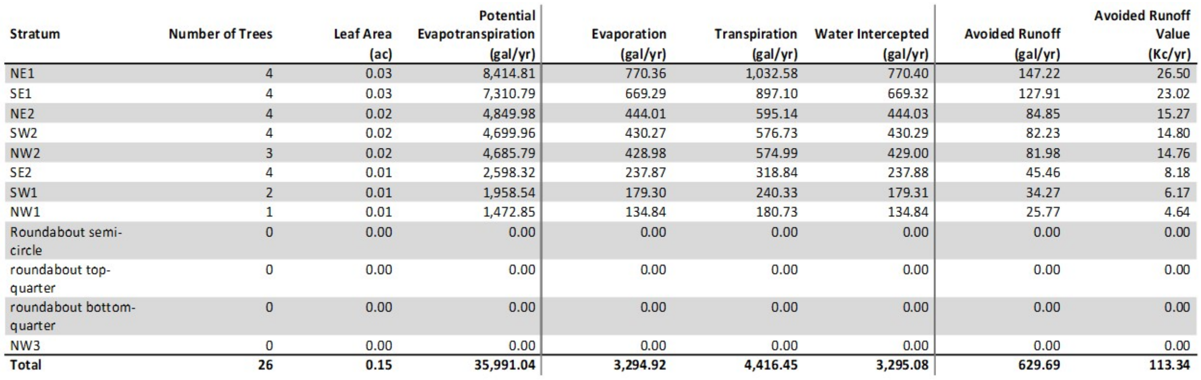


Figure 5.12: Scenario 2 - Annual Net Carbon Sequestration

Hydrology Effects

Figure 5.13 contains calculations for the hydrology effects of scenario 2. There is an unexpected decrease in all values compared to scenario 1. According to the information provided by i-Tree, these tables represent the avoided runoff by trees only. Therefore, this can be interpreted as the trees at the site absorbing less water due to the added shrubs. Evapotranspiration and the other similar characteristics, evaporation, transpiration, and interception, can be explained by many complicated environmental factors. According to the U.S. Geological Survey, ”the more important factors include net solar radiation, surface area of open bodies of water, wind speed, density and type of vegetative cover, availability of soil moisture, root depth, reflective land-surface characteristics, and season of year” (Hanson, 1991). In addition, available soil moisture and vegetation maturity also affects this process. This information correlates to scenario 2 because of the supplementary vegetation. The annual reduction in storm water runoff for both trees and shrubs, according to the written report in i-Tree, in scenario 2 is 1.18 thousand gallons with an associated value of 210 CZK. Water absorption in scenario 2 showed positive improvements compared to scenario 1. The minimal vegetation increase in scenario 2 improved the site by about 30 percent. Its important to keep in mind that these calculations are only the effects of trees/vegetation and do not include bioswale impacts. Therefore, we can expect water reduction to increase if bioswales are implemented. Unfortunately, i-Tree Eco does not have the capacity to calculate the effects of bioswales.



Stratum	Number of Trees	Leaf Area (ac)	Potential Evapotranspiration (gal/yr)	Evaporation (gal/yr)	Transpiration (gal/yr)	Water Intercepted (gal/yr)	Avoided Runoff (gal/yr)	Avoided Runoff Value (Kc/yr)
NE1	4	0.03	8,414.81	770.36	1,032.58	770.40	147.22	26.50
SE1	4	0.03	7,310.79	669.29	897.10	669.32	127.91	23.02
NE2	4	0.02	4,849.98	444.01	595.14	444.03	84.85	15.27
SW2	4	0.02	4,699.96	430.27	576.73	430.29	82.23	14.80
NW2	3	0.02	4,685.79	428.98	574.99	429.00	81.98	14.76
SE2	4	0.01	2,598.32	237.87	318.84	237.88	45.46	8.18
SW1	2	0.01	1,958.54	179.30	240.33	179.31	34.27	6.17
NW1	1	0.01	1,472.85	134.84	180.73	134.84	25.77	4.64
Roundabout semi-circle	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
roundabout top-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
roundabout bottom-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NW3	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**26**	**0.15**	**35,991.04**	**3,294.92**	**4,416.45**	**3,295.08**	**629.69**	**113.34**

Figure 5.13: Scenario 2 - Hydrological Effects

Pollution Removal

The bar graph in Figure 5.14 shows a slightly higher absorption for particulate matter less than 2.5 microns (PM2.5) as opposed to ozone (O3). This is due to the small increase in biomass. Scenario 2 removes about 11 pounds per year of air pollutants in total, with an associated value of 2.2 thousand CZK. This scenario shows an improvement by about 22 percent in comparison to scenario 1.

Scenario 3 - GI Site and Additional Trees

Scenario 3 will be similar to the two previous ones, with the addition of 18 more trees dispersed not only in the inner circle of the roundabout but also on the surrounding green spaces. This scenario also includes the same amount of shrubs considered for scenario 2. Since

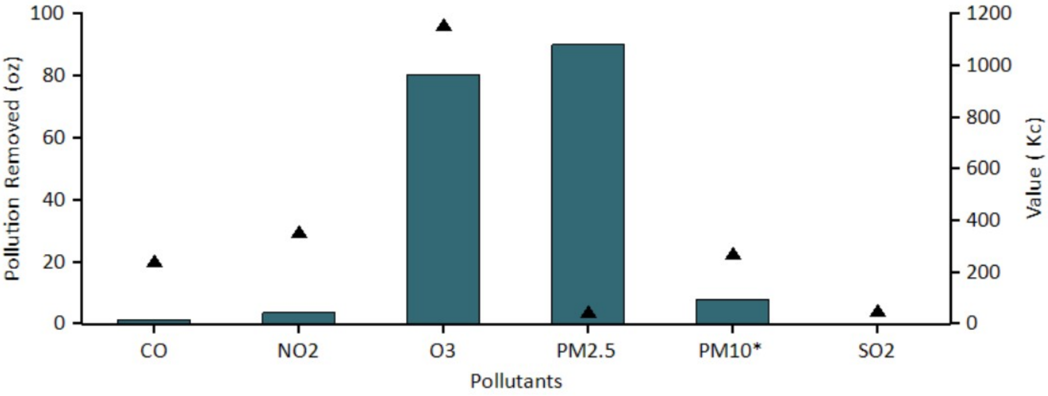


Figure 5.14: Scenario 2 - Pollution Removal

driver's visibility is an important acknowledged restraint, there are native trees that grow fairly short which have great potential for this site . For example, hedge maple (acer campestre) grow to about 8 to 10 feet in height. The following sections will discuss their impact and improvement to the site.

Annual Net Carbon Sequestration

Figure 5.15 shows the annual net carbon sequestration with the additional 18 trees to the site. It is clear that carbon sequestration increased since plots that didn't have trees originally now contain more biomass. Scenario 3 has a net carbon sequestration of 0.46 tons per year or 917 pounds per year, with an equivalent monetary value of about 1.97 thousand CZK. Scenario 3, therefore, presents an improvement by about 14 percent compared to both scenario 1 and 2 with respect to carbon sequestration.

Hydrology Effects

According to output from i-Tree Eco, the water reduction for both trees and shrubs in scenario 3 is at an estimated 1.33 thousand gallons per year. This amount has an associated value of 240 CZK. Therefore, it improves the site by about 46 percent compared to scenario 1, and by about 13 percent compared to scenario 2. As mentioned in scenario 2, water reduction can be expected to increase with the implementation of bioswales. Figure 5.16 shows the hydrology effect results for scenario 3.

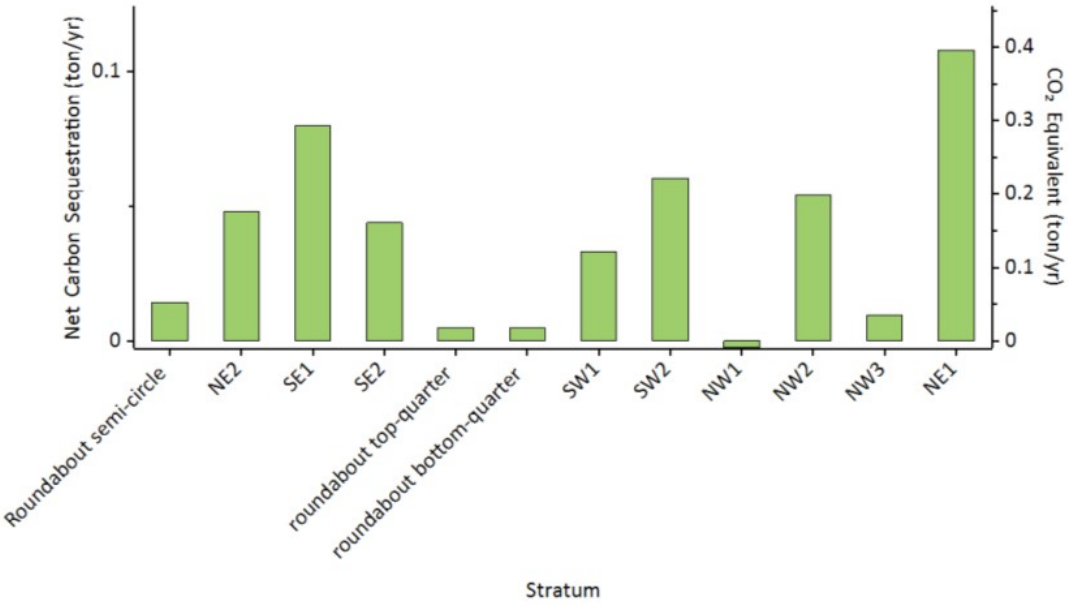
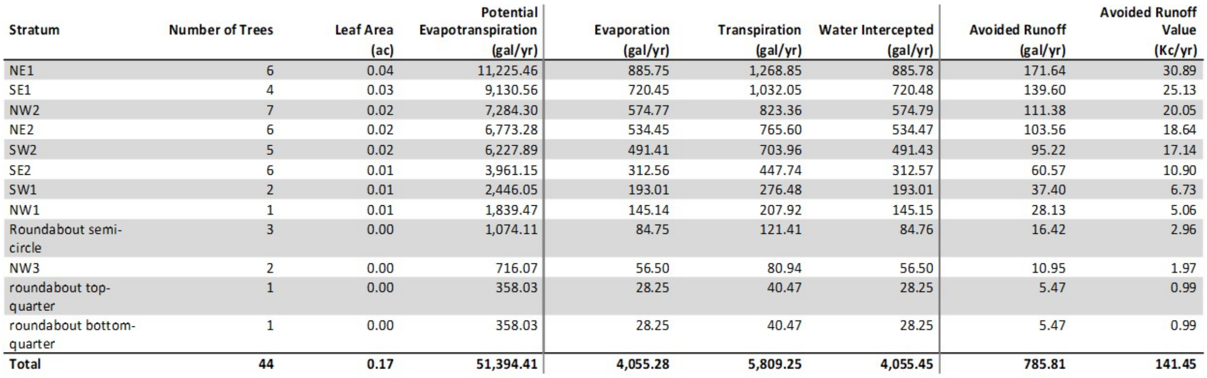


Figure 5.15: Scenario 3 - Annual Net Carbon Sequestration



Stratum	Number of Trees	Leaf Area (ac)	Potential Evapotranspiration (gal/yr)	Evaporation (gal/yr)	Transpiration (gal/yr)	Water Intercepted (gal/yr)	Avoided Runoff (gal/yr)	Avoided Runoff Value (Kc/yr)
NE1	6	0.04	11,225.46	885.75	1,268.85	885.78	171.64	30.89
SE1	4	0.03	9,130.56	720.45	1,032.05	720.48	139.60	25.13
NW2	7	0.02	7,284.30	574.77	823.36	574.79	111.38	20.05
NE2	6	0.02	6,773.28	534.45	765.60	534.47	103.56	18.64
SW2	5	0.02	6,227.89	491.41	703.96	491.43	95.22	17.14
SE2	6	0.01	3,961.15	312.56	447.74	312.57	60.57	10.90
SW1	2	0.01	2,446.05	193.01	276.48	193.01	37.40	6.73
NW1	1	0.01	1,839.47	145.14	207.92	145.15	28.13	5.06
Roundabout semi-circle	3	0.00	1,074.11	84.75	121.41	84.76	16.42	2.96
NW3	2	0.00	716.07	56.50	80.94	56.50	10.95	1.97
roundabout top-quarter	1	0.00	358.03	28.25	40.47	28.25	5.47	0.99
roundabout bottom-quarter	1	0.00	358.03	28.25	40.47	28.25	5.47	0.99
Total	**44**	**0.17**	**51,394.41**	**4,055.28**	**5,809.25**	**4,055.45**	**785.81**	**141.45**

Figure 5.16: Scenario 3 - Hydrology Effects

Pollution Removal

Scenario 3 is estimated to be able to remove 12.42 pounds per year of air contaminants, as shown in the following graph, Figure 5.17. The associated monetary value is 2.36 thousand CZK. Similarly to scenario 2, there's a slightly higher absorption for particulate matter less than 2.5 microns (PM2.5) compared to ozone (O3). Nevertheless, the pollution removal in scenario 3 is slightly increased by about 38 percent in comparison to scenario 1, and by 13 percent compared to scenario 2.

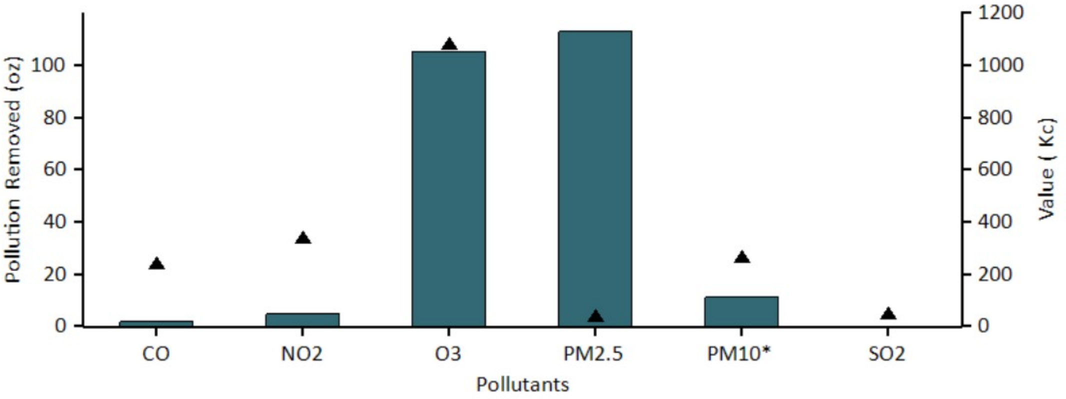


Figure 5.17: Scenario 3 - Pollution Removal

Results from Prague Case Study on Scenario Comparison

As previously discussed, the criteria used to compare results from each scenario were carbon sequestration, runoff reduction, and pollution removal. These factors were selected due to their impact on air quality,storm water management, and atmospheric temperature. The following Table 5.1 shows a value comparison of all scenarios. Its important to acknowledge that the full watershed increase with bioswale technology was not considered in these results, but the main purpose of improving air quality was attainable. There is a variety of impacts that i-Tree Eco estimated, however, they are not shown in this report because they were not necessary to understand the vegetation's effects. Nevertheless, a full copy of the individual scenarios can be found in Appendix A, Appendix B, and Appendix C. The following table summarizes the impacts discussed in the previous sections.

Scenario	Net Carbon Sequestration (lbs/yr)	Runoff Reduction (gal/yr)	Pollution removal (lbs/yr)	Total savings (CZK)
1 (existing site)	806	910	9	3,263
2	806	1,180	11	4,040
3	917	1,330	13	4,570

Table 5.1: Summarized Impacts of Scenarios.

Chapter 6: Discussion of Results

Discussion of El Paso Case Study on Site Selection

The case study for site selection in El Paso, TX, presented in Chapter 4, compared five specific sites for their adequacy as GI sites. This comparison was the first phase of two in the proposed methodology to assess the suitability of site for GI installation. The process included identification of data sources, quantification of each data source, and comparison using AHP.

Suitability of the Approach to Selection of Sites

This case study was presented as an example of the approach. The results indicate that the proposed methodology was an effective approach to rank sites for GI suitability. The study was not without limitations which, if addressed, could make the approach substantially better.

There are certainly use cases where a select number of sites may be compared. However, from a city or municipal perspective, exploring this data in a continuous fashion is likely to be more effective for understanding where GI may be most effective. This would lend itself to city wide mapping of the data identified in the case study.

One way in which the localized approach employed here falls short is through 1 to 1 comparisons across sites. Since the sites are all over different lengths, it is difficult to directly compare. For example, a long site may have an average pavement condition index value that is higher than a shorter site. However, within that long site there may be an area of pavement that is both larger than the shorter site and exhibits a lower pavement condition score that is simply masked by the larger site.

This issue can be addressed through a unit quantification of GI suitability through an index. That would require discretization of the entire right-of-way into equal sized units and calculation of a suitability index for each unit. Future iterations of this work may adopt this approach, but it is beyond the scope of this work.

Additionally, the AHP procedure allows for input from a variety of stakeholders to inform parameter ranks. This flexibility is present, but was not explored in this work. The values used for AHP were set by the author.

Discussion of Prague Case Study on Scenario Comparison

This case study for comparison of GI approaches within a single site in Prague, CR, was presented in Chapter 5. It was the second phase of two in a methodology to assess site suitability for GI installations. The process included conducting a site survey of the current tree canopy and vegetation, creating multiple scenarios for increasing vegetation on the site to improve air quality, among other parameters, and conducting analyses in i-Tree Eco to estimate improvements in the these parameters due to site improvements.

In a relative sense, the analysis demonstrated that effectiveness of increasing tree canopy in particular. It also demonstrated that smaller bushes and shrubs are much less effective than trees for improving air quality and stormwater metrics.

Suitability of the Approach to Single Site Comparison

The approach to single site comparison was limited in that the selected tool, i-Tree Eco, is limited to the effects of vegetation. The addition of GI elements like bioswales was not explicitly considered. Bioswales are often assessed in terms of how well they improve water quality as opposed to the volume of water retained, which is a function of design. The former is not the focus of this work. Since creating unique GI designs was beyond the scope of this work as well, it was not possible to assess their effects in addition to changes in vegetation.

One approach to addressing this shortfall would be to develop an estimate of bioswale (or other GI implementation) effectiveness based on square footage of available area. In other words, one could estimate what percentage of total square footage can practically be dedicated to bioswale installations based on existing GI installations. For example, if one area of the Prague site was approximately 1000 square feet, and the estimate for practical area of bioswale was 65 percent then it would be safe to assume that the total area of bioswale could be 650 square feet. Given that, it would be possible to estimate improvements in storm water management.

Additionally, this work did not consider any changes to the watershed. As an example, the Prague site was considered only relative to the existing green areas. Currently, there are storm water inlets around the circumference of the roundabout that tie into the existing gray infrastructure network. However, with the addition of GI, the whole roundabout could potentially leverage the GI for storm water management of a larger watershed area.

The upshot is that this approach is more effective when more information is available. Therefore it is effective as a comparison between site scenarios when the data available for each scenario is of consistent quality and depth.

Discussion of GI in a Smart Cities Context

GI is an inherently passive approach to managing storm water and improving air quality. The main driver behind this work was to quantify these benefits so that informed decisions about GI were possible. This passivity distinguishes GI from most Smart Cities approaches, which are inherently active processes, owing to the reliance on sensors.

It is certainly possible to integrate sensors into a GI installation. Simple ultrasonic sensors could detect the presence of and depth of water in a bioswale. Other sensors can measure flowrate. Temperature, particulate, and other air quality sensors are available. Given this, it is certainly possible to make an existing GI site ”smart.”

This work is focused on using data to identify sites that would be excellent candidates for GI. This is inherently a Smart Cities approach as well, but it is somewhat non-traditional. Perhaps more directly, the results of a well designed and located GI installation contributes to a smart city by improving quality of life for residents, by more effectively utilizing public funding to manage infrastructure assets, and by sustainably managing natural resources in urban areas. This deviation from a sensor-centric approach to a performance-based, outcome-focused approach aligns with the direction in which Smart Cities is heading.

Chapter 7: Conclusions and Future Work

This chapter will briefly summarize the results discussed in chapter 6 along with some recommendations for the site. Furthermore, another section will describe what challenges were overcome throughout calculating the results. Finally, future work will describe what factors of this research could be improved for quantifying impacts of a GI site.

Summary of results

The results discussed in Chapter 6 indicate that adding vegetation to the round about site improves the existing conditions. However, these effects are significantly noticeable with the incorporation of tree. Shrubs and grass covers have some impact, but not very noticeable. As seen on Table 5.1, scenario 3 is the most beneficial scenario due to the incorporation of both trees and shrubs. Scenario 3 also saves about 4.57 thousand CZK with respect to carbon sequestration, hydrology effects, and pollution removal. However, if the addition of more trees isn't desirable or feasible, additional shrubs can be an option to somewhat improve storm water management as seen on scenario 2. Implementing this method would save the municipality about 4.04 thousand CZK, according to the i-Tree Eco reports.

Challenges

There were several challenges that came across during the data collection phase and the results phase. When collecting data from the municipality's website, some available sources were only in Czech and therefore, difficult to translate or understand. Other data sources were not available in open data or needed permission, which was never obtained due to poor communication and the language barrier. There was also a learning curve when it came to selecting a suitable model for this research. Although, many models or software programs are available in the internet, several of them turned out to not meet the requirements of the study. In addition, some models were only suitable for areas in the United States because of the data already existing or integrated in the program. Finally, when it came to using i-Tree Eco, identification of tree species was an important aspect of the tree inventory or the data collection phase. The tree species in the site were identified to the best of the author's ability and the reliability of resources on the internet.

Future Work

The sought out watershed data/models, like i-Tree Hydro, were not available for this area. As previously acknowledged in chapter 6, we can expect storm water management and reduced storm water runoff to occur with the implementation of bio-swales. Of course, retention rates would need to be analyzed in future work through another model or program perhaps. To accomplish an effective water retention system for the roundabout, storm water inlets, which can already be found in the outer edges, can be incorporated into the design. In other words, a link between inlets and bio-swales may be necessary, without disregarding the high current utilities. Although, this design implementation poses as a difficult task, it would be greatly beneficial to the efficiency and functionality of the GI system.

Recommendations

As verified on many research reports, including this one, GI has the capacity of accomplishing environmental improvements. Although, the quantified results found in this study specifically were very minimal, there is great potential for the incorporation of bio-swales to maximize the full benefits of GI. These results can also be incremented by incorporating GI more consistently throughout the city of Prague. A single site may not show a significant improvement and solve all the city's issues, but dispersing this infrastructure can lead to greater impacts. Furthermore, models like i-Tree Eco can assist stakeholders or city planners in making and designing a GI site by understanding naturally based solutions.

References

(2020, Mar). Green values strategy guide: Linking green infrastructure benefits to community priorities.

Baldauf, R. (2016, Jul). Recommendations for constructing roadside vegetation barriers to improve near-road air quality. *U.S. Environmental Protection Agency*.

Baránek, T. and A. Kurzok (2023). Czech republic air quality index (aqi) and air pollution information.

Copernicus (2014). Carbon dioxide forecasts.

Crncevic, T., L. Tubic, and O. Bakic (2017). Green infrastructure planning for climate smart and "green" cities. *Spatium* (38), 35–41.

Currie, B. A. and B. Bass (2008). Estimates of air pollution mitigation with green plants and green roofs using the ufore model. *Urban Ecosystems 11*(4), 409–422.

Environmental Protection Agency, U. S. (2022). Green infrastructure modeling tools.

Gallet, D. (2011). The value of green infrastructure: A guide to recognizing its economic, environmental and social benefits. *Proceedings of the Water Environment Federation 2011*(17), 924–928.

Hanson, R. L. (1991). Evapotranspiration and droughts.

Hasan Chowdhury, M. and M. Sujoun Lasker (2018). Roadside landscaping with native plants in the czech republic: A review. *Horticulture International Journalnbsp; 2*(3).

Institute, T. W. (2020). What is a smart city? – definition and examples.

Jarden, K. M., A. J. Jefferson, and J. M. Grieser (2015). Assessing the effects of catchment-scale urban green infrastructure retrofits on hydrograph characteristics. *Hydrological Processes 30*(10), 1536–1550.

Kaluarachchi, Y. (2020). Potential advantages in combining smart and green infrastructure over silo approaches for future cities. *Frontiers of Engineering Management 8*(1), 98–108.

MacAdam, J., T. Syracuse, J. DeRoussel, K. Roach, A. Denomy, D. Alexander, and L. Ignatowski (2012). *Green Infrastructure for Southwestern Neighborhoods*. Watershed Management Group.

McEnchroe, T. (2020, Sep). Czechs used up more water than last year.

Mingjiang, T. and R. B. Mallick (2019).

Muvuna, J., T. Boutaleb, S. B. Mickovski, K. Baker, G. S. Mohammad, M. Cools, and W. Selmi (2020). Information integration in a smart city system—a case study on air pollution removal by green infrastructure through a vehicle smart routing system. *Sustainability 12*(12), 5099.

Noll, C. (2015, Jun). where does our water come from....?

of City Transportation Officials, N. A. (2017). *Urban Street Stormwater Guide*. Island Press.

of Planning, I. and D. of Prague (2022). Bonita klimatu z hlediska přirozené ventilace území.

Praha, I. (2020). Digital technical map of prague.

Prostredi, P. Z. (2006). Wastewater.

Report, L. P. (2021, Mar). Prague's new blue-green infrastructure initiative.

Selmi, W., C. Weber, E. Rivière, N. Blond, L. Mehdi, and D. Nowak (2016). Air pollution removal by trees in public green spaces in strasbourg city, france. *Urban Forestry amp; Urban Greening 17*, 192–201.

Thales (2020). Secure, sustainable smart cities and the iot.

Vargas, R. V. (2010, Jan). Using the analytic hierarchy process (ahp) to select and prioritize projects in a portfolio.

Weidner, J., L. Castrejon, and R. L. Cheu (2022). Green transportation infrastructure in desert cities. *Center for Transportation, Environment, and Community Health*.

životního prostředí, P. (2019). Prague environment selected information.

Appendix A: Scenario 1

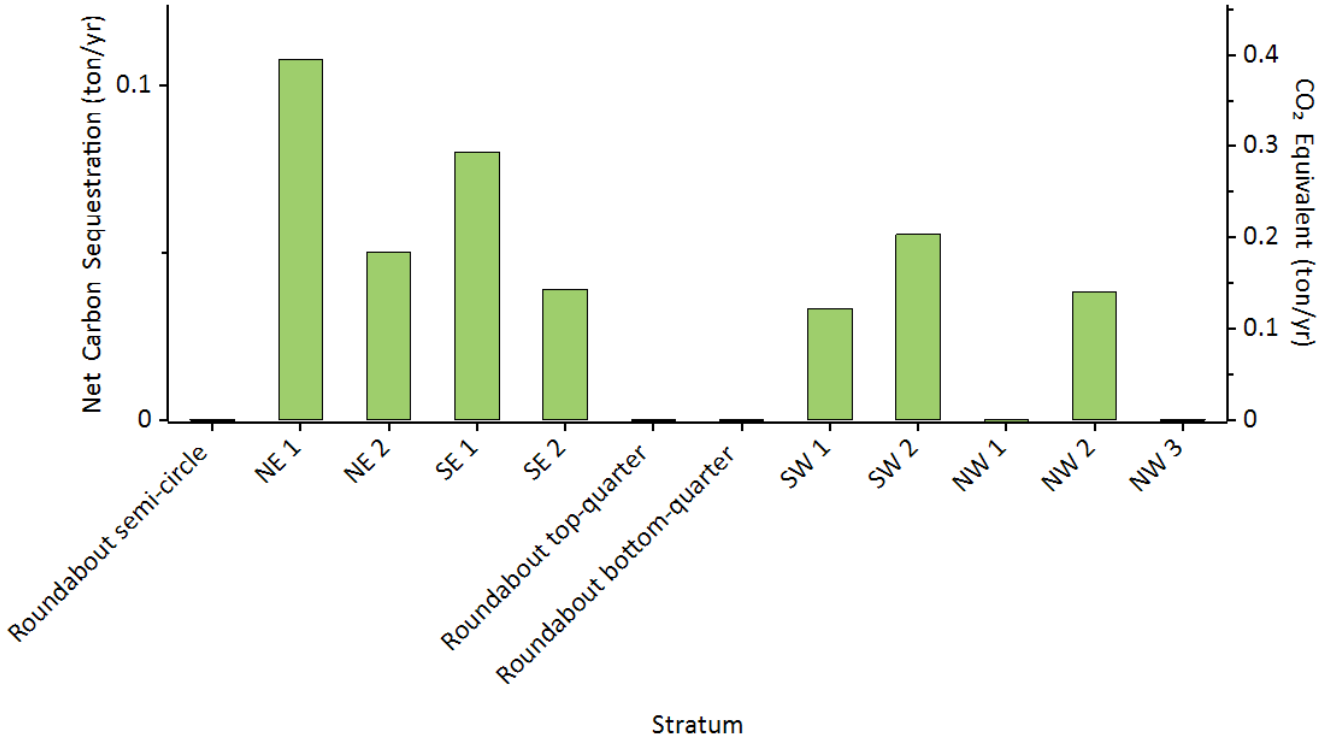
Annual Net Carbon Sequestration of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Roundabout before GI, Series: 2, Year: 2023
Generated: 4/24/2023

Stratum	Net Carbon Sequestration (ton/yr)	CO_2 Equivalent (ton/yr)
Roundabout semi-circle	0.00	0.00
NE 1	0.11	0.40
NE 2	0.05	0.18
SE 1	0.08	0.29
SE 2	0.04	0.14
Roundabout top-quarter	0.00	0.00
Roundabout bottom-quarter	0.00	0.00
SW 1	0.03	0.12
SW 2	0.06	0.20
NW 1	0.00	0.00
NW 2	0.04	0.14
NW 3	0.00	0.00
Study Area	**0.40**	**1.48**

Annual Net Carbon Sequestration of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Roundabout before GI, Series: 2, Year: 2023
Generated: 4/24/2023



Hydrology Effects of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Roundabout before GI, Series: 2, Year: 2023
Generated: 4/24/2023

Stratum	Number of Trees	Leaf Area (ac)	Potential Evapotranspiration (gal/yr)	Evaporation (gal/yr)	Transpiration (gal/yr)	Water Intercepted (gal/yr)	Avoided Runoff (gal/yr)	Avoided Runoff Value (Kc/yr)
NE 1	4	0.03	20,361.05	1,043.49	2,055.50	1,043.51	212.66	38.28
SE 1	4	0.03	17,689.67	906.58	1,785.82	906.60	184.75	33.26
NE 2	4	0.02	11,735.33	601.43	1,184.71	601.44	122.57	22.06
SW 2	4	0.02	11,372.34	582.82	1,148.07	582.84	118.78	21.38
NW 2	3	0.02	11,338.06	581.07	1,144.61	581.08	118.42	21.32
SE 2	4	0.01	6,287.08	322.21	634.70	322.21	65.66	11.82
SW 1	2	0.01	4,739.01	242.87	478.42	242.88	49.50	8.91
NW 1	1	0.01	3,563.81	182.64	359.78	182.65	37.22	6.70
Roundabout semi-circle	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roundabout top-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roundabout bottom-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NW 3	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**26**	**0.15**	**87,086.36**	**4,463.12**	**8,791.61**	**4,463.20**	**909.55**	**163.72**

Avoided runoff value is calculated by the price Kc0.180/gal. The user-designated weather station reported 14.8 inches of total annual precipitation. Eco will always use the hourly measurements that have the greatest total rainfall or user-submitted rainfall if provided.

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees in Roundabout before GI was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees remove 9.063 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5), particulate matter less than 10 microns and greater than 2.5 microns (PM10*)[2], and sulfur dioxide (SO2)) per year with an associated value of Kc1.47 thousand (see Appendix I for more details).

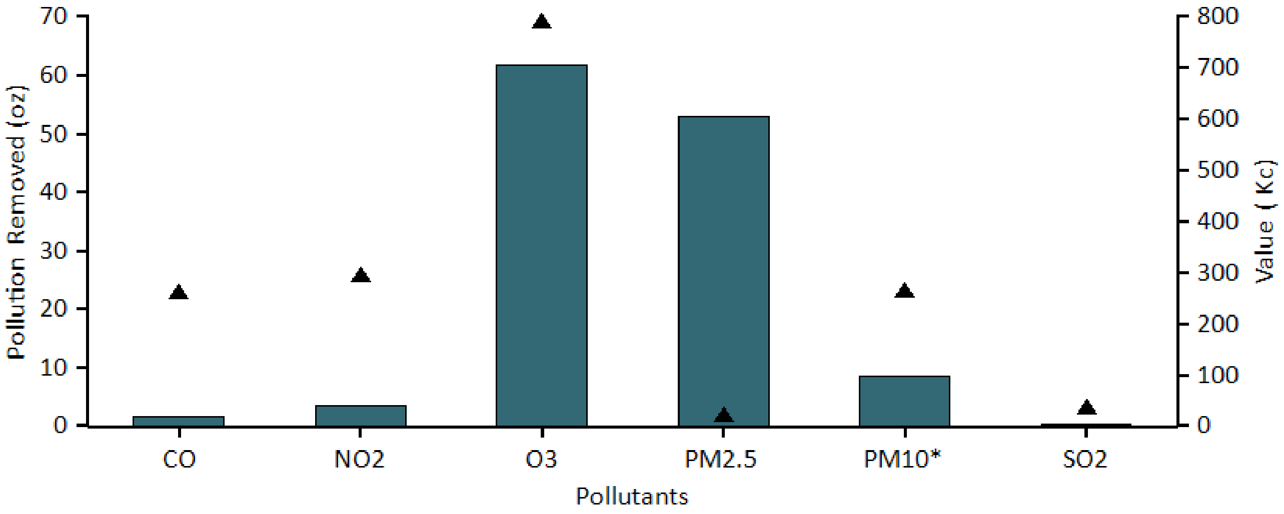


Figure 7. Annual pollution removal (points) and value (bars) by urban trees, Roundabout before GI

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[1] PM10* is particulate matter less than 10 microns and greater than 2.5 microns. PM2.5 is particulate matter less than 2.5 microns. If PM2.5 is not monitored, PM10* represents particulate matter less than 10 microns. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 and PM10* when particulate matter is deposited on leaf surfaces. This deposited PM2.5 and PM10* can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2023, trees in Roundabout before GI emitted an estimated 6.05 ounces of volatile organic compounds (VOCs) (4.42 ounces of isoprene and 1.63 ounces of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Seventy- four percent of the urban forest's VOC emissions were from Sycamore spp and Necklacepod spp. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

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[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Roundabout before GI trees is about 864.1 pounds of carbon per year with an associated value of Kc1.63 thousand. Net carbon sequestration in the urban forest is about 806.3 pounds. See Appendix I for more details on methods.

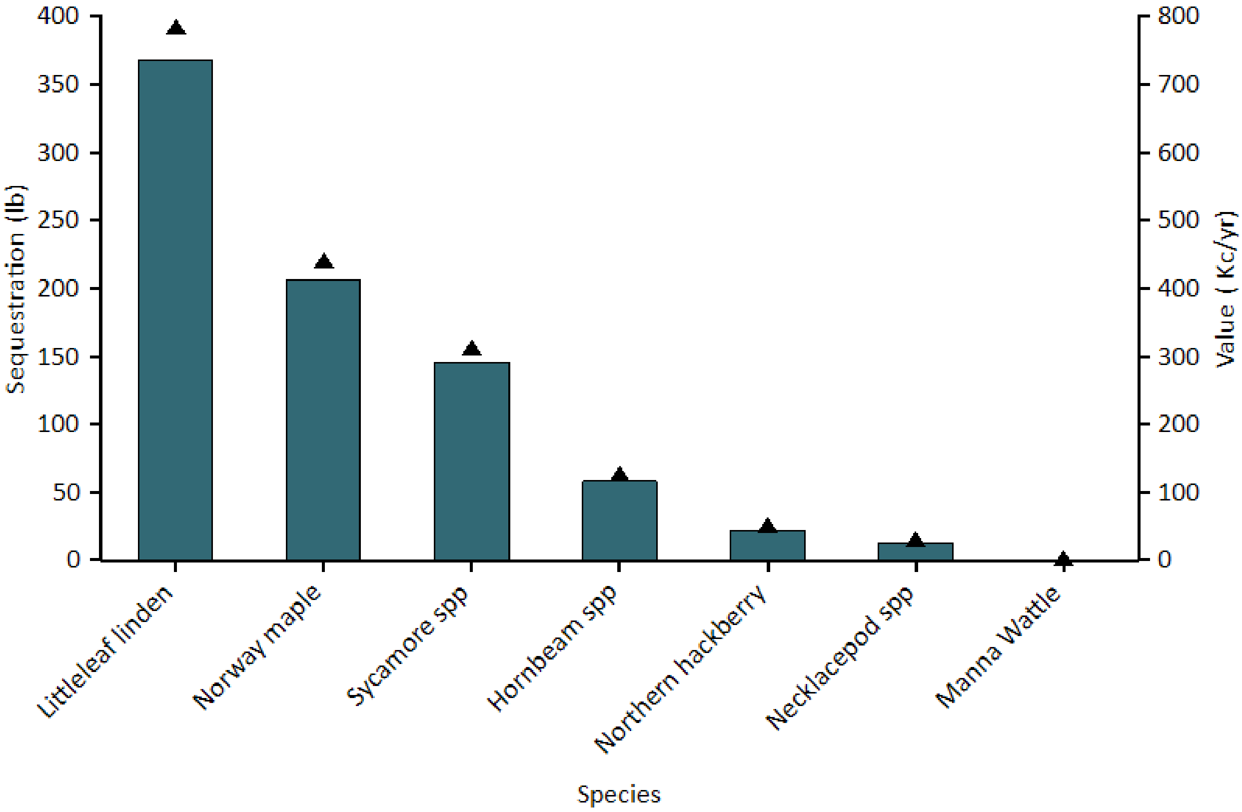

Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Roundabout before GI

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Roundabout before GI are estimated to store 31.2 tons of carbon (Kc117 thousand). Of the species sampled, Hornbeam spp stores the most carbon (approximately 34.2% of the total carbon stored) and Littleleaf linden sequesters the most (approximately 45.2% of all sequestered carbon.)

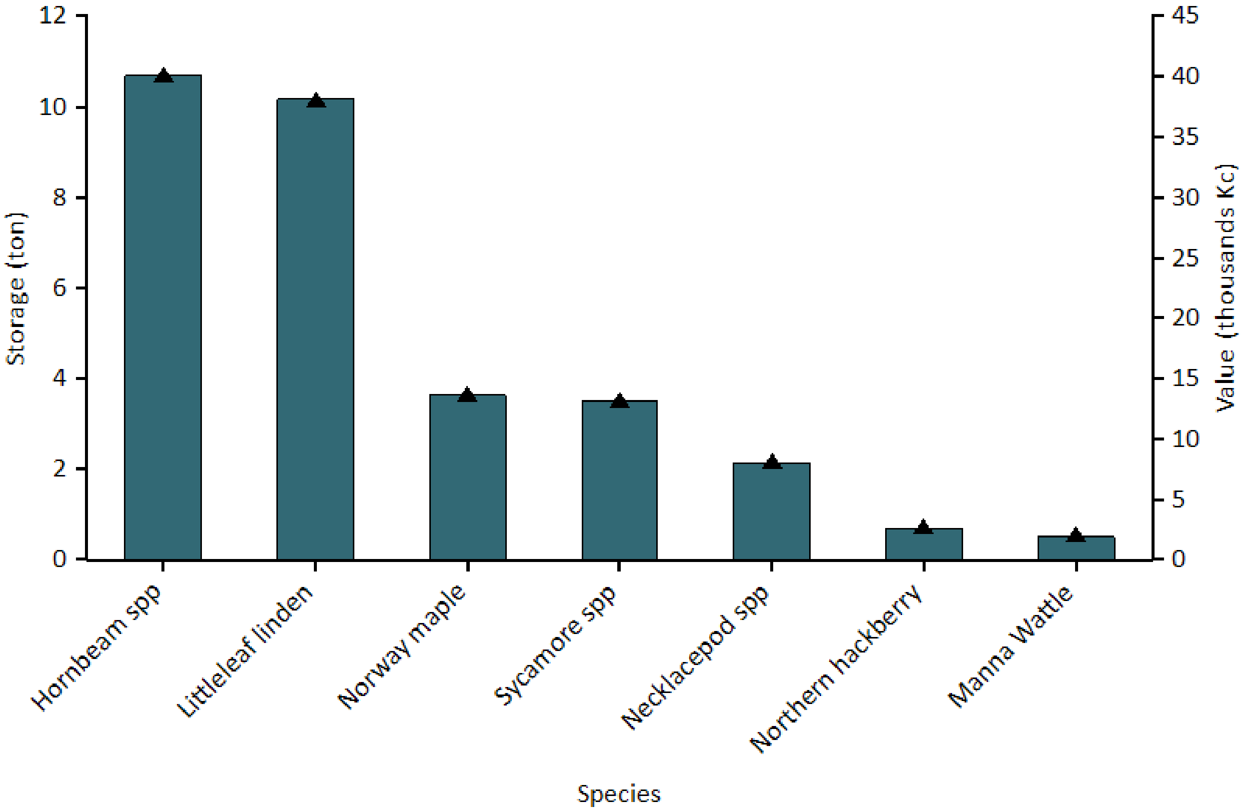

Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Roundabout before GI

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Roundabout before GI are estimated to produce 2150 pounds of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 7 oxygen production species.

Species	*Oxygen (pound)*	*Net Carbon Sequestration (pound/yr)*	*Number of Trees*	*Leaf Area (square feet)*
Littleleaf linden	987.21	370.20	8	0.00
Norway maple	570.82	214.06	3	0.00
Sycamore spp	389.85	146.19	4	0.00
Hornbeam spp	117.35	44.01	5	0.00
Northern hackberry	58.73	22.02	3	0.00
Necklacepod spp	29.39	11.02	2	0.00
Manna Wattle	-3.22	-1.21	1	0.00

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[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Roundabout before GI help to reduce runoff by an estimated 910 gallons a year with an associated value of Kc160 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Roundabout before GI, the total annual precipitation in 2015 was 14.8 inches.

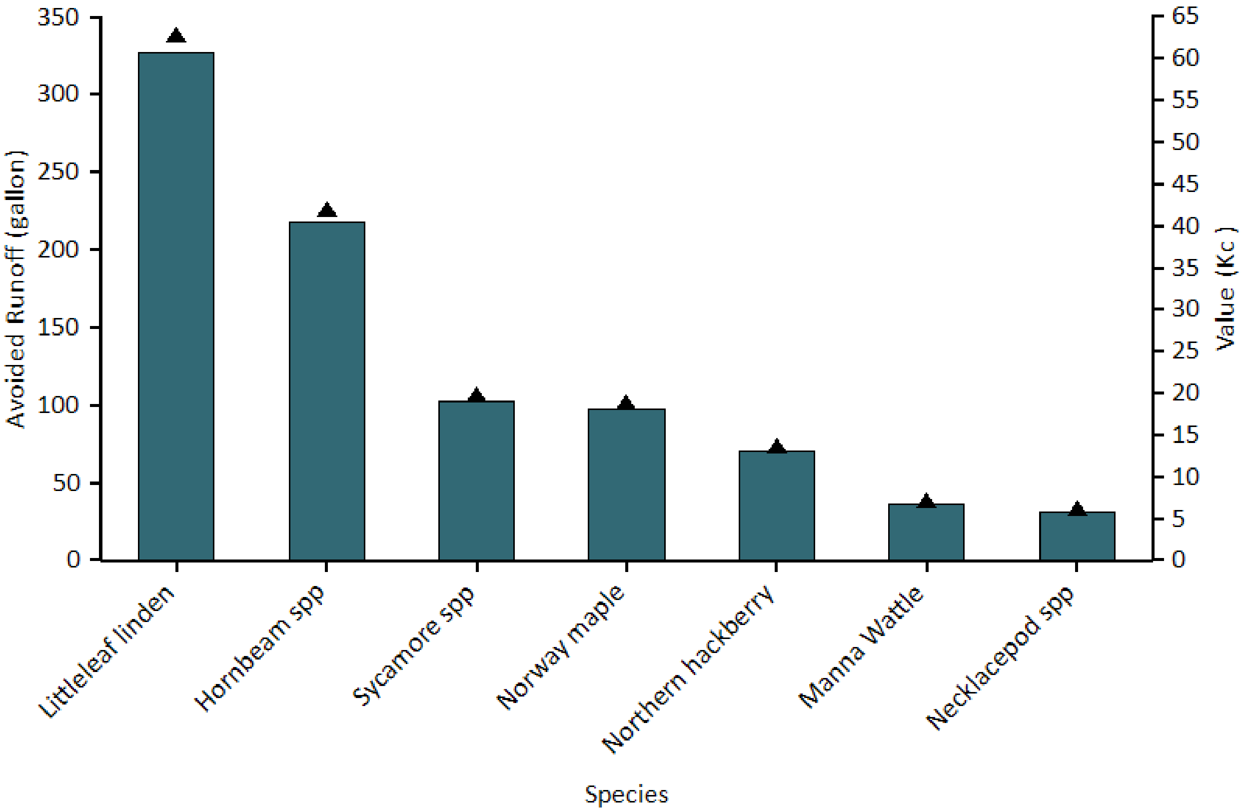


Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Roundabout before GI

Appendix B: Scenario 2

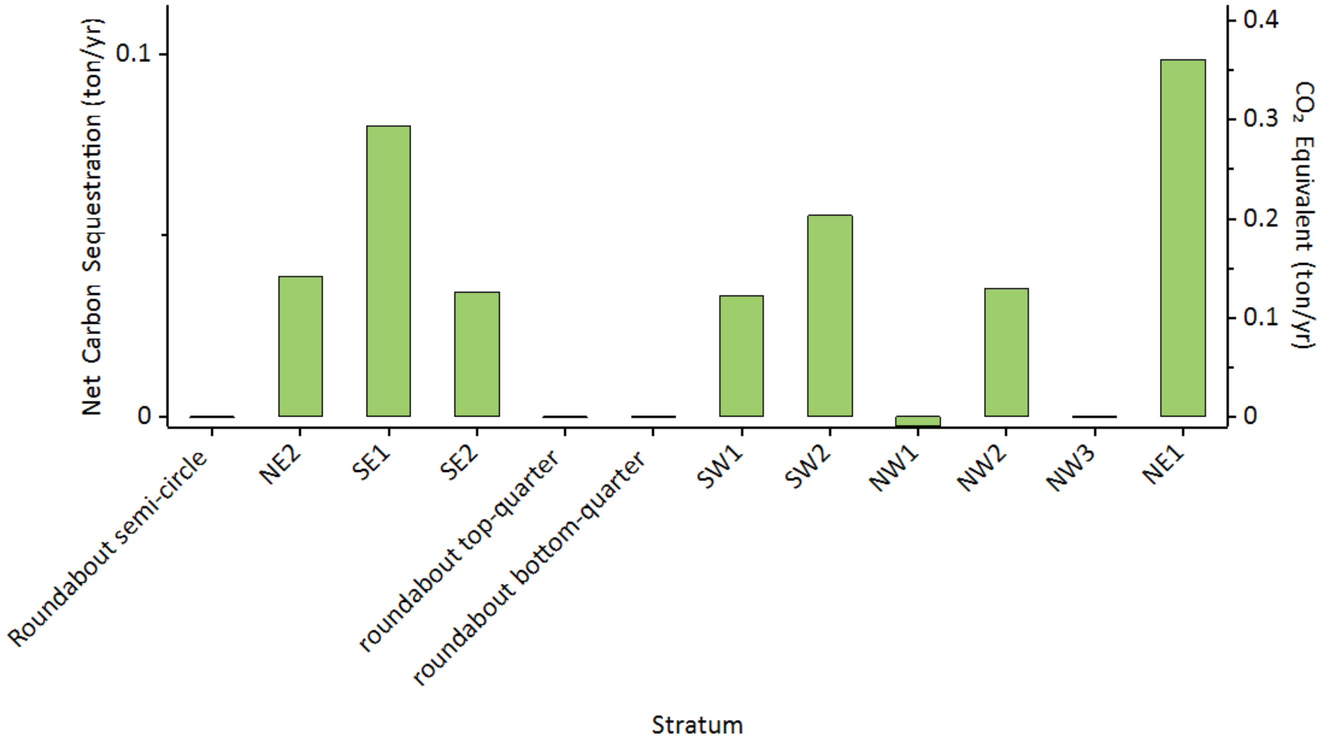
Annual Net Carbon Sequestration of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Smart Green Infrastructure Prediction, Series: 1, Year: 2023
Generated: 4/24/2023

Stratum	Net Carbon Sequestration (ton/yr)	CO_2 Equivalent (ton/yr)
Roundabout semi-circle	0.00	0.00
NE2	0.04	0.14
SE1	0.08	0.29
SE2	0.03	0.13
roundabout top-quarter	0.00	0.00
roundabout bottom-quarter	0.00	0.00
SW1	0.03	0.12
SW2	0.06	0.20
NW1	0.00	-0.01
NW2	0.04	0.13
NW3	0.00	0.00
NE1	0.10	0.36
Study Area	**0.37**	**1.37**

Annual Net Carbon Sequestration of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Smart Green Infrastructure Prediction, Series: 1, Year: 2023
Generated: 4/24/2023



Hydrology Effects of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Smart Green Infrastructure Prediction, Series: 1, Year: 2023
Generated: 4/24/2023

Stratum	Number of Trees	Leaf Area (ac)	Potential Evapotranspiration (gal/yr)	Evaporation (gal/yr)	Transpiration (gal/yr)	Water Intercepted (gal/yr)	Avoided Runoff (gal/yr)	Avoided Runoff Value (Kc/yr)
NE1	4	0.03	8,414.81	770.36	1,032.58	770.40	147.22	26.50
SE1	4	0.03	7,310.79	669.29	897.10	669.32	127.91	23.02
NE2	4	0.02	4,849.98	444.01	595.14	444.03	84.85	15.27
SW2	4	0.02	4,699.96	430.27	576.73	430.29	82.23	14.80
NW2	3	0.02	4,685.79	428.98	574.99	429.00	81.98	14.76
SE2	4	0.01	2,598.32	237.87	318.84	237.88	45.46	8.18
SW1	2	0.01	1,958.54	179.30	240.33	179.31	34.27	6.17
NW1	1	0.01	1,472.85	134.84	180.73	134.84	25.77	4.64
Roundabout semi-circle	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
roundabout top-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
roundabout bottom-quarter	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NW3	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**26**	**0.15**	**35,991.04**	**3,294.92**	**4,416.45**	**3,295.08**	**629.69**	**113.34**

Avoided runoff value is calculated by the price Kc0.180/gal. The user-designated weather station reported 14.8 inches of total annual precipitation. Eco will always use the hourly measurements that have the greatest total rainfall or user-submitted rainfall if provided.

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees and shrubs in Smart Green Infrastructure Prediction was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees and shrubs remove 10.85 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5), particulate matter less than 10 microns and greater than 2.5 microns (PM10*)[2], and sulfur dioxide (SO2)) per year with an associated value of Kc2.2 thousand (see Appendix I for more details).

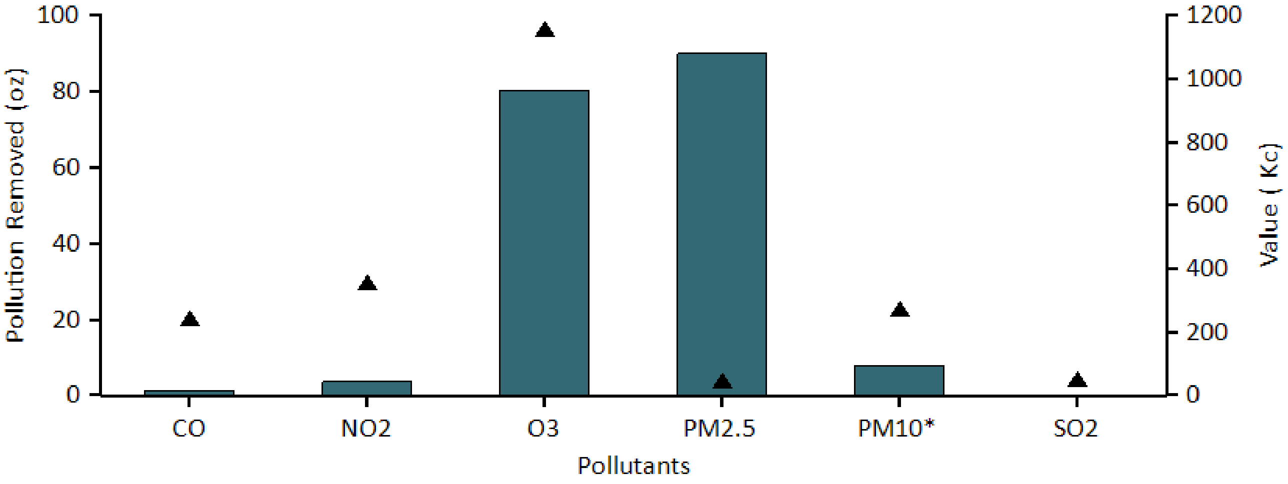


Figure 7. Annual pollution removal (points) and value (bars) by urban trees and shrubs, Smart Green Infrastructure Prediction

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[1] PM10* is particulate matter less than 10 microns and greater than 2.5 microns. PM2.5 is particulate matter less than 2.5 microns. If PM2.5 is not monitored, PM10* represents particulate matter less than 10 microns. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 and PM10* when particulate matter is deposited on leaf surfaces. This deposited PM2.5 and PM10* can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2023, trees in Smart Green Infrastructure Prediction emitted an estimated 5.569 ounces of volatile organic compounds (VOCs) (3.939 ounces of isoprene and 1.63 ounces of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Seventy- one percent of the urban forest's VOC emissions were from Sycamore spp and Necklacepod spp. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

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[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Smart Green Infrastructure Prediction trees is about 864.1 pounds of carbon per year with an associated value of Kc1.63 thousand. Net carbon sequestration in the urban forest is about 745.4 pounds. See Appendix I for more details on methods.

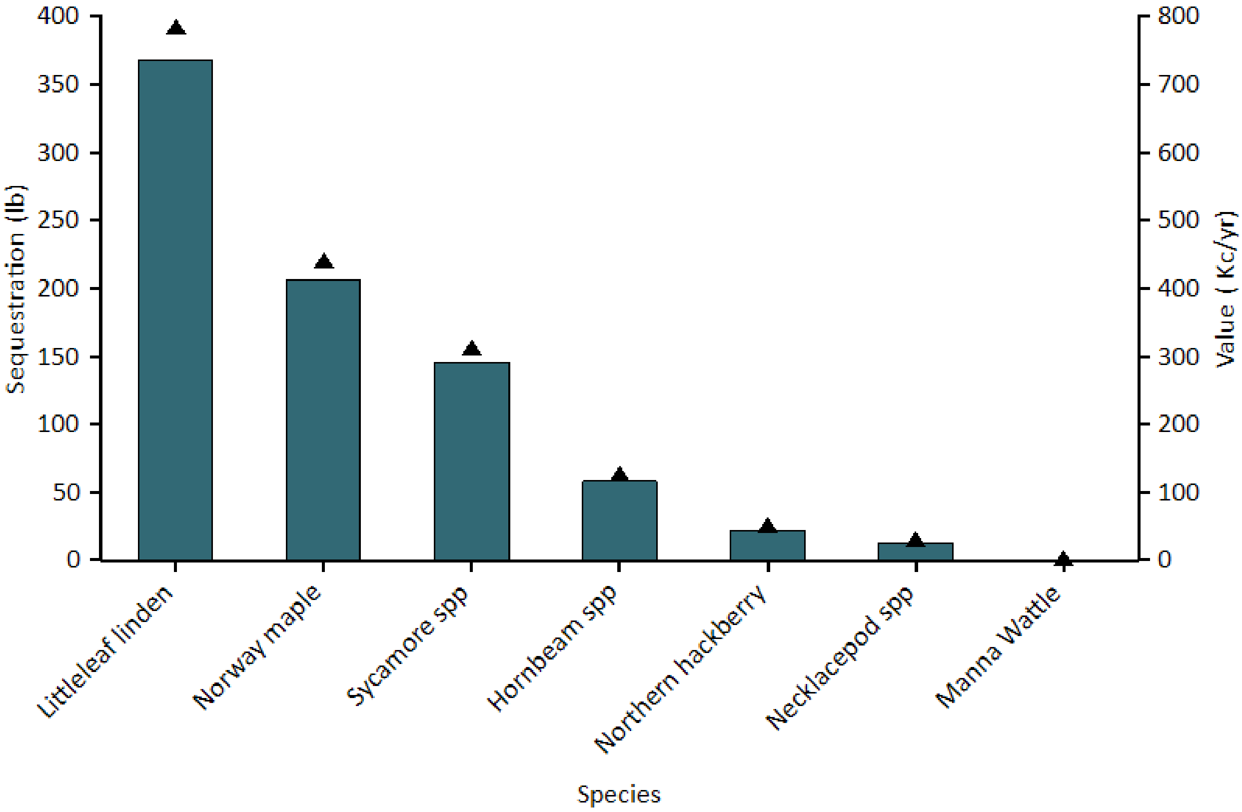

Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Smart Green Infrastructure Prediction

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Smart Green Infrastructure Prediction are estimated to store 31.2 tons of carbon (Kc117 thousand). Of the species sampled, Hornbeam spp stores the most carbon (approximately 34.2% of the total carbon stored) and Littleleaf linden sequesters the most (approximately 45.2% of all sequestered carbon.)

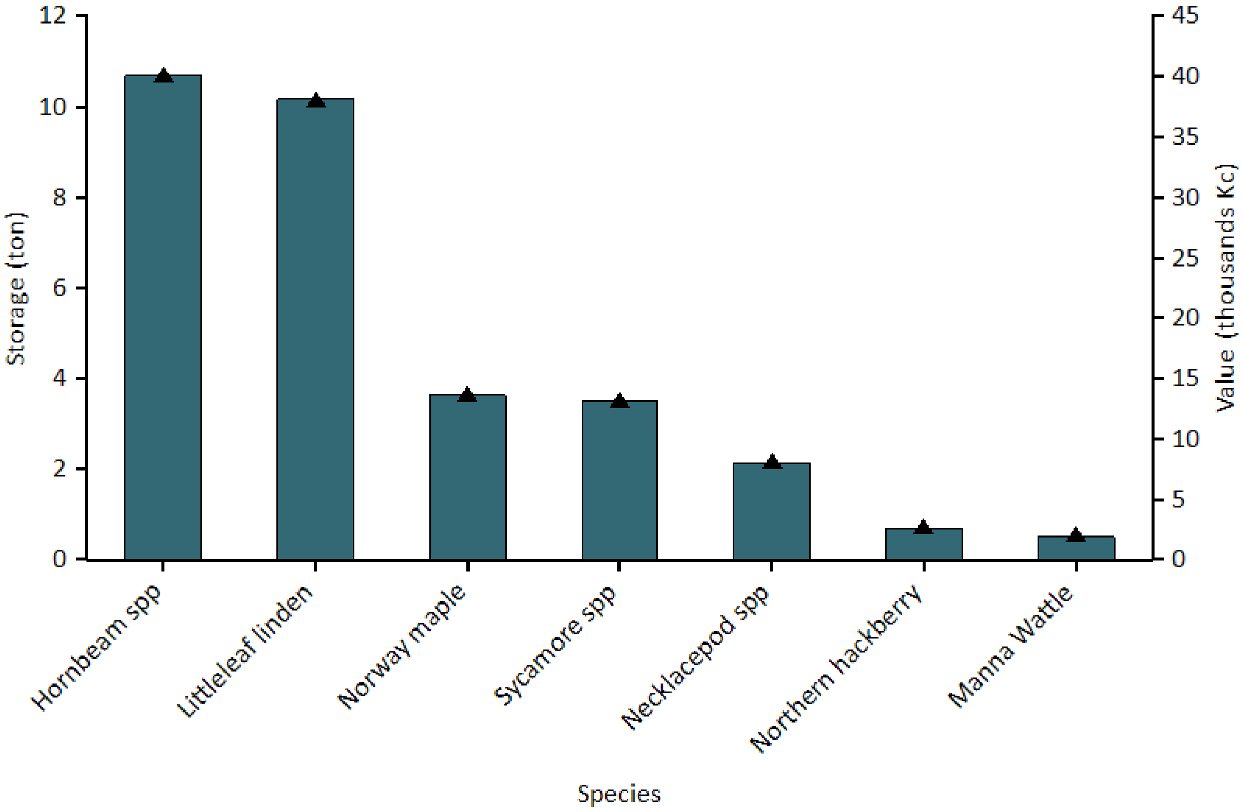

Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Smart Green Infrastructure Prediction

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Smart Green Infrastructure Prediction are estimated to produce 1988 pounds of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 7 oxygen production species.

Species	*Oxygen (pound)*	*Net Carbon Sequestration (pound/yr)*	*Number of Trees*	*Leaf Area (square feet)*
Littleleaf linden	931.47	349.30	8	0.00
Norway maple	562.44	210.92	3	0.00
Sycamore spp	375.22	140.71	4	0.00
Hornbeam spp	65.41	24.53	5	0.00
Northern hackberry	49.22	18.46	3	0.00
Necklacepod spp	17.29	6.48	2	0.00
Manna Wattle	-13.23	-4.96	1	0.00

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[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Smart Green Infrastructure Prediction help to reduce runoff by an estimated 1.18 thousand gallons a year with an associated value of Kc210 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Smart Green Infrastructure Prediction, the total annual precipitation in 2015 was 14.8 inches.

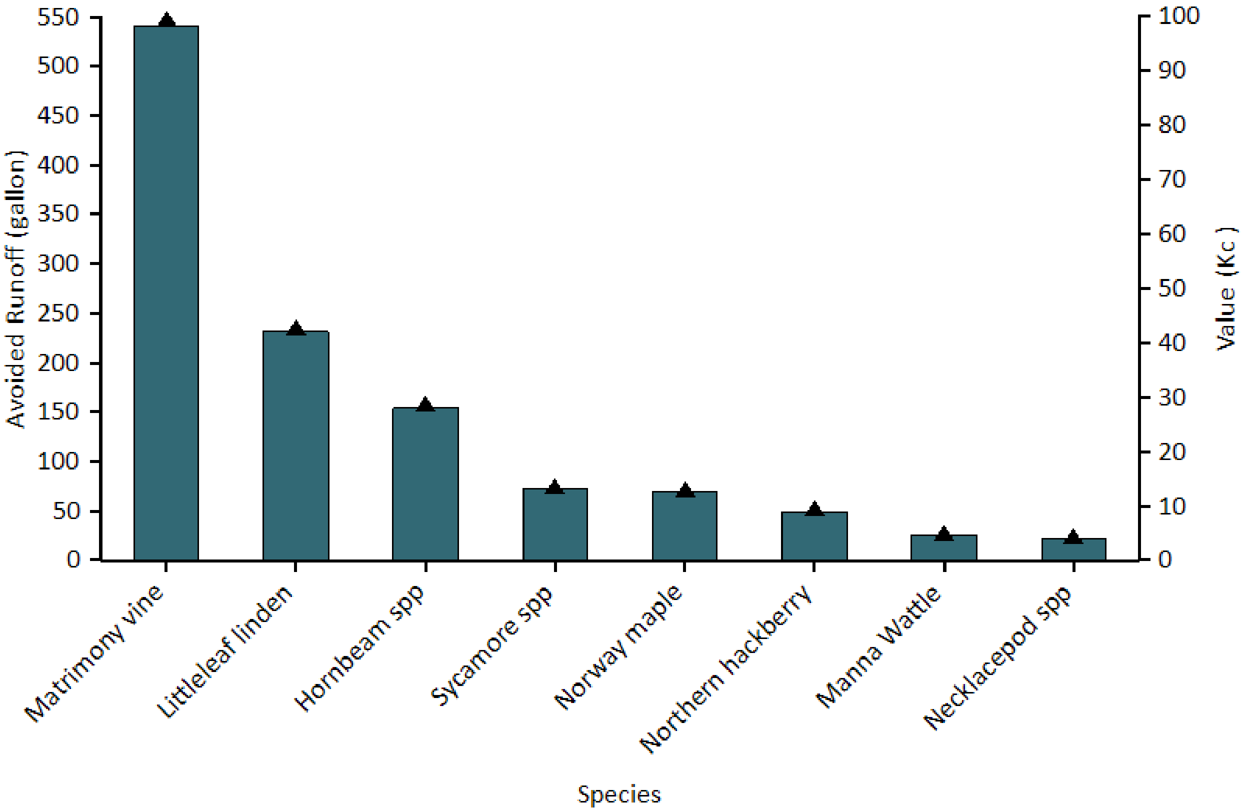


Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Smart Green Infrastructure Prediction

Appendix C: Scenario 3

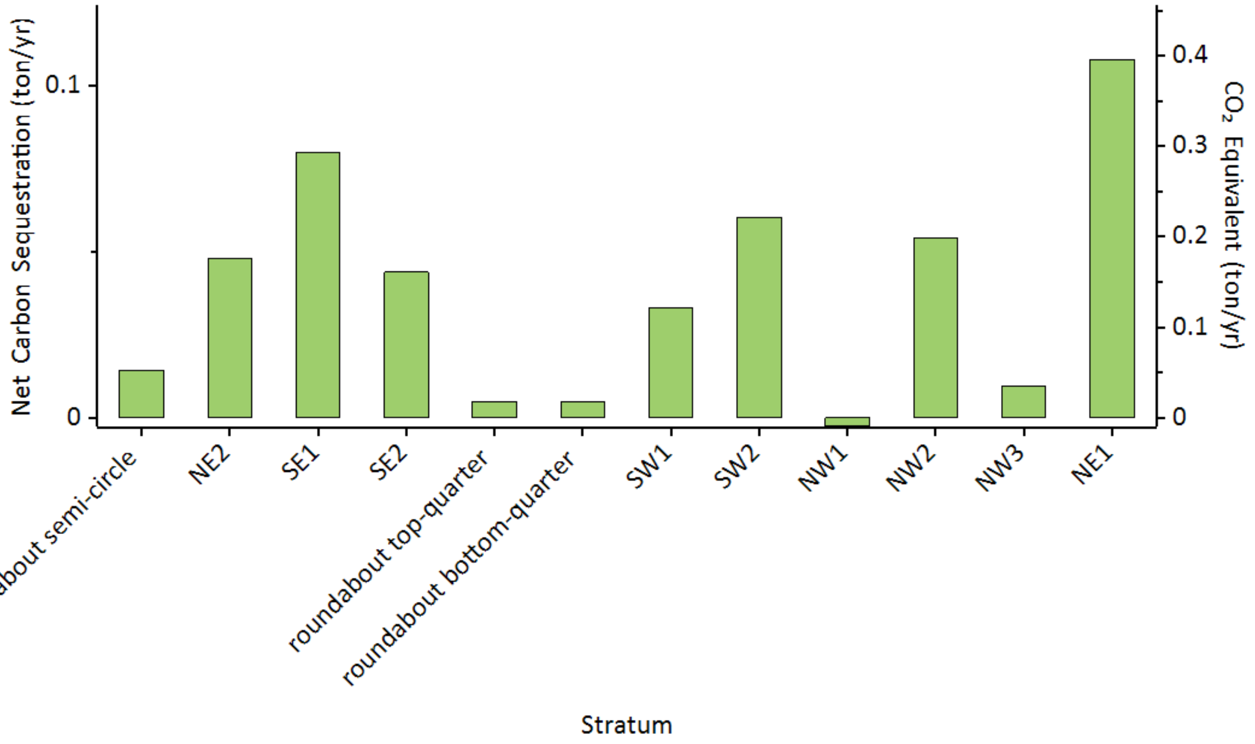
Annual Net Carbon Sequestration of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Smart Green Infrastructure 2, Series: 2, Year: 2023
Generated: 4/24/2023

Stratum	Net Carbon Sequestration (ton/yr)	CO_2 Equivalent (ton/yr)
Roundabout semi-circle	0.01	0.05
NE2	0.05	0.18
SE1	0.08	0.29
SE2	0.04	0.16
roundabout top-quarter	0.00	0.02
roundabout bottom-quarter	0.00	0.02
SW1	0.03	0.12
SW2	0.06	0.22
NW1	0.00	-0.01
NW2	0.05	0.20
NW3	0.01	0.03
NE1	0.11	0.40
Study Area	**0.46**	**1.68**

Annual Net Carbon Sequestration of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Smart Green Infrastructure 2, Series: 2, Year: 2023
Generated: 4/24/2023



Hydrology Effects of Trees by Stratum

Location: Praha, Hlavni mesto Praha, Ceska Republika, Czech Republic
Project: Smart Green Infrastructure 2, Series: 2, Year: 2023
Generated: 4/24/2023

Stratum	Number of Trees	Leaf Area (ac)	Potential Evapotranspiration (gal/yr)	Evaporation (gal/yr)	Transpiration (gal/yr)	Water Intercepted (gal/yr)	Avoided Runoff (gal/yr)	Avoided Runoff Value (Kc/yr)
NE1	6	0.04	11,225.46	885.75	1,268.85	885.78	171.64	30.89
SE1	4	0.03	9,130.56	720.45	1,032.05	720.48	139.60	25.13
NW2	7	0.02	7,284.30	574.77	823.36	574.79	111.38	20.05
NE2	6	0.02	6,773.28	534.45	765.60	534.47	103.56	18.64
SW2	5	0.02	6,227.89	491.41	703.96	491.43	95.22	17.14
SE2	6	0.01	3,961.15	312.56	447.74	312.57	60.57	10.90
SW1	2	0.01	2,446.05	193.01	276.48	193.01	37.40	6.73
NW1	1	0.01	1,839.47	145.14	207.92	145.15	28.13	5.06
Roundabout semi-circle	3	0.00	1,074.11	84.75	121.41	84.76	16.42	2.96
NW3	2	0.00	716.07	56.50	80.94	56.50	10.95	1.97
roundabout top-quarter	1	0.00	358.03	28.25	40.47	28.25	5.47	0.99
roundabout bottom-quarter	1	0.00	358.03	28.25	40.47	28.25	5.47	0.99
Total	**44**	**0.17**	**51,394.41**	**4,055.28**	**5,809.25**	**4,055.45**	**785.81**	**141.45**

Avoided runoff value is calculated by the price Kc0.180/gal. The user-designated weather station reported 14.8 inches of total annual precipitation. Eco will always use the hourly measurements that have the greatest total rainfall or user-submitted rainfall if provided.

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees and shrubs in Smart Green Infrastructure 2 was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees and shrubs remove 12.42 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5), particulate matter less than 10 microns and greater than 2.5 microns (PM10*)[2], and sulfur dioxide (SO2)) per year with an associated value of Kc2.36 thousand (see Appendix I for more details).

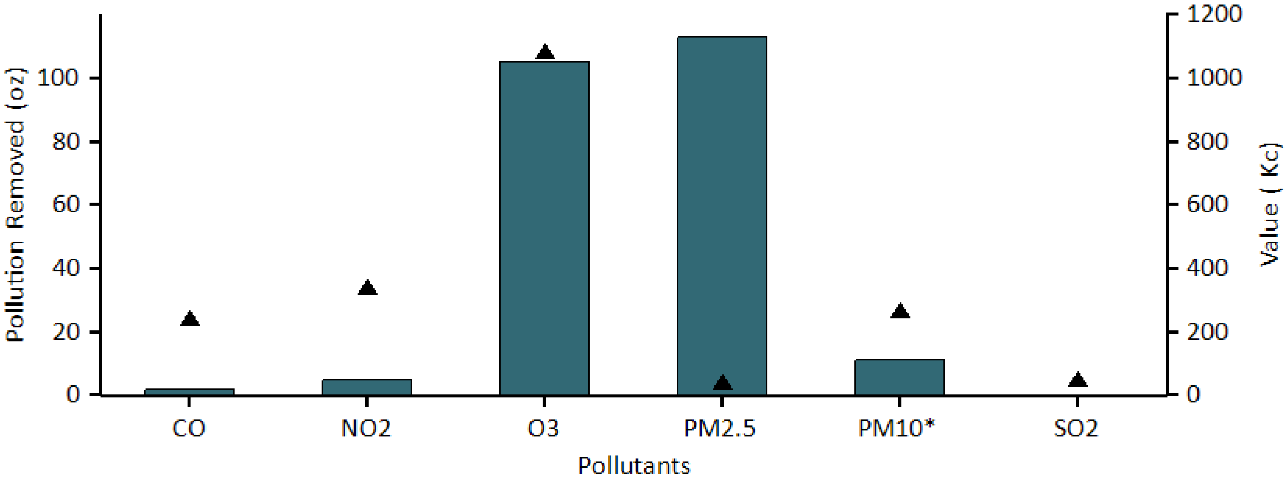


Figure 7. Annual pollution removal (points) and value (bars) by urban trees and shrubs, Smart Green Infrastructure 2

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[1] PM10* is particulate matter less than 10 microns and greater than 2.5 microns. PM2.5 is particulate matter less than 2.5 microns. If PM2.5 is not monitored, PM10* represents particulate matter less than 10 microns. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 and PM10* when particulate matter is deposited on leaf surfaces. This deposited PM2.5 and PM10* can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2023, trees in Smart Green Infrastructure 2 emitted an estimated 6.238 ounces of volatile organic compounds (VOCs) (4.095 ounces of isoprene and 2.143 ounces of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Sixty- six percent of the urban forest's VOC emissions were from Sycamore spp and Necklacepod spp. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

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[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Smart Green Infrastructure 2 trees is about 1044 pounds of carbon per year with an associated value of Kc1.97 thousand. Net carbon sequestration in the urban forest is about 916.8 pounds. See Appendix I for more details on methods.

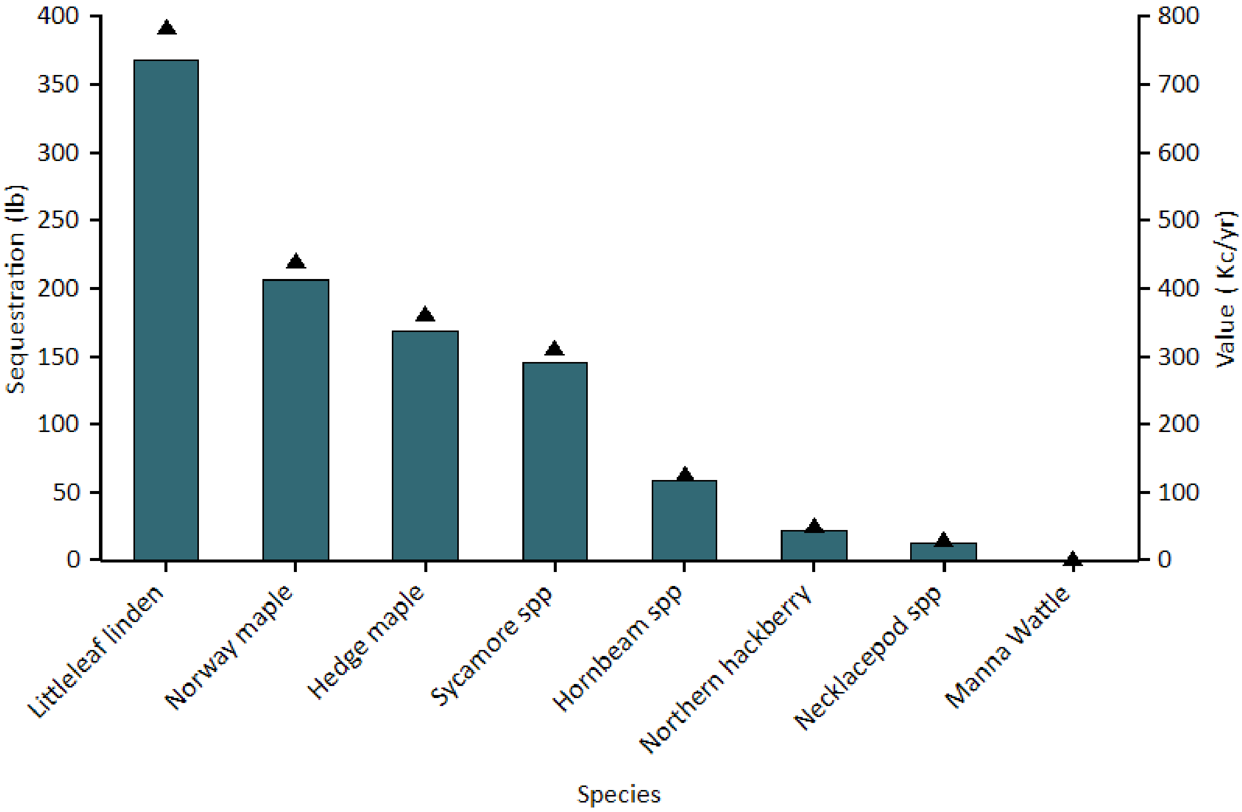

Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Smart Green Infrastructure 2

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Smart Green Infrastructure 2 are estimated to store 33 tons of carbon (Kc124 thousand). Of the species sampled, Hornbeam spp stores the most carbon (approximately 32.3% of the total carbon stored) and Littleleaf linden sequesters the most (approximately 37.5% of all sequestered carbon.)

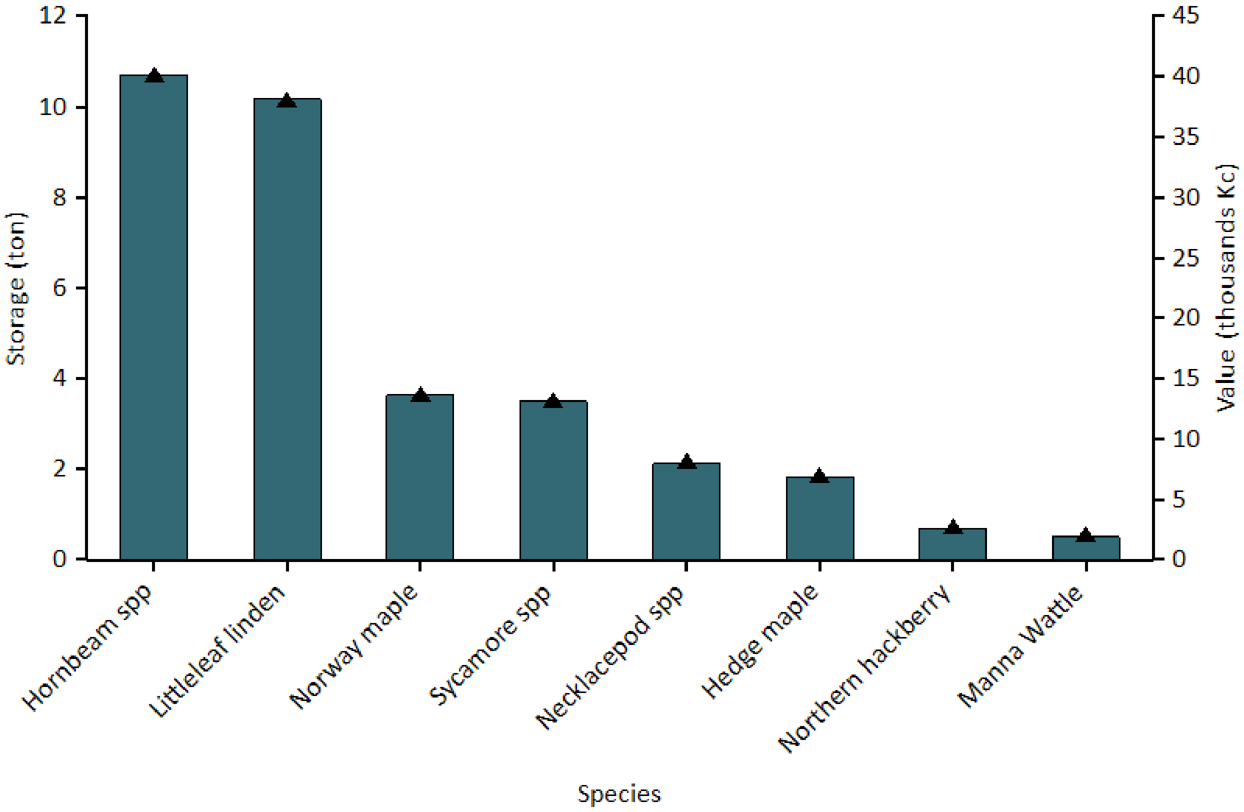

Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Smart Green Infrastructure 2

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Smart Green Infrastructure 2 are estimated to produce 1.222 tons of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 8 oxygen production species.

Species	*Oxygen (pound)*	*Net Carbon Sequestration (pound/yr)*	*Number of Trees*	*Leaf Area (square feet)*
Littleleaf linden	931.47	349.30	8	0.00
Norway maple	562.44	210.92	3	0.00
Hedge maple	457.07	171.40	18	0.00
Sycamore spp	375.22	140.71	4	0.00
Hornbeam spp	65.41	24.53	5	0.00
Northern hackberry	49.22	18.46	3	0.00
Necklacepod spp	17.29	6.48	2	0.00
Manna Wattle	-13.23	-4.96	1	0.00

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[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Smart Green Infrastructure 2 help to reduce runoff by an estimated 1.33 thousand gallons a year with an associated value of Kc240 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Smart Green Infrastructure 2, the total annual precipitation in 2015 was 14.8 inches.

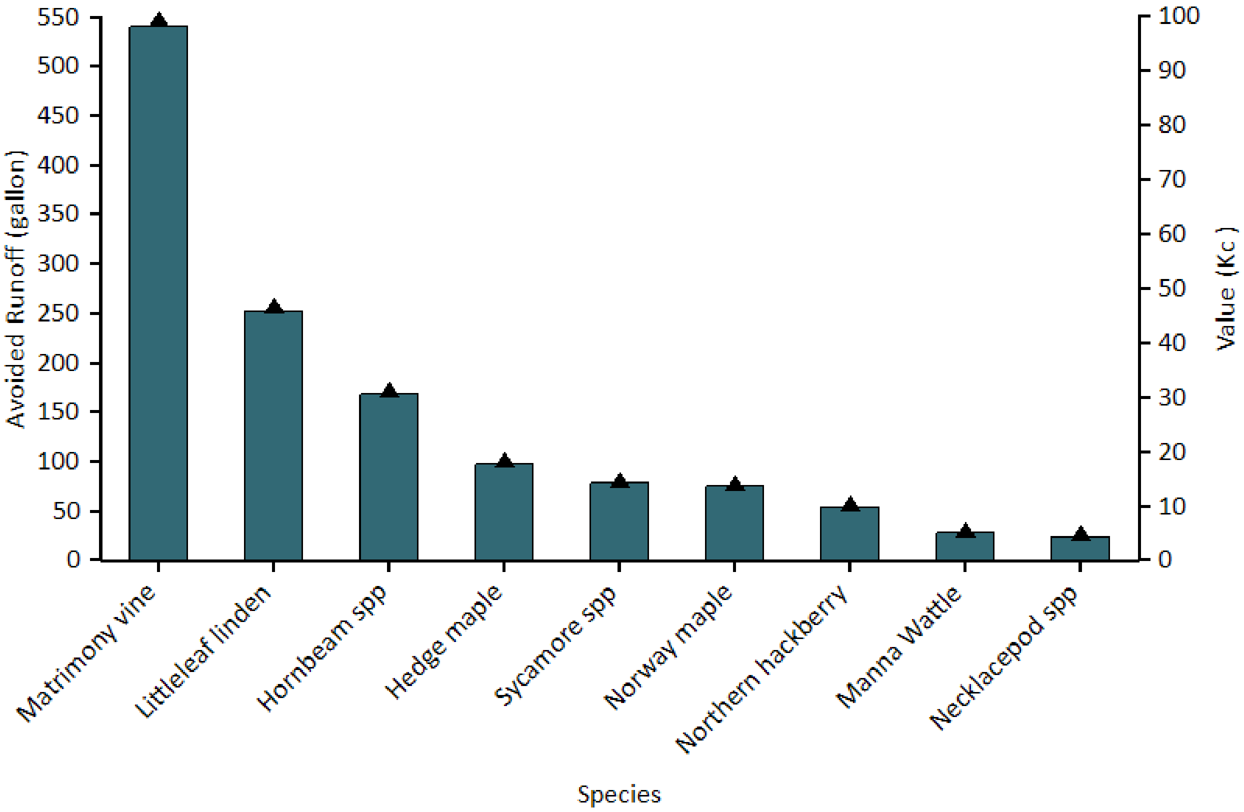

Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Smart Green Infrastructure 2