Mitigating environmental injustice and flood hazards: a study of Green Infrastructure in low-income neighborhoods around Austin, TX

by

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1. Problem Statement

Globally, there is a growing concern regarding an increase in high-risk floods. This is due to factors such as anthropogenically induced changes to global climate, which increases rainfall intensity, as well as the increase of urban growth and impervious urban surfaces, and rapid population growth within urban centers (Conley et al. 2022; Demuzere et al. 2014). Green infrastructure (GI) has been implemented throughout growing urban areas as an aid in runoff catchment. GI can successfully mitigate water pollution, reduce the risk of flooding hazards, can aid in conservation and sustainability efforts, and provide health and economic benefits to communities (Bahaya et al. 2019; McPhillips et al. 2021; Shakya and Ahiablame 2021). GI, when implemented successfully, can be an effective, low-cost way to fight against exacerbated flood hazards and implementing GI into the urban landscape is needed to build resilient cities in an ever-changing climate. However, there are patterns of injustice in the spatial placement of GI, leaving low-income neighborhoods, which are the most vulnerable to climate change effects, susceptible to flood hazards (Christman et al., 2018). This study aims to temporally and spatially illuminate the placement of small-scale GI and explore possible injustices around the city of Austin.

Austin, Texas is no exception to increased risk due to climate change, urban infrastructure increase, and rapid population growth. According to the city of Austin and the 2020 Census Bureau, Austin is one of the fastest growing cities in the U.S. with a 21 percent population growth from 2010 to 2020 (City of Austin 2021). The population is expected to hit 2.5 million people by 2025 with an expansion of the suburban and exurban communities (Tretter, 2016). Despite the population growth, there was a decline in urban development between 2011-2016 in central Texas due to environmental policies pushing for more eco-friendly development in the

Edward's Aquifer recharge and contributing zones. This shifted the land use around the city of Austin towards a more sustainable urban center (Guerra and Debbage, 2021). Austin has been the leader in environmental initiatives in America since the 1990s (Tretter, 2016) and likewise, has been a leader in implementing GI projects in Texas (Ferrell-Sherman, 2020). However, there has been little study done to provide feedback on the placement of GI projects around the city and little exploration of how GI projects are placed in relation to income level, vulnerability, and other economic factors within the city. This project seeks to explore whether there is injustice for low-income neighborhoods in the placement of GI, and how future placement of GI could lower the risk of flooding in vulnerable neighborhoods across the city.

1.1. Research Questions

More specifically, my questions are as follows:

1) Do low-income neighborhoods have equal access to GI around the City of Austin?
2) Are there areas of the city where no GI is present, but suitability and priority of GI implementation is found?
3) What changes could be made in the future regarding city planning focused on flood resilience within underserved communities?

To answer these questions, I took a positivist approach, relying heavily on data collection and quantifiable observations such as statistical analyses to answer my research questions. I used a suitability model to analyze the locations of already built small-scale GI around the city in relation to optimal placement of GI. This analysis is based on urban impervious cover, flood zones, elevation and drainage, distances from waterbodies, and land cover layers. This will then be compared to priority sites in low-income neighborhoods and previously existing GI around the city of Austin to uncover any disparities or disproportions of GI placement between different economic groups. Once this comparison is made, I will look at past data to illuminate any patterns in the placement of GI that cannot be revealed by the suitability model alone.

1.2. Hypotheses

I hypothesize that the placement of GI will be optimal for flood zones but will have disproportionate placement between higher-income neighborhoods and lower-income neighborhoods, leaving the low-income neighborhoods with little to no GI. Therefore, I hypothesize there is a lack of spatial justice in the placement of GI around the city of Austin for low-income neighborhoods.

Studies, such as this one, are important because the disadvantaged population of Austin, Texas is included in the wider conversation about the benefits of GI. This type of technology not only benefits the environment, but also plays a role in benefiting people socially and economically, providing many ecosystem services. s GI provides improvements to water quality, air quality, improves urban heat island affects, and mitigates against flood hazards. In addition, GI provides spots of beautification providing economic benefits, improving human health through the environmental impacts, and providing many other co-benefits between human-environmental interactions (Omitaomu et al., 2021).

The results of this study can guide the city of Austin to make better judgements of the placement of green infrastructure and serve as a model to encourage other cities to consider factors such as vulnerability, climate resilience, and income level in the placement of GI. This study will contribute to the growing body of literature focused on green cities by illuminating factors of green infrastructure that are under-studied such as the unequal GI placement in an urban setting. Understanding these perspectives will not only impact the City of Austin and its low-income residents but will also provide extra structure for optimal GI placement.

2. Background

2.1. History, implementation, benefits, and types of GI

There are many types and sizes of GI, all with different functions and purposes (EPA 2023). Some forms of GI include bioswales, green roofs, rain gardens, rain barrels, green streets and alleys filled with permeable pavement, and planter boxes (EPA 2023).

Bioswales (Figure 1) are usually found on the side of curbs and sidewalks to catch rainfall and filter stormwater flows (EPA 2023). These projects help to mitigate water pollution and control overflow, allowing for percolation of rainwater into the soil (EPA 2023).

Figure 1:Bioswales.

Figure 2: Rain Garden.

Similarly, rain gardens (Figure 2) are implemented to catch rainfall and act as a natural pathway for water flow collected from roofs, sidewalks, and streets, controlling water pollution (EPA 2023).

Planter boxes (Figure 3) are used to filter stormwater and beautify urban spaces (EPA 2023). They are usually placed off urban sidewalks and parking lots and can be used in a vertical setting on the sides of buildings (EPA 2023).

Figure 3: Planter Box.


Figure 4: Permeable Pavers.

Permeable pavements (Figure 4) are an inventive way to transform concrete areas into pervious surfaces by allowing water to pass through the porous material (EPA 2023). These projects allow for infiltration, filtration, and storage of stormwater (EPA 2023). Permeable pavements include porous concrete or asphalt, or pervious pavers that are a cost-effective way to turn a space into a sustainable space (EPA 2023).

GI projects provide a host of ecosystem services such as flood mitigation, air pollution control, water quality control, human health benefits, economic benefits, and urban heat control (Abdulateef and Al-Alwan 2022, Li et al. 2022, Abhijit and Kumar 2019, and Bussi et al. 2022). For the purpose of this study, flood mitigation and economic benefits are investigated further. As rainfall and runoff flow across the surface, GI provides as a catchment area to allow for instant infiltration into the water table. During floods, this is useful in reducing the immediate impacts of extreme overland flow, allowing the water to instantly infiltrate through porous and permeable surfaces. On the other end of the spectrum, these types of projects provide economic benefits. GI provides beautification increasing property values, impacting the economy of an area (Vandermuelen et al, 2011).

In urban settings, grey infrastructure – culverts, gutters, pipes, etc. were used as catchment areas for stormwater (EPA 2023). These structures are not as reliable nor do they hold their value after time, making them high maintenance and not as useful as green infrastructure (EPA 2023). The term GI was coined in 1994 in Florida in a report to the governor on land conservation strategies (Firehock, 2010). The intention behind the term was to illuminate the usefulness of natural infrastructure, ng giving recognition to the benefits of GI to the urban ecosystem throughout communities (Firehock 2010). The Water Infrastructure Improvement Act was enacted by Congress in 2019, defining GI and providing the EPA structure on implementation of such projects into the urban landscape (EPA 2023). There are many national, state, and local initiatives to research, plan and implement all scales of GI projects into different urban and watershed landscapes (EPA 2023).

Green Infrastructure has been found to have many impacts on different scales and different situations across the globe. From having positive impacts on surface urban heat island to air quality and water quality, there are many benefits to GI implementation into the landscape that could help reverse adverse effects from climate change (Abdulateef and Al-Alwan 2022, Li et al. 2022, Abhijit and Kumar 2019, and Bussi et al. 2022).

In Baghdad, two climate change models were used to assess GI impacts on Surface Urban Heat Island in two different scenarios (Abdulateef and Al-Alwan, 2022). In both scenarios, GI reduced the effects Surface Urban Heat Island to some extent, enough to make an impact and show that GI can be effective (Abdulateef and Al-Alwan, 2022). Another study in four different cities in East Africa found that blue green infrastructure, if tailored to the specific climate regions, could in fact reduce and moderate Surface Urban Heat Island (Li et al., 2022). Two separate studies across the globe show similar results that GI is impactful on reducing Surface Urban Heat Island, revealing the useful effects of GI.

A study conducted in Guildford, UK assessed the effectiveness of various types of GI on the reduction of various particulate matter and other air pollutants from vehicles (Abhijit and Kumar 2019). The study focused on three different GI configurations – *hedges only*, *trees only*, and *mixed* (Abhijit and Kumar 2019). Out of the six scenarios, it was found that the "hedge only" scenarios were the best at improving air quality, the "mixed shrubs and trees" were the second best, and the "trees only" did not impact the concentrations of air pollution at all (Abhijit and Kumar 2019).

In London, the INCA water quality model was used to assess catchment in constructed wetlands to see if there were any significant reductions in sediment transportation and improvement of pollution control (Bussi et al., 2022). The results showed that there can be a significant reduction of both sediment transportation and improvement in nutrient control, improving water quality (Bussi et al., 2022). This study, among numerous others within the literature, illuminates the success of GI in improving water quality.

2.2. Study Area

The city of Austin, located in Central Texas (Figure 5) along the I-35 corridor, is known as a sunbelt city (Tretter, 2016). The study area falls across the Balcones Fault Escarpment, extending from the Blackland Prairies to the Hill Country on the Eastern side of the Edwards Plateau (Slade et al., 1982). This area of Texas is filled with unique terrain and climate, where winters are short and mild, and summers are long and moderate with moderate humidity (Slade et al. 1982). Yearly rainfall averages 35.5 inches with May, October and June being the wettest (National Weather Service).

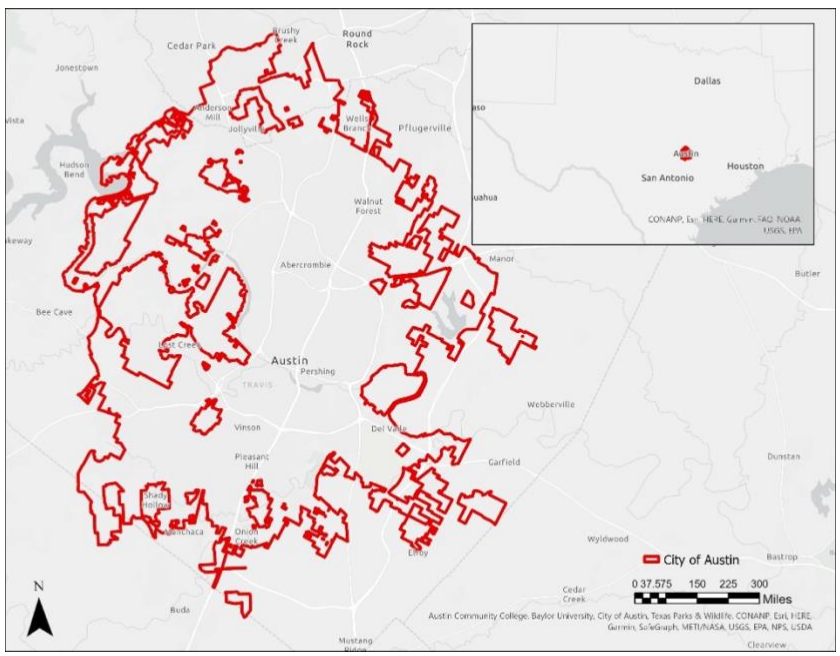

Figure 5: Study Area of the City of Austin.

There are many small rain fed and groundwater fed streams that flow through the study area throughout the year (Slade et al. 1982). Among those streams are Barton Creek, Bull Creek, Onion Creek, Walnut Creek, Williamson Creek, and Waller Creek (Slade et al. 1982). The Edwards Aquifer contributing, recharge and transition zones fall towards the southwest land of the study area (Slade et al., 1982). The Austin area lies on the transitional zone between several ecoregions, the Edwards Plateau to the west, and the Blackland Prairie and Post Oak Savanna floodplains to the east. . The soils in east Austin are mostly composed of deep black and reddish clays, which have a high shrink-swell capacity. Within floodplain and along river bottoms in the southeastern portions of Austin the soils are often deep sandy loams, which typically sit onto a hard layer of calcareous clay, which quickly saturates and is prone to flooding. West of I-35, soils are thin, calcareous clays, clay loams, and stony clays developing weakly on limestone. This area is prone to runoff and flash flooding. (Werchan et al, 1974; Slade et al., 1982). Add a sentence here about infiltration to connect soils, groundwater, and flooding.

The city of Austin has a history of flooding and in the last decade has seen three major, 100-year floods occur, devastating the communities around the city (The City of Austin 2013). The first of the three floods occurred on Halloween, 2013, damaging 659 homes and peaking flow rates in the Onion Creek to its highest recorded levels (The City of Austin Open Data Portal). The second of the major floods was the 2015 Memorial Day flood, which led to devastation all around the city of Austin and left major erosion impacts on several creeks (Guerrero and Shunk 2015). The third and most recent major flood, the Central Texas Hill Country Flood of 2018, caused significant damage to the surrounding areas of the LBJ Lake and Lake Buchanan (City of Austin Office of Homeland Security and Emergency Management 2019). All three of these floods occurred due to higher-than-normal precipitation events and the current infrastructure was not able to contain the excess precipitation during such events. Climate change will only continue to exacerbate these issues (Zoll 2021). As global temperatures rise, the odds of extreme weather increase as well. Rainfall intensity is expected to increase across Texas, and the odds of extreme rainfall events may increase as well (Nielsen-Gammon, 2020).

The total population of Austin is roughly 960,000 people with a median household income of $75,752 per year based on the 2020 Census Bureau data (City of Austin, Demographic Hub). According to the City of Austin's Demographic hub, about 50 percent of the city population earns a low to moderate income. These groups of disadvantaged people within Austin are most susceptible to climate change hazards such as flooding due to the unequal mitigation strategies (Zoll, 2021). Zoll (2021) found that age, income, and race are the most significant factors in predicting flooding hardships and recovery times. This issue of vulnerable community's disproportionality placed in higher flood and environmental risk areas within the city of Austin is seen throughout the literature (Zoll, 2021; Bixler et al, 2021; Pace, 2022; Busch, 2017). An increase in economic opportunities in Austin, Texas has created unaffordable housing, disproportionate access to transportation, and gentrification, all exacerbated by higher-intensity flooding and climate change effects (Bixler et al, 2021). Gentrification and neighborhood displacement specifically seen among the black and Latinx communities around Austin has been an issue throughout Austin's history and has displaced vulnerable groups to the most susceptible spots of climate change hazards (Pace, 2022). In the 80s, the white population in Austin rapidly increased due to a shift in economics focusing on high tech, oil and defense industries (Busch, 2017). Because these industries brought with them production facilities and there was already a large environmental movement in the city, these industrial facilities moved into the East to keep the North and West parts of the cities "pristine" (Busch, 2017). This further divided the lower-income East side from the higher-income West and North sides and left the lower-income communities. East side communities were left with little help in the environmental movement and therefore lack similar infrastructure as higher-income communities. These communities in the east sit at lower elevations, making these areas more susceptible to flooding than communities at higher elevations, and with the lack of proper infrastructure, this issue is exacerbated further (Busch, 2017). There are 68 different watersheds that flow through Austin with a lot of them flowing off the major waterways such as Lake Austin, Barton Creek, and the Colorado River that flows into Lady Bird Lake. Lady Bird Lake runs through central Austin and flows towards the East, where the most vulnerable populations reside. With a lack of proper infrastructure, lower elevations, and the majority of the watersheds in the city flowing towards these communities, they are left even more vulnerable to flood hazards.

2.3. Green Infrastructure around Austin, TX

The City of Austin has held the title of being one of the greenest cities in the world and has received praised for its "forward thinking" urban planning and sustainability (Busch 2017). There are many green infrastructure projects that have been implemented or are expected to be integrated into the city of Austin. A few of these projects include bioretention ponds, rain gardens, rain barrels, and green roofs (Austin's Small Scale Green Infrastructure, AustinTexas.gov). The impacts of these projects are mostly focused on flood risk management and improving water quality. Green infrastructure (GI) has been used in the Austin urban landscape since the 1980s and more specifically in the Austin Tomorrow Plan (recently renamed Imagine Austin Plan) since 1979 (Wade 2012). GI has been used to mitigate flood hazards and provide a source of runoff catchment and watershed ecosystem protection, all of which have been exacerbated due to climate change effects (Bahaya et al. 2019; McPhillips et al. 2021). The City of Austin is no stranger to implementing sustainable environmental projects to alleviate such issues (Tretter 2016). Examples of such projects include the integration of technology into retrofitted stormwater management systems to control stormwater facilities more accurately (Klenzendorf et al. 2015) and a rain catchment program rendered through the Austin Watershed Protection Department and Austin Water to provide reusable water for commercial and residential use (Diringer et al. 2020).

Likewise, under the Austin Watershed Protection Department, there are various protection projects to help mitigate flooding and other runoff hazards to protect important watershed ecosystems. The Regional Stormwater Management Program (RSMP) provides the necessary funding and construction of various stormwater infrastructures to help fight against flooding and water pollution (Watershed Protection). Environment Texas is another program with the goal of creating "natural cities" around Texas to fight against flooding hazards while also informing and educating the public on the benefits of GI (Natural Cities, Healthy Waters). Environment Texas argues that the state water board should be funding green infrastructure to mitigate flooding instead of continuously relying on grey infrastructure (Farrell-Sherman 2019). Based on the records of the Texas Stormwater Scorecard, Austin is tied with San Antonio for the top stormwater managers in Texas (Farrell-Sherman 2020). These green infrastructure programs help to mitigate flooding hazards and water quality issues.

The City of Austin has mapped out the small-scale GI projects implemented around the city (Figure 6). The small-scale projects include rain barrels, rain gardens, basins, and green roofs (Austin's Small Scale Green Infrastructure, AustinTexas.gov). Most of these small-scale projects are funded through the Neighborhood Partnering Program started in 2010 (City of Austin). There are three types of programs that help to establish these small-scale projects: the neighborhood cost share program, the Adopt-A-Median Program, and the Grant Assistance Program (City of Austin). The requirements of the proposed projects include that the location of the project must be on city-owned property, submitted by a local group, demonstrate the support of neighbors, and be accessible to the public and benefit the community (City of Austin). These programs have helped to establish 60 community projects since the program's inception in 2010 (City of Austin).

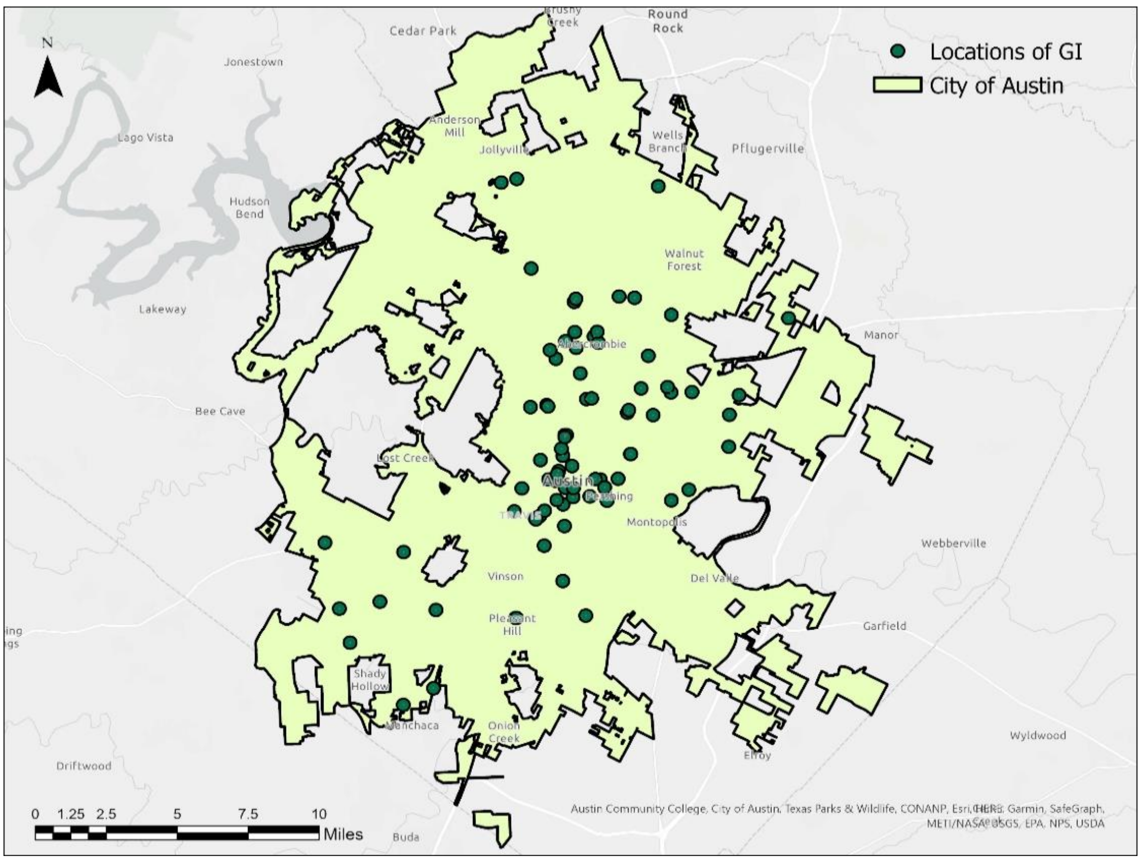

Figure 6: Locations of GI around the city of Austin.

3. Literature Review

3.1. Methods of GIS comparative analysis

3.1.1. Optimal placement of GI

As seen across several recent studies, there are multiple tools being developed or improved to make GI placement more effective. The placement of Green Infrastructure in the landscape is important in the effectiveness of its functioning. If implemented inappropriately and errors are made, the design of the project will hinder the effectiveness of the function (EPA 2023). Parameters to consider implementation of GI are the soil types, space constraints, amount of water supply, weather, and overall climate patterns (EPA 2023). Knowing this specific information will help to avoid errors in GI's design and implementation (EPA 2023). There have been many tools developed, and more that are being developed, to help determine the optimal placement of GI in the landscape.

The Spatial Suitability Analysis Tool (SSANTO) is a tool to map suitability of Water Sensitive Urban Design (the Australian term for GI) within the landscape. (Kuller et al. 2019) The criteria are based on "Needs" (ecosystem services) and "Opportunities" (biophyiscal, socioeconomics, planning and governance criteria). The program is still in development stage but has promise to aid urban planning in finding more suitable locations for GI to work more efficiently, socially, and physically.

The Storm Water Management tool (SWMM) is the primary design tool for GI and since its implementation there have been various tools created in conjunction with SWMM to help optimize the placement of GI in different scenarios. One of those variations of the SWMM tool is the Optimization Software Toolkit for Research Involving Computational Heuristics (OSTRICH) (Macro et al. 2019). The OSTRICH was used to look at the tradeoffs of rain barrel placement and the reduction of combined sewer outflows. This tool can be used to do single and multi-objective optimization of model components – something that SWMM is not able to do on its own. For now, the tool is still in development, but it could be used to optimize other types of GI, not just rain barrels. A similar tool that performs with the SWMM tool is the Green Infrastructure Placement tool (GIP) (Shojaeizadeh et al. 2021). The GIP tool is used to place GI in optimal locations at multiple scales. The benefits of this tool are that it can analyze multi-benefit options and revitalize communities while reducing sewage overflows and improving water quality. This approach helps to meet target flow and pollutant load reduction while minimizing costs of GI implementation. Shojaeizadeh et al. (2021) assessed this tool in South Dakota and analyzed multiple target levels of discharge, TSS, E. Coli, and Fecal coliform. Cost effectiveness curves were created for each of these indicators. Results concluded that GI costs increased as target discharge, TSS, E Coli, and Fecal coliform decreased at the outlet of the watershed. Thus, GI was placed at the origins of most of the discharge and pollutant loads.

Another useful tool is the Green Infrastructure Space and Traits model (GIST) that considers both optimal placement of GI and vegetation type to maximize multifunctionality of GI in the landscape. Tran et al. (2020) conducted a study in Philadelphia (a big GI player) and found that optimization of GI had not been fully utilized in the area. The model proved to be successful in allowing for the proper multifunctional GI placement .

Christman et al. (2018) conducted a similar study in Philadelphia using a suitability model based on several parameters based on expert opinions regarding the influence of social factors to site GI. More specifically, the NEAR tool in ArcMap was used to calculate proximity metrics prioritizing stormwater inlets, transit stops, Neighborhood Advisory Committees, schools, universities, and recreation centers . These criteria were ranked 1 to 5 (minimally influential to critically influential) and were then summed together to show the percent influence of each criterion per GI feature. A linear combination was used to weigh the influence of all scaled distance factors for GI site selection. The setup of this study will influence and contribute to my research as I will use a linear weight for my suitability model to illuminate the optimal GI sites around the city of Austin.

3.1.2. Change detection of GI

When implementing GI into the landscape, it is important to factor in land-use change. Considering the changing of land use for the future will help to implement GI into the land in the most efficient and effective ways.

Various GI combinations were explored by Li et al. (2019) according to their cost-efficiencies along with a simulation of scenarios in 2050 based on projected land use and rainfall data in a study of land-use change on GI cost-efficiencies. This study concluded that grassed swales, rain barrels, and dry ponds were the top 3 most cost-effective GI structures while green roofs and rain cisterns were the most expensive. The GI structures that were most cost effective also reduce the quantity of runoff. In the future scenario, each GI practice shows positive water quantity and management (Li et al. 2019). This study helps to understand the most cost-effective GI to use in different scenarios.

Padró et al. (2020) evaluated four different land cover scenarios and two types of agricultural management in a study that looked at the SIA tool in Barcelona. When using the tool, there were signs of significant improvements in job provisioning and nutrient cycling closures, but certified organic, as is, was not enough to overcome the effects, such as low energy efficiency or greenhouse gas emissions, of traditional agriculture. The SIA tool was found to be important for creating a steadier transition towards more sustainable land use (Padró et al. 2020). In another study, the methodology that would help communities to set up GI Sustainability Maps as a tool for land-use planning was illuminated (Senes et al. 2021). These sustainability maps consider the non-urbanized areas where water can potentially infiltrate as well as soil characteristics. With maps of potential infiltration and exclusion areas, the sustainability maps are created showing GI capability areas and areas where no infiltration will occur (Senes et al. 2021). This tool is useful in considering where the land has potential to be urbanized and therefore to see land-use change and it is important to recognize potential changes when implementing GI into a landscape that is highly susceptible to flooding hazards. Similarly, Sun et al. (2022) integrated GI Conservation into scenario design to simulate the land use patterns and landscape connectivity. They found that the multiple conservation scenarios effectively protected the area and landscape connectivity of natural spaces making this study important for land-use change and GI implementation.

3.2. Spatial Inequality of GI in low-income neighborhoods

The placement of GI can be effective in mitigating against environmental hazards, but if not implemented into the urban landscape properly, the social and economic benefits of these projects are lost. Considering economics and the environment will maximize the use of GI and will help to consider the disadvantaged people who are most vulnerable to environmental hazards (Omitaomu et al. 2021).

A study conducted in Philadelphia, one of the leading cities of implementing GI into the urban landscape (Christman et al. 2018), investigated the social, economic, and environmental benefits of GI specifically to address concerns of disproportionate and inequitable benefits of GI in disadvantaged areas. This study is the main driver of my methodology, and I have taken inspiration from this study to site areas of concern for inequitable GI benefits around Austin, TX.

3.3. *Impacts of GI on flood risk zone*

Urban impervious cover exacerbates already increasing flooding hazards by inhibiting infiltration (Li et al. 2021, Omitaomu et al. 2021). This issue can be mitigated at local scales by including the implementation of GI into urban landscapes to allow for infiltration of flood waters into the ground (Li et al. 2021, Raczková et al. 2021, Omitaomu et al. 2021).

In Shenyang, China, a city with a large amount of impervious cover, flooding is a common occurrence due to the prime location in an area with high yearly rainfall (Li et al. 2021). To evaluate the storage supply and demand of runoff, a method was developed to calculate the storage supply of GI by rainfall and max rainwater storage capacity of the soil and canopy (Li et al. 2021). The results of the study found GI to provide the city of Shenyang with enough storage capacity to mitigate urban flooding if implemented and maintained properly (Li et al. 2021). This study highlights the benefits of implementing GI into the landscape as these projects do work to fight against flooding in urban landscapes.

When implemented, GI can be beneficial for both the environment and humans (Omitaomu et al. 2021). Integrating these projects into urban spaces can be advantageous and an impactful strategy to mitigating flood hazards (Omitaomu et al. 2021). A study in Knoxville, TN determined the planning of GI implementation needs to consider the change in precipitation for local sites, incorporating projections of future precipitation events that could cause impactful flooding risks to determine which sites are both suitable and high priority for the most vulnerable - low-income people (Omitaomu et al. 2021). It was found that the integration of projected precipitation with flood zones and elevation is vital to uncovering priority sites for GI where it benefits the disadvantaged and is the most useful in mitigating against flood hazards (Omitaomu et al. 2021). This study provides useful information for the layers of my suitability model as I used flood zones and elevation data along with other important data to find the most suitable sites of GI around the city of Austin.

4. *Methods*

My research will take a positivist approach, allowing me to quantify and map GI locations, flood zone areas, and low-income neighborhoods around the City of Austin while using economic data to investigate possible spatial inequalities in access to GI around the city. The comparison between the variables – GI placement, flood zones, and low-income neighborhoods - will enable me to understand if GI placement is optimal for both flood zones and inclusivity for low-income neighborhoods.

4.1. *Data Collection*

I collected the following data layers for this study (Table 1) to better understand the placement of GI and any possible spatial inequities in this placement.

Data Layer	What purpose does it serve for this study?	Previous studies	Data Source
Urban Impervious Cover	This layer of data will allow me to uncover areas of impervious cover that can be developed with GI as we don't want to develop GI projects in already pervious areas.	Christman et al. 2018	NLCD 2019 Percent Developed Imperviousness (CONUS) from MLRC (Multi-Resolution Land Characteristics Consortium)
Flood Zones	This layer of data will illuminate locations of low to high risks of flooding by looking at the 5, 10, 50, and 500 year-floodplains. This will give me hotspots where GI will be most suitable for mitigate flood hazards.	Omitaomu et al. 2021, Zoll 2021	Downloaded from the TWDB
Land Cover	This layer uncovers the different types of land use within the city of Austin and when used in the suitability analysis, it will show which types of land cover will be suitable for GI.	Christman et al. 2018	Received from the NLCR: NLCD 2019 Land Cover (CONUS
River Distance	This layer of data will allow me to look at the distance from waterbodies around the city of Austin. This layer will work in tandem with the flood zones layer as it will help to make the suitable sites fall closer to water bodies instead of further away where	Zoll 2021	Received the nhdplus data from the USGS

	they will be less likely to provide flood relief.		
Slope	The slope layer goes in tandem with the DEM layer as it will help to find suitable locations based on lower slope where it is easier to implement GI projects.	Christman et al. 2018, Zoll 2021, MACC	Used the DEM layer: 2017 Contour data from the city of Austin Open Data Portal
Digital Elevation Model	The contour data will be used to create a DEM layer that will allow me to exclude high elevation points that will not be affected by flooding in the suitability model.	Omitaomu et al. 2021, Zoll 2021	2017 Contour data from the city of Austin Open Data Portal
Already built small-scale GI	This layer of data will show the already built small-scale GI around the city of Austin and will allow me to compare the most suitable sites of GI to already built GI to see if these projects will have any impact on mitigating against flood hazards.	Christman et al. 2018	Map Austin's Small-Scale Green Infrastructure from the city of Austin Open Data Portal
Low-income neighborhoods	This layer of data will be used to illuminate the low-income neighborhoods around the city of Austin and will be used to compare to the suitability model and already built GI to uncover any disproportions of built projects, illuminating possible injustices.	Christman et al. 2018, Zoll 2021	Census Bureau through the Austin Community Survey: S1901INCOME IN THE PAST 12 MONTHS (IN 2021 INFLATION-ADJUSTED DOLLARS)

Table 1: Data Layers used in analysis.

4.2. Data Analysis

Data analysis was completed using ArcPro by ESRI and began with clipping the data to the city boundary and ensuring all the layers were projected in the same coordinate system: NAD 1983 State Plane Texas Central FIPS 4203 (US Feet) and all raster layers had a cell size of 98.425 feet. From there, I built the map showing low-income and non-low-income areas containing GI and ran basic calculations to illuminate the number of already built GI in these two distinct economic areas. To do this, I used the ESRI Low Income Community Census Tracts – 2016-2020 to show the areas that qualify as low-income areas based on two differing criteria:

- The poverty rate is at least 20 percent, OR
- The median family income does not exceed 80 percent of statewide median family income or, if in a metropolitan area, the greater of 80 percent statewide median family income or 80 percent of metropolitan area median family income

This data reflects income statistics from 2016 to 2020 and shows the qualification of low-income in Austin as around $70,000 or less per year. To be considered low-income in Austin today, a household must make $78,000 or less a year. To compare locations of GI to this low-income dataset, I overlayed the already built GI buffer layer, with a buffer of 50 US survey feet, to the income layer and ran the *summarize within tool* to calculate the number of GI points within each income level polygon. I then changed the symbology to *Unique Values* to show the breakup of the data into no points of GI, points of GI within higher-income areas, and points of GI within low-income areas.

I then grouped together the polygons within each category to show the geographical patterns of GI placement between low-income and higher-income groups.

To create the suitability model, I built several layers: land cover, urban impervious cover, DEM, slope, flood zones, and river distance. These layers define the requirements to find suitable sites of GI and were all manipulated to be useable in the suitability modeler.

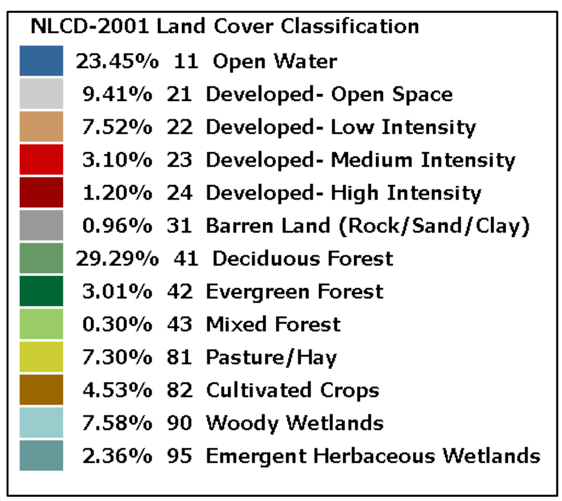

Figure 7: NLCD Land Classification System.

The land cover data was received in raster format as the suitability modeler requires this format to work. For the land cover layer to be useful in the model, I clipped and projected the layer to the city boundary layer and reclassified the data. To do this, I used the clip raster tool, the project raster tool, and the reclassify tool. Figure 7 shows the standard NLCD classifications of the land cover data.

I reclassified this data to show which land cover classifications would be the best fit for my suitability model (Table 2). Using a tiering classification system, I classified the different land cover areas with a number from 0 to 4, 0 being the least suitable cover type. I focused on the developed open space, classifying these spaces as my most suitable areas (4) as these areas are filled with parks, golf courses, and open, developed land that could benefit from GI implementation. The next highest suitable areas (3) were the developed low and medium intensity areas. These areas contain single-family houses, and a percentage of impervious cover that would benefit from small-scale GI. Tier 2 includes the highly developed areas as these areas are filled with a high percentage of impervious cover and have intense urban development. The reason these areas are not ranked higher is due to portions of the areas are highways which are not conducive to GI locations, but the other portions of these areas contain the sides of roads which are more conducive to GI. Tier 1 includes barren land, shrub/scrub, grasslands, pastures, and cultivated land as these areas could benefit from GI implementation such as rain barrels but are already areas where rain catchment occurs. The final tier of 0 includes the forested areas, open water, and wetland areas that are present in the city. These areas are not conducive to GI and would not be suitable sites.

Land Cover Classification Number	Land Cover Classification	Classification Scale
11	Open water	0
21	Developed open space	4
22	Developed low intensity	3
23	Developed medium	3

24	Developed high	2
31	Barren land	1
41	Deciduous forest	0
42	Evergreen forest	0
43	Mixed forest	0
52	Shrub/Scrub	1
71	Grasslands	1
81	Pasture	1
82	Cultivated	1
90	Woody wetlands	0
95	Emergent wetlands	0

Table 2: Land cover classification scale for suitability model.

The urban impervious cover layer was already set up in raster format and the only tools used to create a usable layer were the clip raster and project raster tools to format the layer the same way as the city boundary layer. Similarly, the DEM layer was already formatted as a raster layer. I used the reclassify tool to change the cell size of the layer to 98.245 to match the other layers. This will help the process of the suitability modeler in having a uniform cell size. Using the DEM layer, I used the slope tool to transform the DEM data into a slope layer.

My biggest challenge was building the flood zones layer as finding the proper and most useful data for my study area was difficult. The data I found was split into both pluvial (rainwater fed) and fluvial (groundwater fed) water ways around the city of Austin and was split further into a 1 in 5 percent chance of occurring, 1 in 10 percent chance, 1 in 100 percent chance, and 1 in 500 percent chance, showing the differing levels and magnitudes of floods. To build this layer, I began by combining the pluvial and fluvial datasets for each flood zone. I then reclassified each layer based on the value, changing the continuous data format to a binary format to create an output of either:

1 = yes, this cell is a flood zone or
0 = no, this area is not a flood zone

These were created for each flood zone. The 0 (not a flood zone) was reclassified once more to reflect no data instead of just a 0 due to the way it would read when each level flood zone layer were combined. When combined, the 0 would read as the minimum number, but to stack the flood zones properly with the mosaic new raster tool, I needed the tool to read 1 as the minimum number. The mosaic new raster tool allowed me to combine the flood zones on top of one another, illuminating the buildup of the levels of flood zones and areas where more frequent, regular flooding occurs.

To create the river distance layer, downloaded rivers, culverts, and waterbodies within my study area, rasterized both datasets, and combined them into a binary raster set of:

1 = water and
0 = everything else

Once the data was combined, I ran the Euclidean distance tool to output a raster with each cell value representing the distance in feet to the nearest water.

With all my layers built, I began the suitability model building process. I set up the suitability scale to read 1 to 5 levels of suitability as this suited the parameters of my dataset the best. I left the *Weight By* as multiplier, meaning that once the layers are combined, the weight of each cell from each layer will be multiplied all the way down to give an output of which cell is most suitable. I then added my raster layers and weighted them as follows:

Slope = 1.25	Elevation = 1.25	Urban Imperviousness = 1
Land Cover = 1.25	River Distance = 1.25	Flood zones = 1.5

I weighted the flood zones layer higher than the rest as this is a major requirement in determining the location of GI. From there, I set the parameters for the number of regions and total area. The highest number of regions I could use was 30, so I used that number as if I were to implement 30 new GI projects around the city. With that in mind, I used the buffer distance of 50 feet from my already built GI layer to use as a base for the total area. When calculated, the total area equaled 1500 feet. This is a very small portion of the city, but because I am looking at small-scale GI projects, it fits the criteria. Once this criterion was set, I set the parameters for each layer as follows.

For the DEM or elevation layer, I used the continuous linear function to transform the data. I inverted the dataset to reflect the most suitable sites which occur in the lowest elevations. Details are shown in Figure 8.

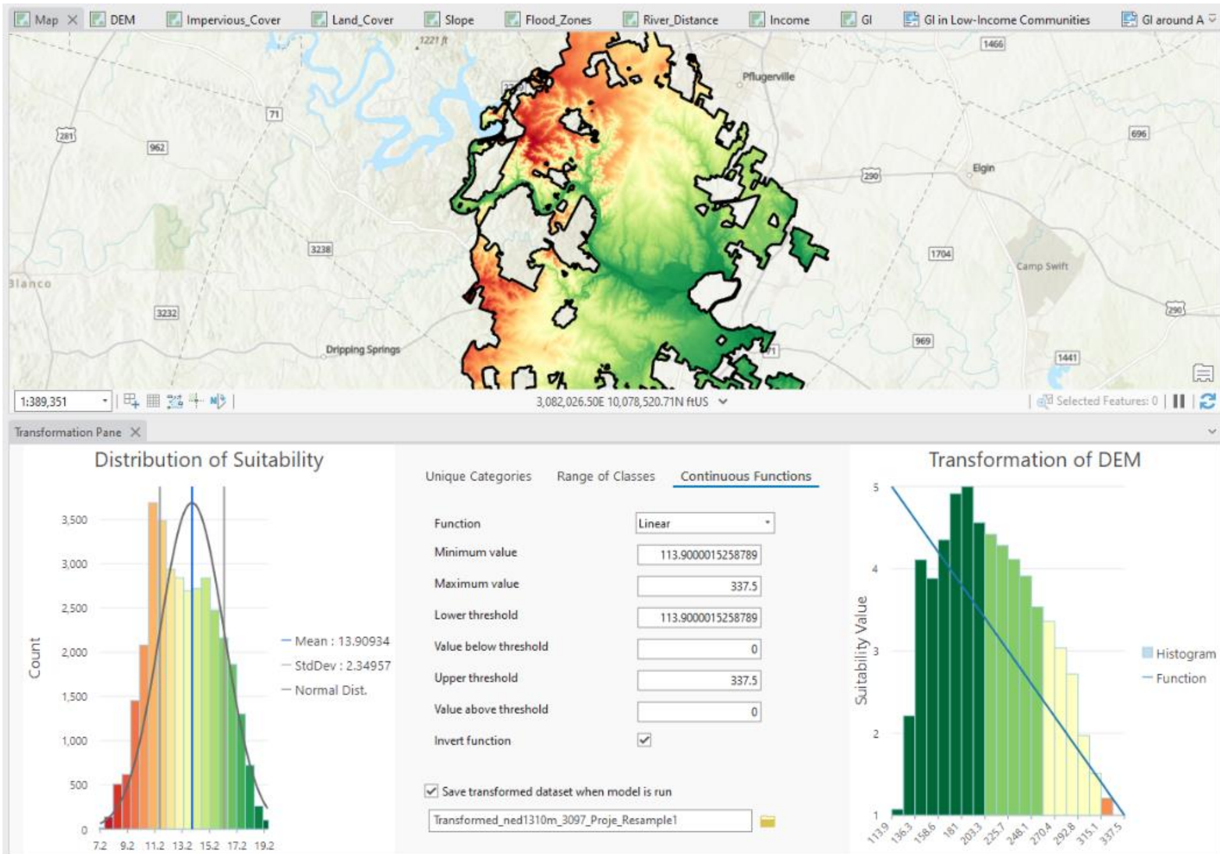

Figure 8: Elevation Layer in Suitability Modeler.

The slope layer was transformed to the continuous linear function. I inverted this data to target locations of lower slope. Details are shown in Figure 9.

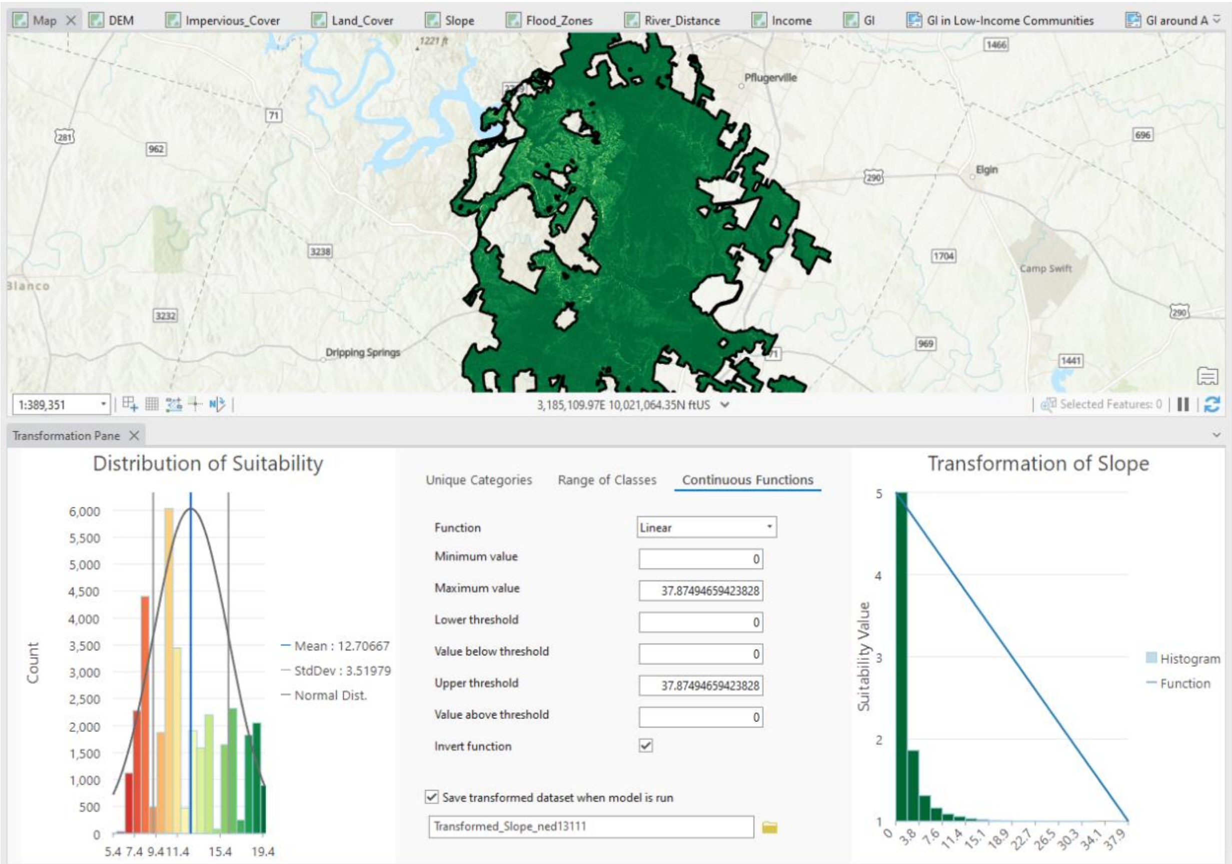

Figure 9: Slope Layer in the Suitability Modeler.

The Land cover layer was transformed into the unique categories function to classify the different levels of suitability based on the types of land cover in each cell area. The more developed open space, the higher the suitability. Details are shown in Figure 10.

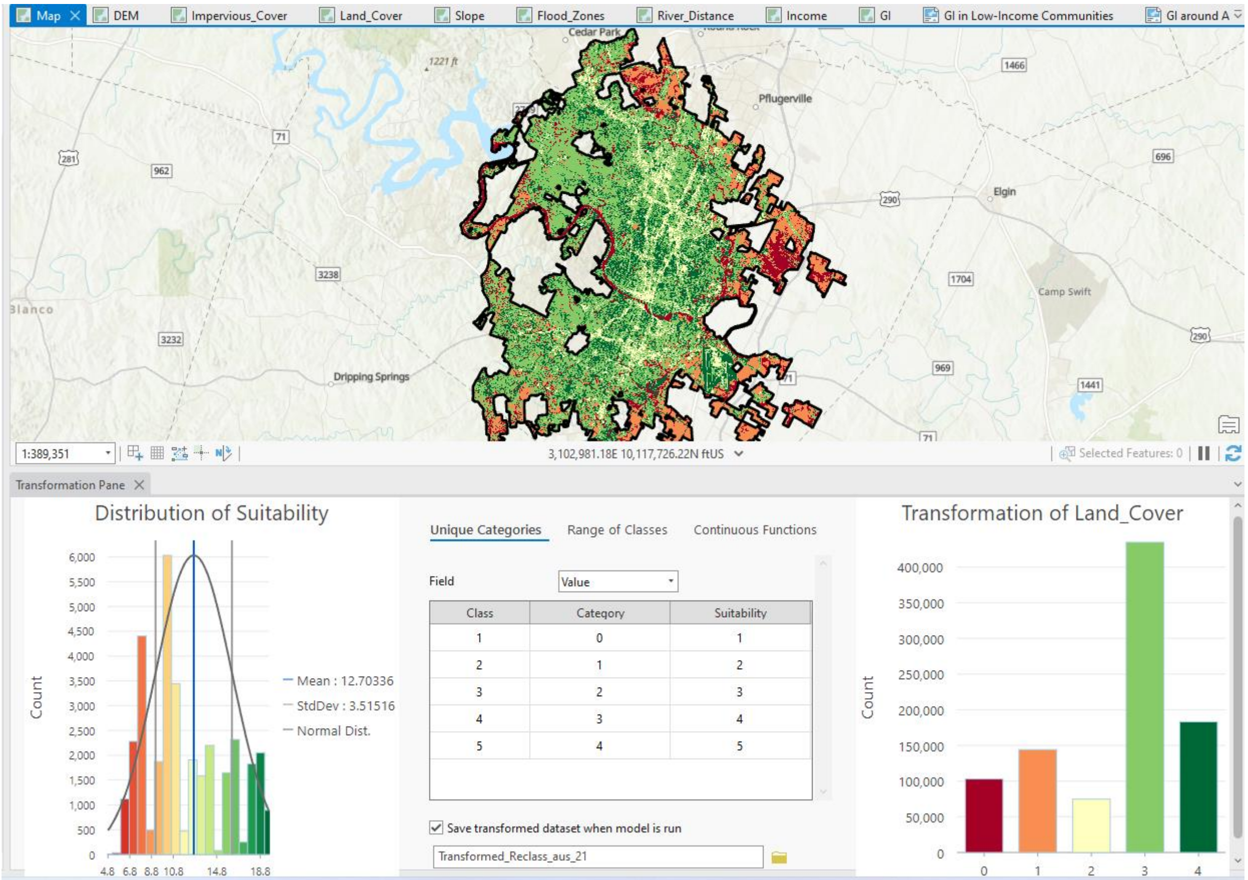

Figure 10: Land Cover Layer in Suitability Modeler.

The flood zones layer was transformed in the unique categories function. The most suitable sites were defined by class 1 due to the frequent occurrence of these types of floods. As each flood zone increased in severity, the lower the suitability ranking. This was done to focus on the areas that flood the most frequently, which are also areas impacted by larger, less frequent floods. Details are shown in Figure 11.

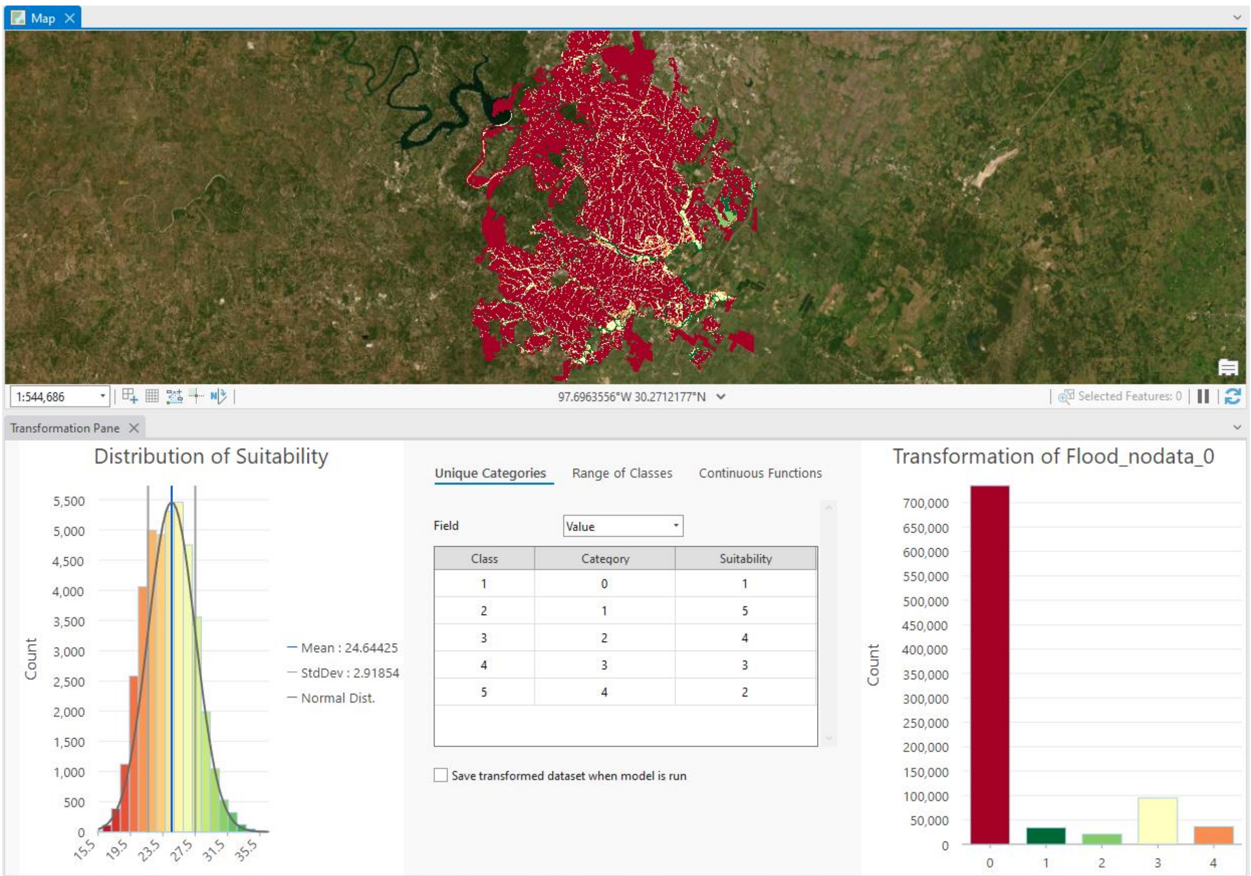

Figure 11: Flood Zones Layer in the Suitability Modeler.

The distance from river layer was similar to both the slope and elevation layers as the continuous linear function was used to transform the layer. It was then inverted to make the shortest distance from a water body the most suitable spot. Details shown in Figure 12.

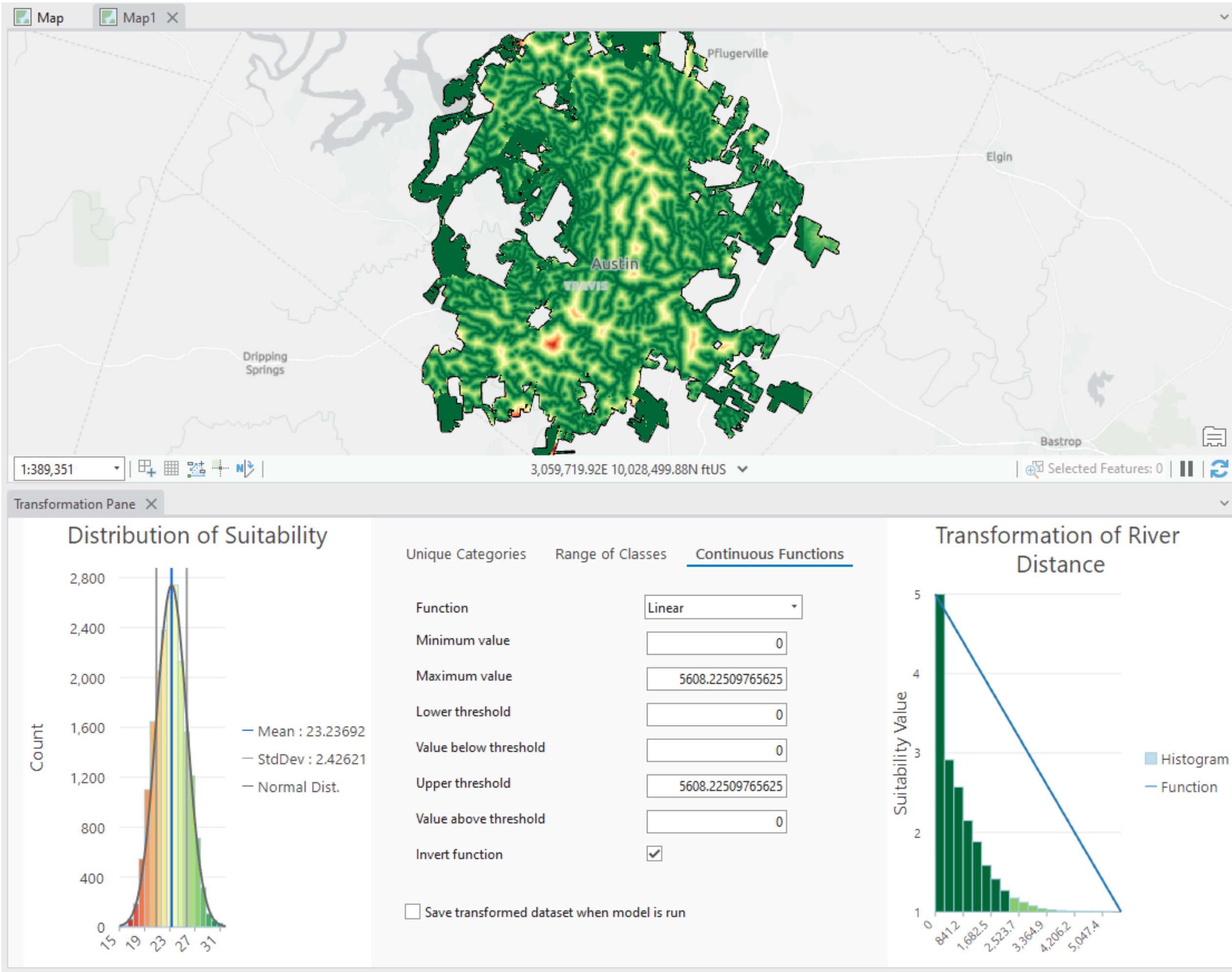

Figure 12: River Distance Layer in the Suitability Modeler.

The impervious cover was transformed using the range of classes function. This allowed me to rank the suitability of each section of range of impervious cover. I ranked the first and last classes (the lowest amount of impervious cover and highest amount of imperious cover) as the lowest suitability level due to the lack of impervious cover in the lowest class (1) and the inclusion of major highways in the highest amount of impervious cover class (10). From there I classified class 2 and 9 as suitability level 2 due to similar reasonings as the class 1 and 10. Class 3 and 8 were ranked with a suitability of 3 due to the balance of impervious cover and more suitable areas for GI within these areas. Class 4 and 7 were ranked with a suitability level of 4 and classes 5 and 6 were ranked with a suitability score of 5 for having the most suitable impervious cover within the cell regions. Details shown in Figure 13.

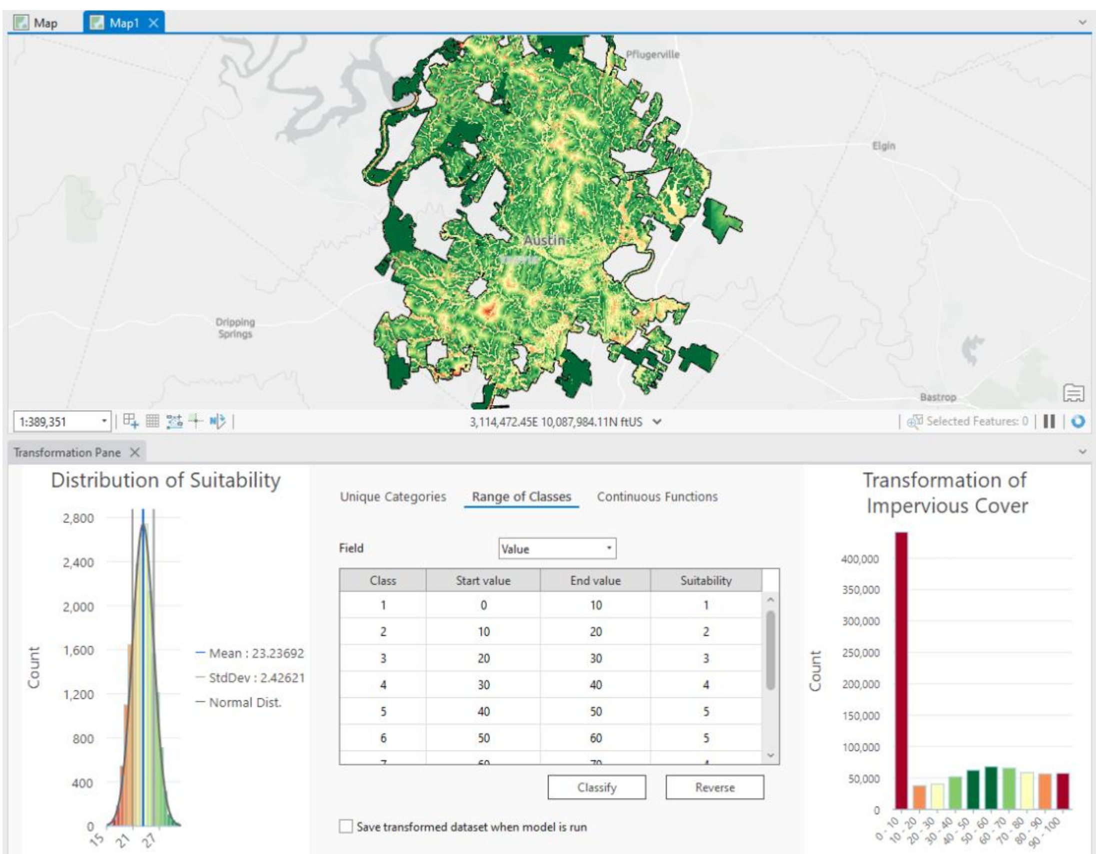

Figure 13: Impervious Cover Layer in the Suitability Modeler.

5. Results

Figure 14 shows the comparison of low-income areas to points of GI around the city of Austin to Income classes. As shown in Figure 14, there are 34 GI locations in higher-income neighborhoods and 20 GI locations in low-income neighborhoods.

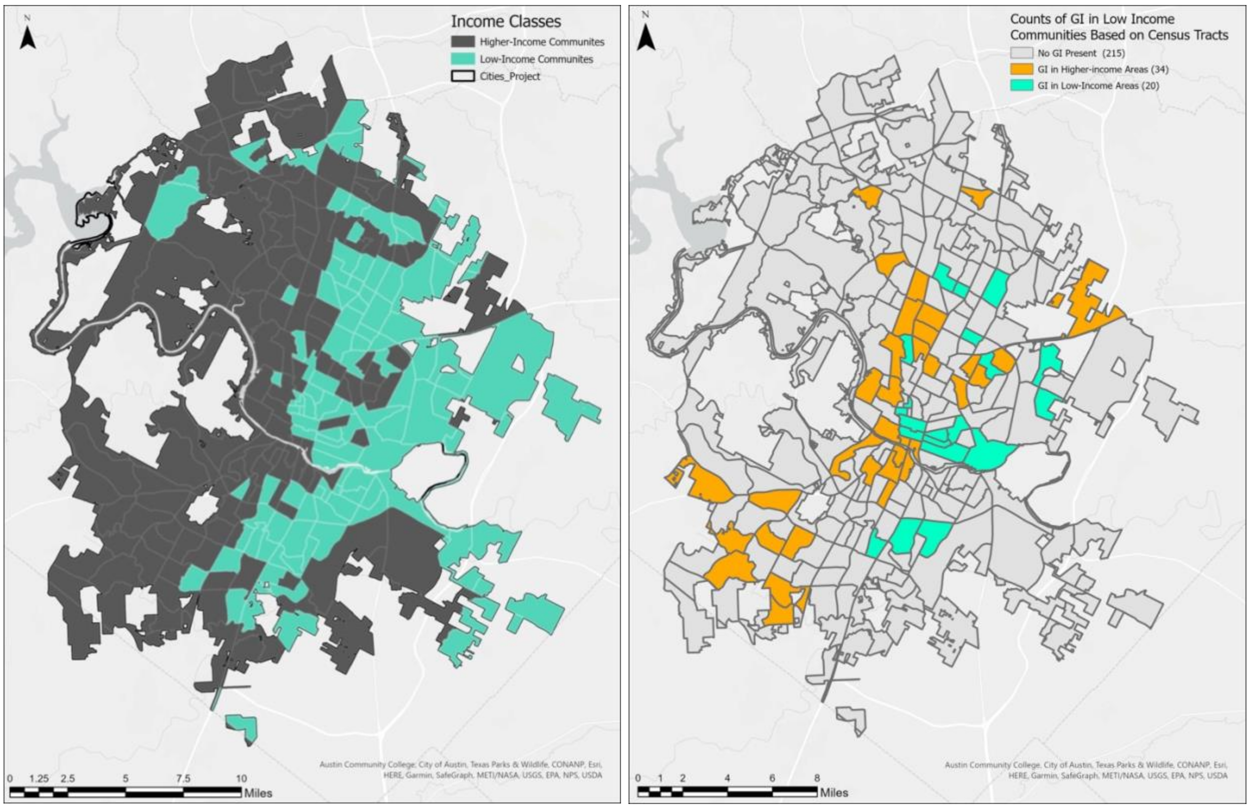

Figure 14: A side-by-side comparison of Income Class Map to Total number of GI locations within Low-income areas.

The suitability modeler produced the output raster in Figure 15. The output was created with a range of 14.91 to 37.13, and to normalize this range, the normalize raster tool was used to produce a range of 0 to 100, allowing the output raster to have a more understandable range. To produce this output in Figure 15, the land cover layer was reclassified once more to transform the no data class into a class of 0. Leaving the land cover layer with a class of no data would change the pattern of the output completely and would not reflect a proper suitability map.

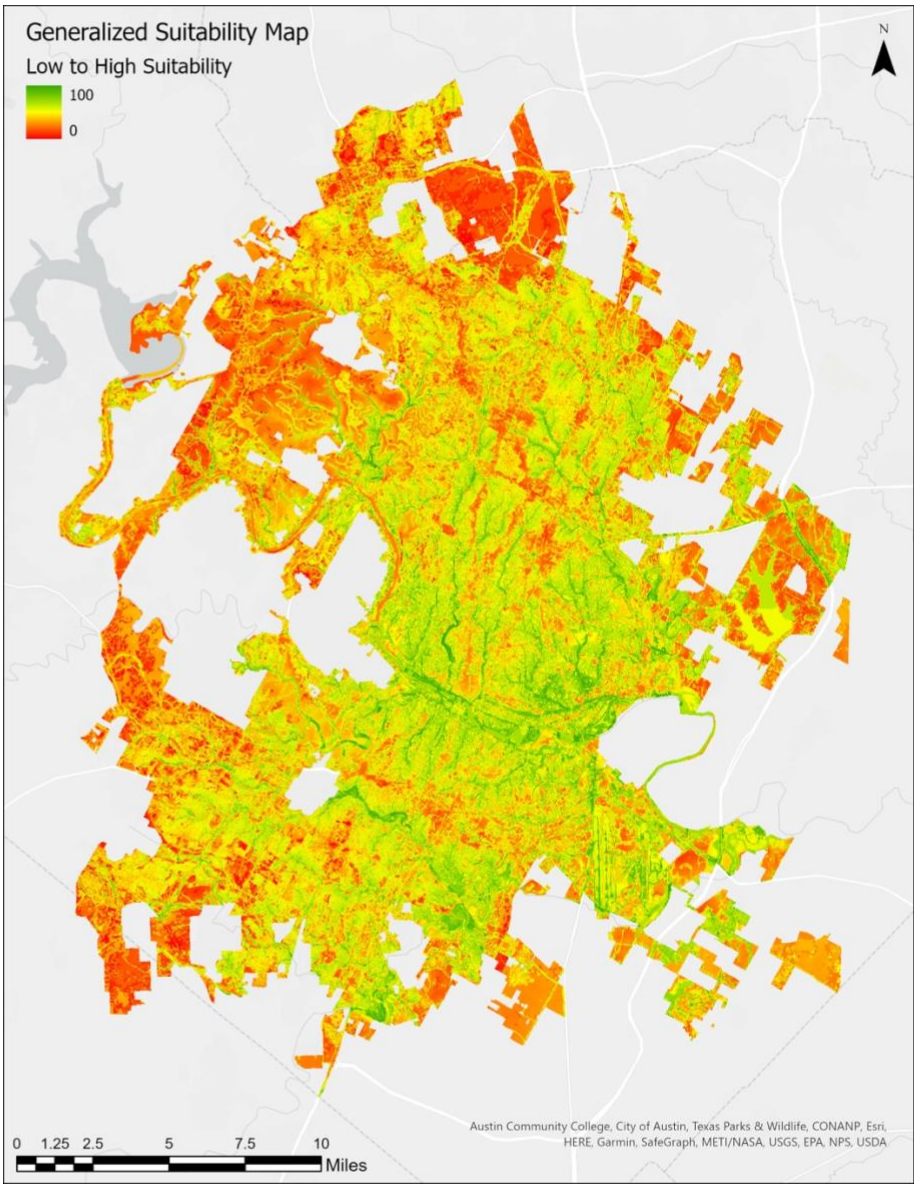

Figure 15: General Suitability Map Output.

Once the layers were built and the general suitability model was created, parameters were set in the locate section of the suitability modeler to locate suitable GI sites. Parameters were set to produce a minimum GI area size of 1 acre and a maximum size of 10 acres. Ten suitable areas were found (in the red circles in Figure 16). A closer perspective of suitable sites can be seen in Figure 17.

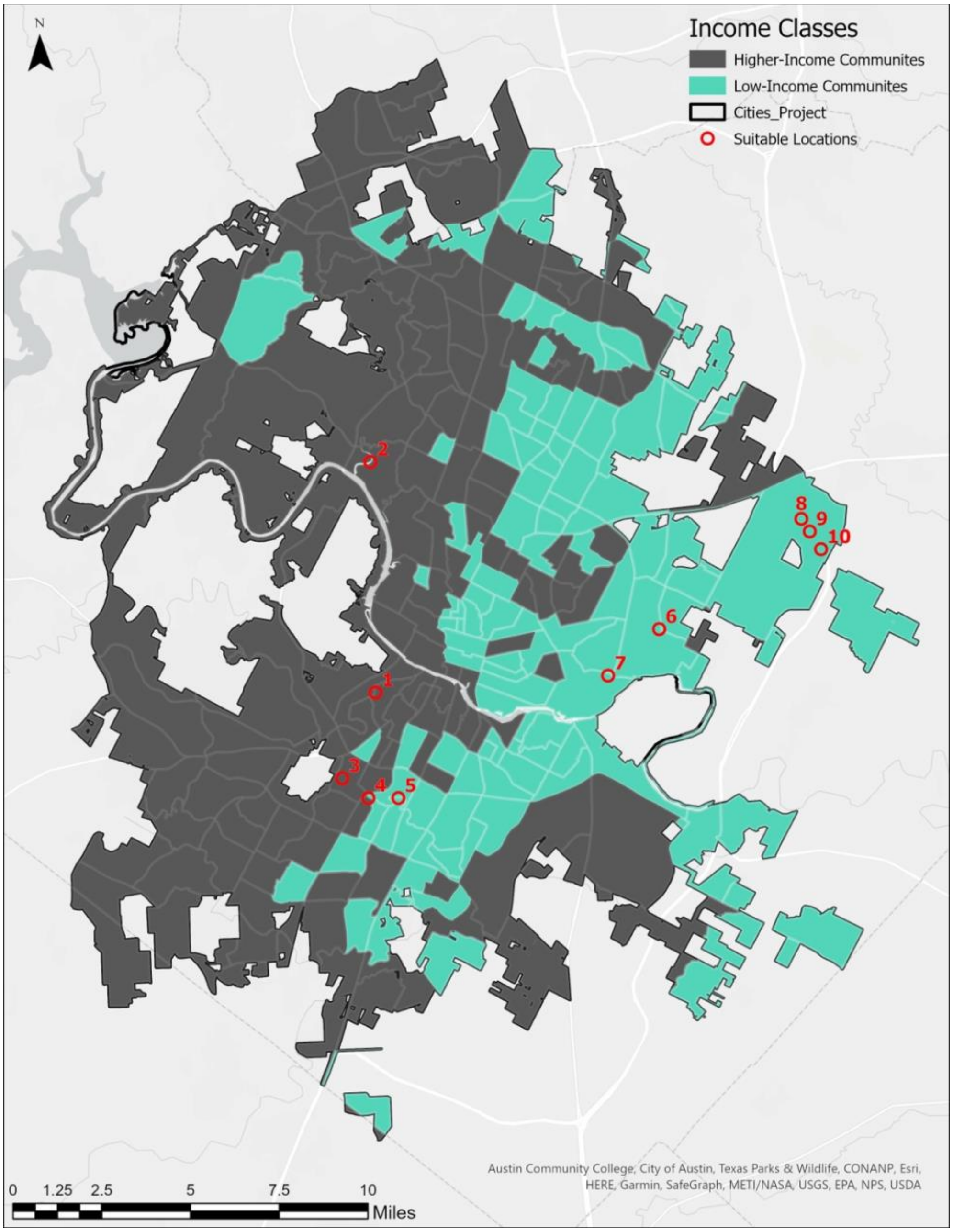

Figure 16: GI Suitability Locations Output

The raster to polygon tool was used to change the 10 suitable sites output (a raster output) to points. This allowed me to create a 500-meter buffer around each site.

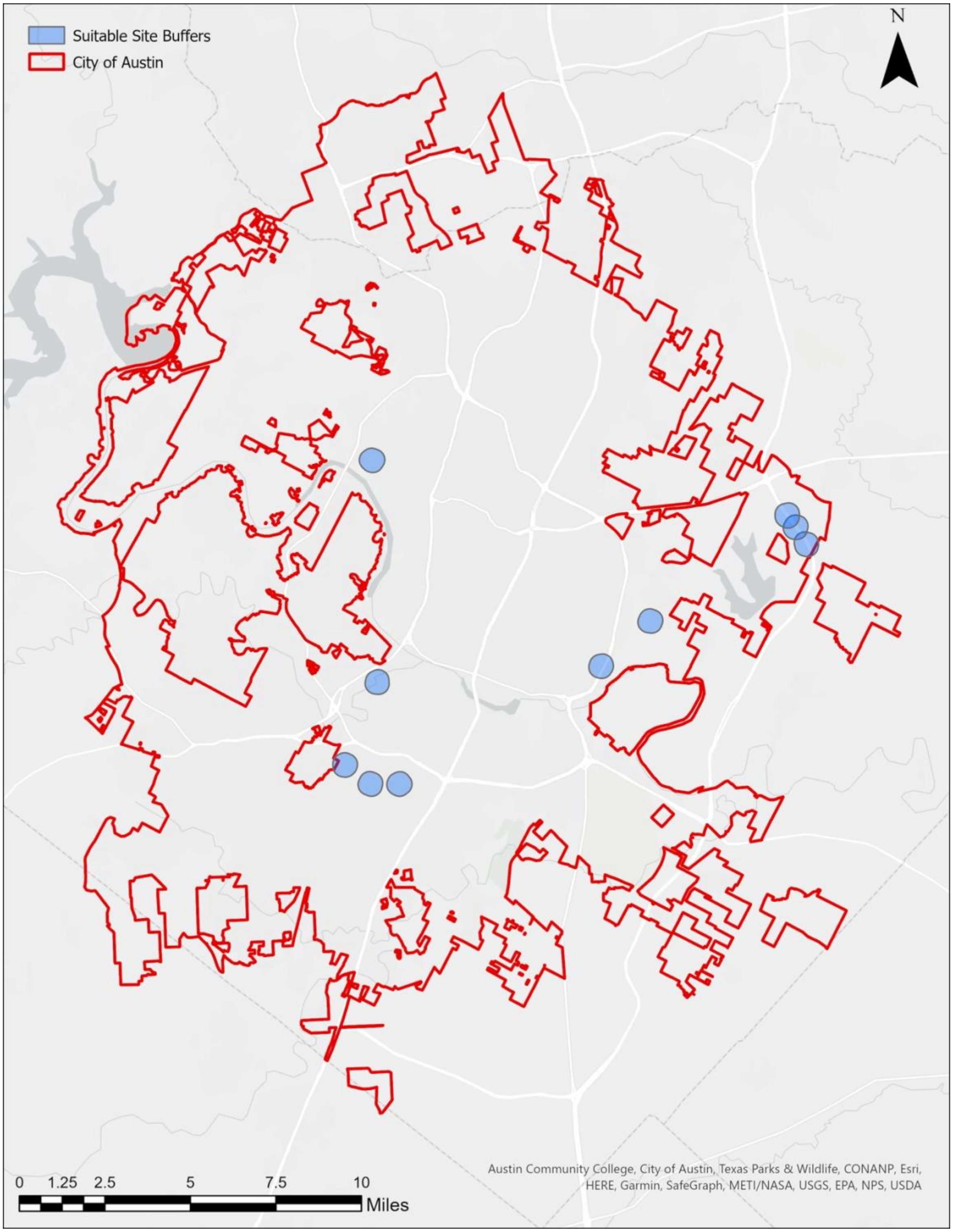

Figure 17: 500m buffers around each suitable site.

Figure 18: Suitable site number 1.

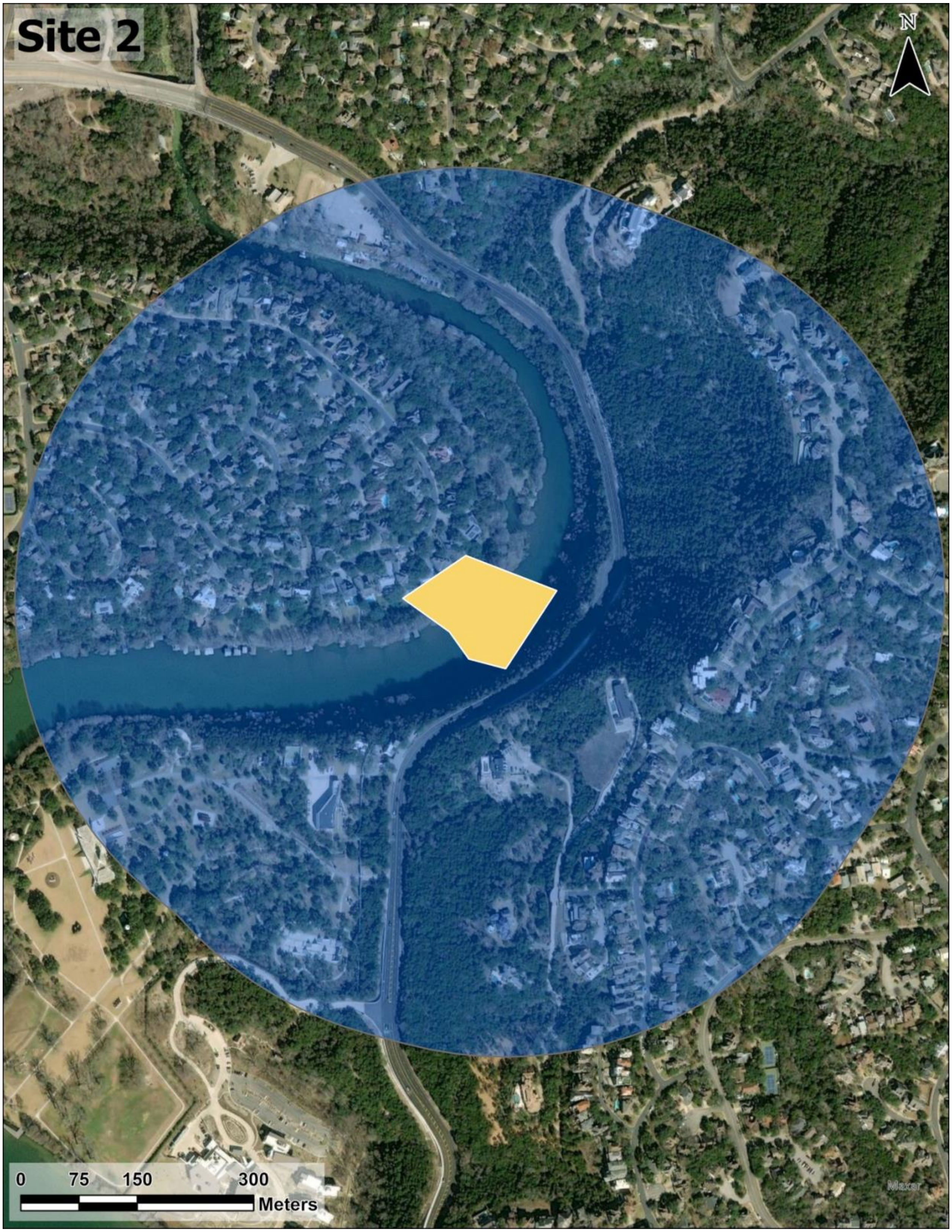

Figure 19: Suitable site number 2.

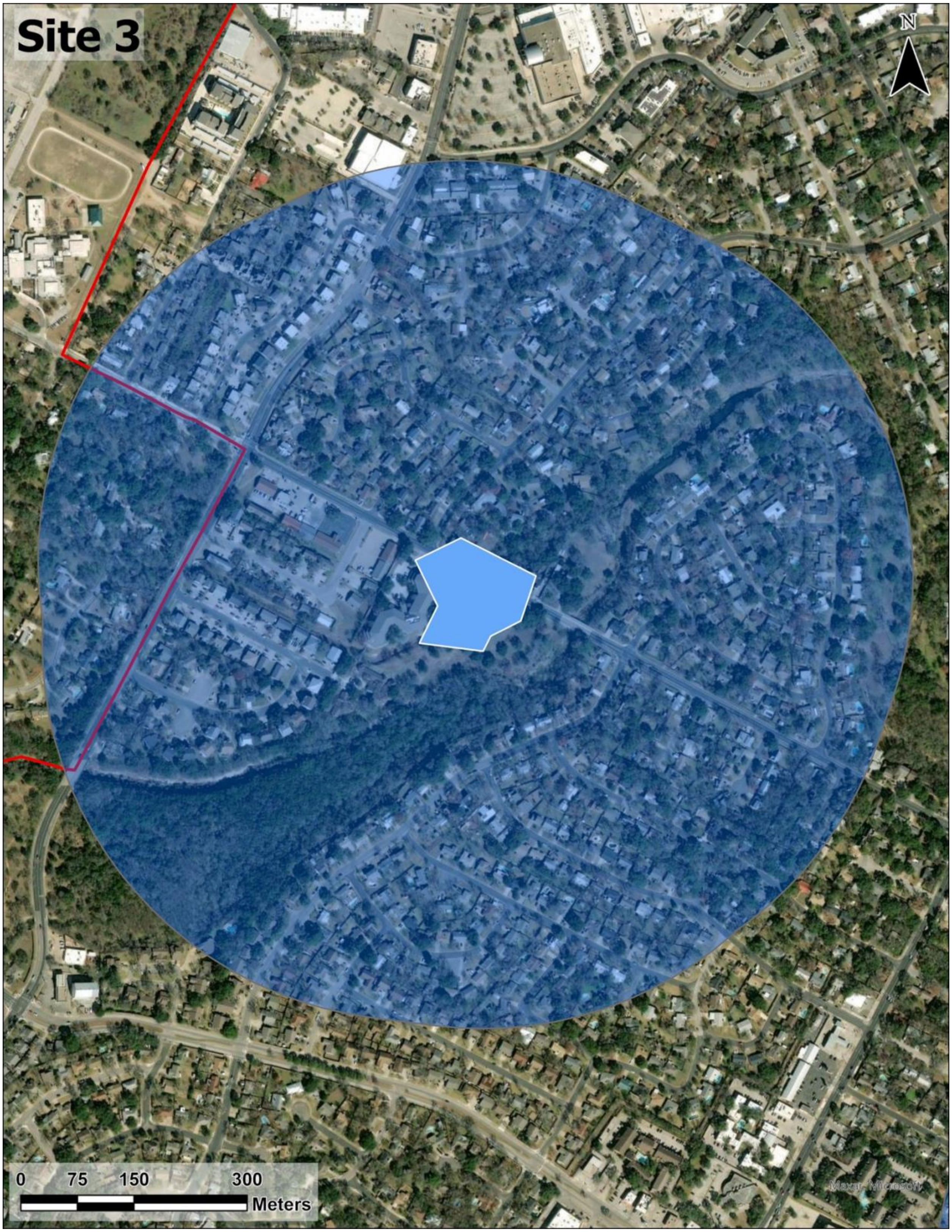

Figure 20: Suitable site number 3.

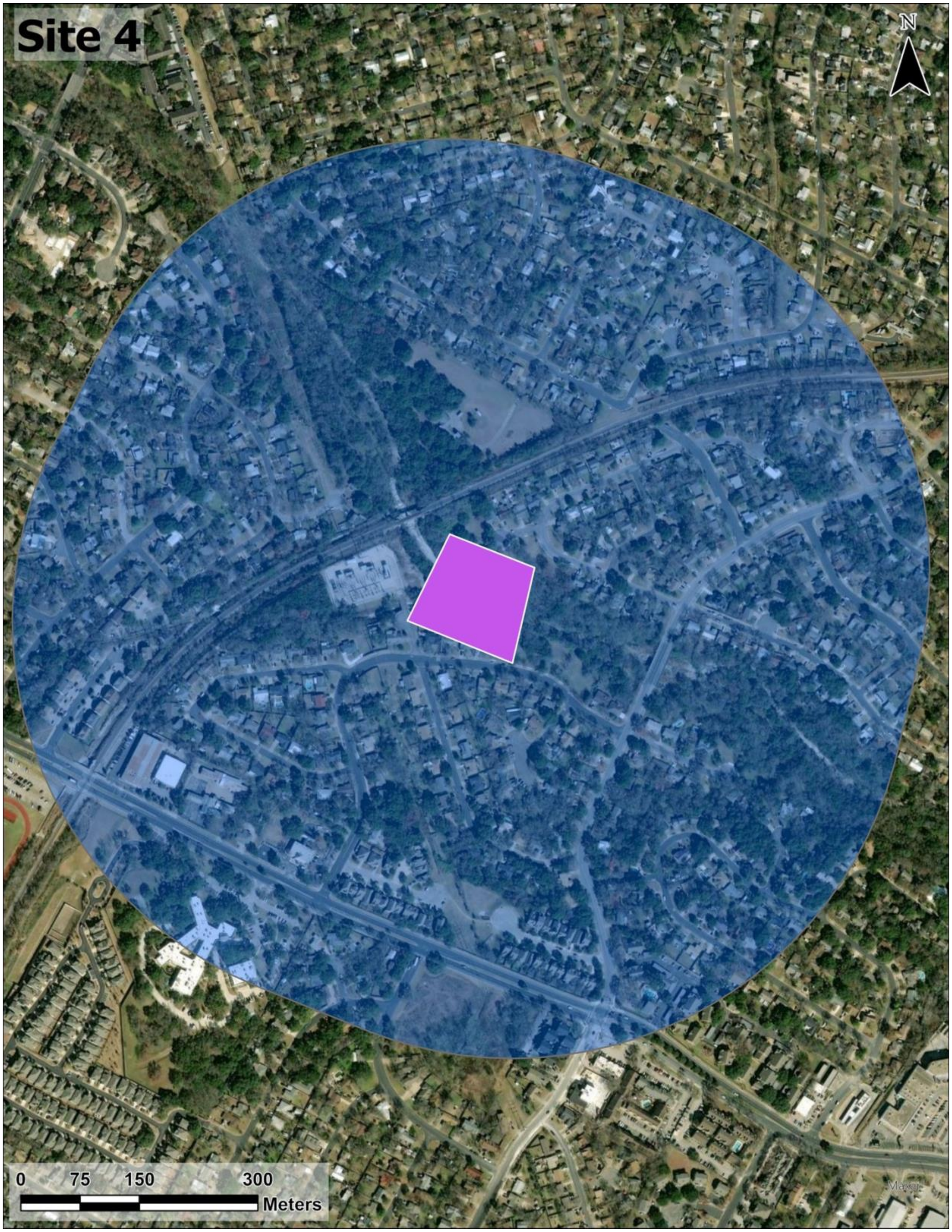

Figure 21: Suitable site number 4.

Figure 22: Suitable site number 5.

Figure 23: Suitable site number 6.

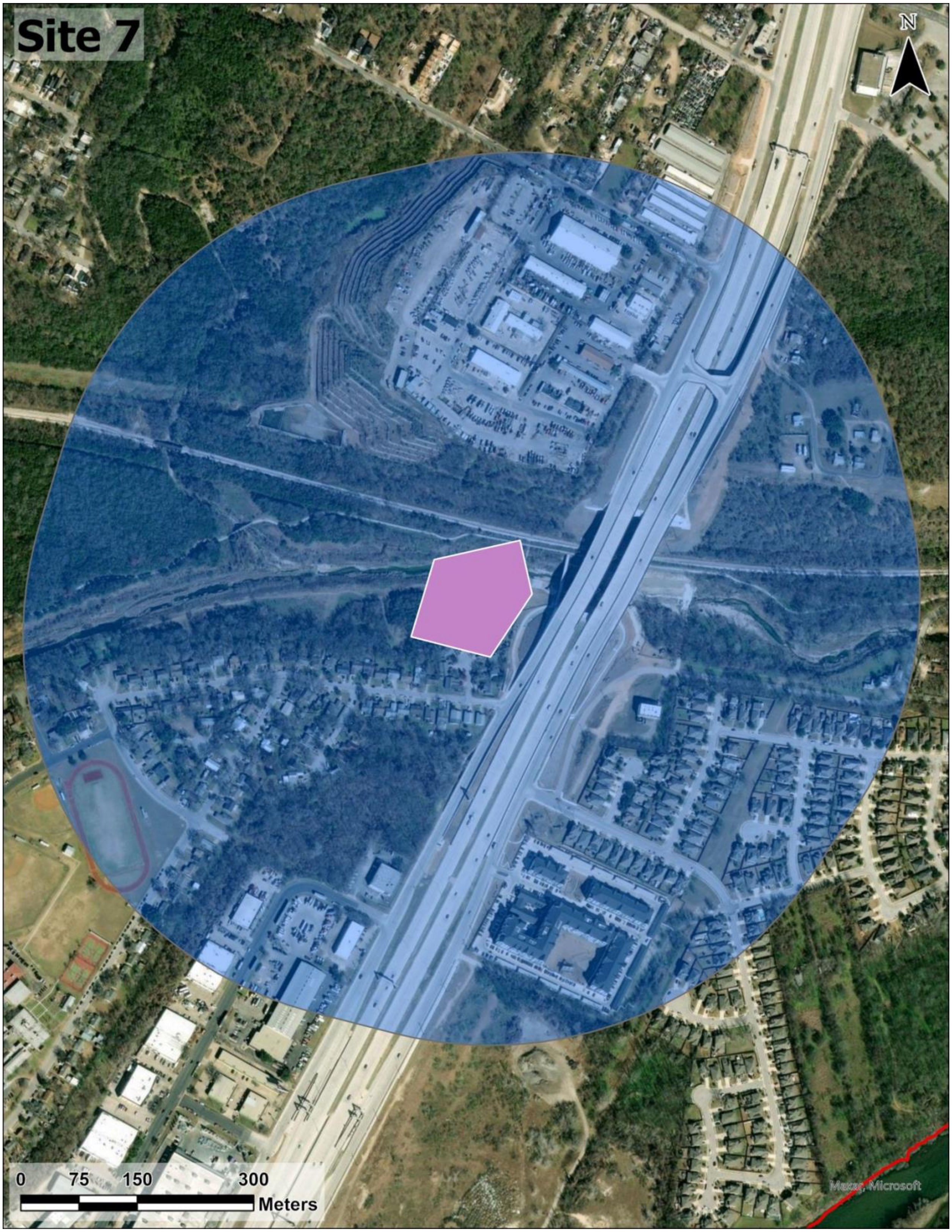

Figure 24: Suitable site number 7.

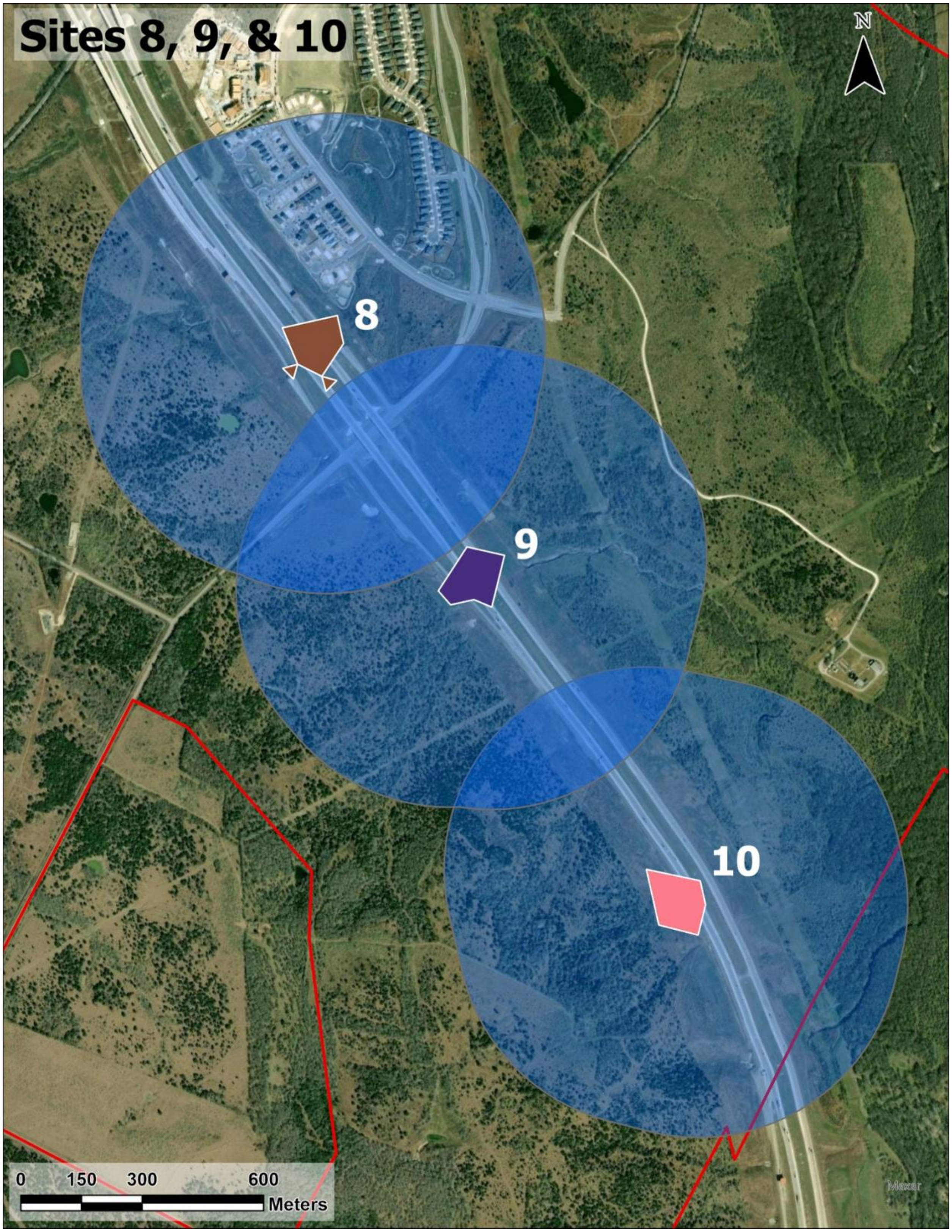

Figure 25: Suitable site number 8, 9, & 10.

Figure 18 is a side-by-side comparison of the suitable locations of small-scale GI around the city of Austin and the actual built small-scale GI to give a sense of what areas are being focused on and which areas need more focus.

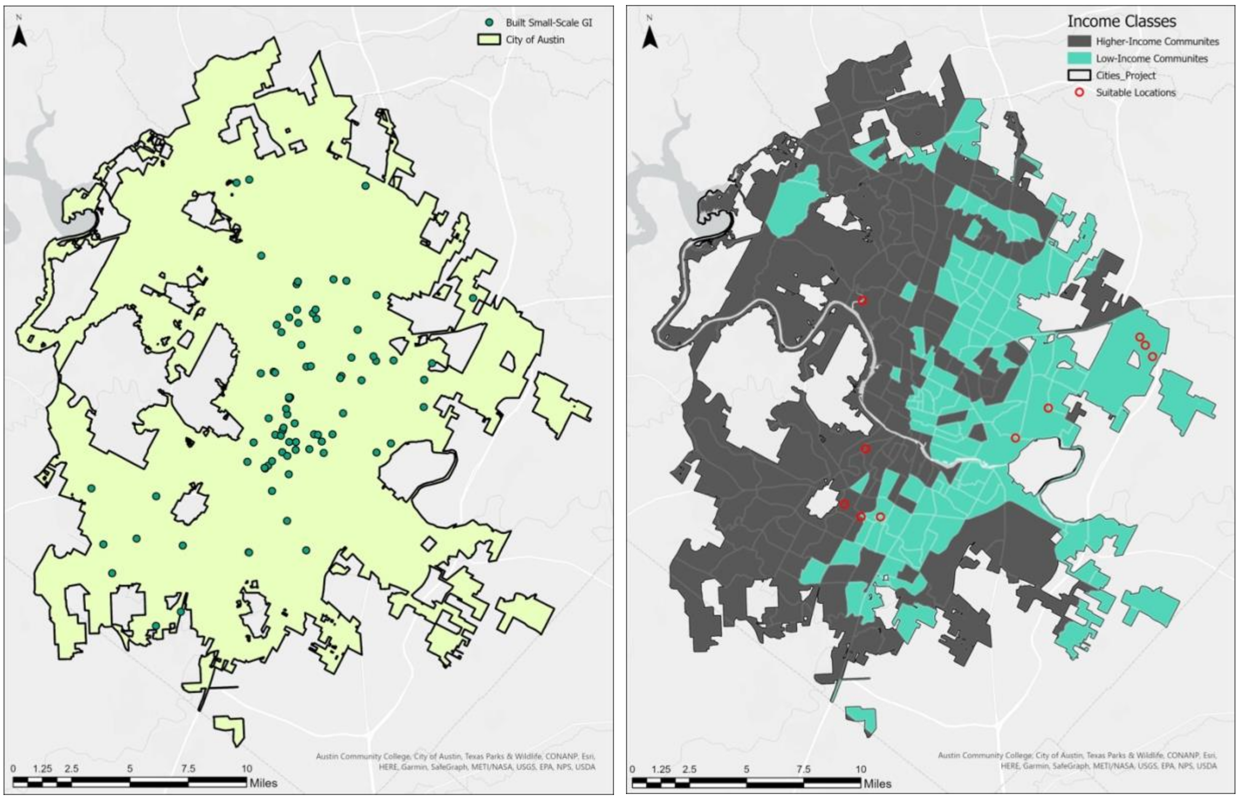

Figure 26: Side-by-side comparison of suitable sites of GI in different economic classes to actual built GI around Austin.

6. *Discussion*

6.1. Major Findings

As hypothesized, there is a pattern of a disproportionate number of small-scale GI locations between different income levels (Figure 14). There are 20 locations of GI within low-income areas and 34 locations of GI within higher-income areas, showing a disproportionate pattern. Figure 14 illustrates a clear cluster of census tracts containing locations of GI in the central part of the city. In contrast, many low-income neighborhoods in the East part of the city do not have GI. This pattern is not surprising as East Austin encompasses a large portion of low-income neighborhoods. While this pattern does not show cause, there is evidence that lower-income areas are not being prioritized in the implementation decisions of small-scale GI. Despite there being programs through the city that provide incentives and grants for small-scale projects, there might not be enough time or resources that allow for low-income communities to take advantage of these opportunities. This area includes the watershed of Lady Bird Lake, which flows right through central Austin, making it a major priority for flood mitigation strategies. Similarly, there is a portion of GI locations in higher-income areas in the southwest region of the city (Figure 14). This area is predominately neighborhoods located in the Williamson creek watershed.

The general output of the suitability model (Figure 15) shows suitability levels of potential sites around the City of Austin with the most suitable areas in green. The green areas are predominantly in the central, east, and south regions of the city. These areas are in close proximity to the rivers and streams, which is exactly where GI will be most beneficial in mitigating flood hazards. The locate tool within the suitability modeler (an analysis tool in ArcPro) helped to define 10 of the most suitable sites for GI (Figure 16). Surprisingly, the suitability model results did not follow the pattern of centrally located GI already placed in the city. This pattern is seen more clearly in Figure 26. As indicated in Figure 26, most of the existing GI is located centrally within the city, whereas the most suitable sites are located mostly in the east and a few points in southwest regions of the city. Half of the suitable sites are located in the eastern region of the city, again, revealing a need to start implementing GI into low-income, communities in the east side of the city. There needs to be a shift to provide resources for these low-income communities to implement small-scale GI projects that have the potential to not only help mitigate flooding, but to also provide a host of ecosystem services. This push needs to come from policy and incentive and grant program reform that provide accessibility to these projects in the disadvantaged communities. Through outreach programs that target low-income communities with educational flyers and special rebates for GI projects, these disadvantaged communities would have more opportunity to implement such projects and fight against flood hazards.

Looking more specifically at each suitable site (Figures 18 through 25), the suitable locations are set in similar conditions – off roadsides, rivers, and next to already green space. Site 1 (Figure 18) is located in the riparian zone of a Barton Creek tributary. This location is reasonable, as it provides the area with flood relief during flooding events. Geographically, this site sits in higher-income neighborhoods. Looking closely at the surrounding neighborhoods, there is a lot of roadway infrastructure where small bioretention ponds could be implemented off the sidewalks. There is also a major road just north of the site surrounded by open space. Bioretention ponds could be built in these open spaces to help with quicker infiltration rates to help mitigate roadway damage from flooding. The Neighborhood Partnering Program could advertise a collective program throughout the neighborhoods and businesses in the area to educate those in the area about flood mitigation strategies and to help raise money for such projects.

Figure 19 shows the area Site 2 is located. The suitability modeler was strongly correlated to waterways and flood zones making this raster site fall on top of the waterway. Although the site placement is questionable, there is potential for GI placement in the surrounding neighborhoods. This site falls in the higher-income areas where it might be more accessible for some to implement small-scale GI. Ranch Road 2222 passes right through the study area and looking at the map, the medians look solidly concrete making these spots the perfect opportunity to build bioretention ponds or green gardens in those open medians. Similarly to Site 1, the Neighborhood Partnering Program could provide educational outreach to these communities and provide their current initiatives to persuade these communities to implement these projects. The Adopt-a-median program under the Neighborhood Partnering Program could also be an option for these communities to participate in.

Site 3, in Figure 20, sits just to the side of a stream within a highly urbanized area. The surrounding neighborhoods are higher-income status and would be the perfect fit for rain barrels. To implement rain barrels into this area, the Neighborhood Partnering Program could be used to educate the communities on the use of rain barrels and provide information on the incentives and grants they currently have for such programs. This information could be spread through HOAs via email. Similarly, to site 3, site 4 is in a heavily urbanized area, just off a stream (Figure 21). Because this area is made up of mostly neighborhoods in a higher-income status, programs such as the rain barrel program through the Neighborhood Partnering Program could be used to entice these communities to implement such projects into their landscapes. Again, the rain barrel program could be spread around through the different HOAs, providing these residents with information on the use, impacts and ways to implement rain barrels into their communities.

Site 5 is in close proximity to sites 3 and 4 but are in a low-income status community (Figure 22). The site is in the southwest region of the city and is located along a creek in the middle of the cityscape. This is an ideal spot based on GI implementation for flood mitigation, especially for low-income neighborhoods. Implementing projects into the lower-income communities might be harder as these communities might not have the time nor the education to implement these kinds of projects into their landscapes. Focusing on these disadvantaged communities is important as they have been left out of the environmental movement for a long time. With the Neighborhood Partnering Program, pamphlets with educational information on flooding and mitigation strategies such as GI can be placed at each residence to provide these communities with the extra information they might be lacking. Town Hall meetings could be arraigned to provide such information to these neighborhoods in an open forum setting. For site 5 specifically, a rain barrel assistance program would be beneficial to help the surrounding communities mitigate against flooding. Through the Neighborhood Partnering Program, and with the aid of the City, a rain barrel assistance program could be provided to those who sign up and are eligible based on a certain amount of income set by the city. Likewise, sites 6 and 7 are situated in low-income communities. Site 6 is adjacent to MLK Blvd (shown in Figure 23) while Site 7 is adjacent to Ed Bluestein Blvd and a railroad track in some green space (shown in Figure 24). This area is just northwest of the Colorado River, making it an ideal spot for the parameters of this study – low-income areas and flood zones. Both sites are surrounded by neighborhoods and small businesses with a Wastewater Treatment Plant (WWTP) within the buffer of site 6. The WWTP is important to protect as this is the water supply for these surrounding communities. Adding bioretention ponds in the open space to the West of the WWTP would be beneficial for mitigating against floods as there is a river running past the area that has the potential to cause damage if overland flow occurs. Because the neighborhoods surround a major highway in both sites, it would be beneficial to implement a rain barrel program in these neighborhoods, similar to site 5. These sites reside in low-income areas meaning they might not have the means or time to think about projects such as the ones suggested above. To include these communities in the environmental movement and allow them to benefit from the GI projects, similar strategies – the pamphlets, town hall meetings, and rain barrel assistance program – from the city for site 5 could be used in the neighborhoods in sites 6 and 7.

The last three sites, 8, 9, and 10, are clustered in the northeast region of the city, in low-income areas (Figure 25). These sites are interesting as they are located over a major road (IH130). However, there are green spaces between the road that could be a potential spot for bioretention ponds that allow water to infiltrate into the ground quickly. Lake Walter is just southwest of these three sites, making them important spots to protect as they are areas that see flooding more regularly. The surrounding area is not highly urbanized, but the major highway is an important piece of infrastructure that could easily be damaged by flooding along with the small neighborhood just North of Site 8. Because of the little urban infrastructure around these sites, implementing GI could be potentially difficult. The city of Austin could provide the neighborhood with the rain barrel assistance program, pamphlets, and town hall meetings to educate and implement rain barrels into the community.

Through this study and analysis of vulnerable areas and locations of GI, there is evidence of unequal implementation of GI in low-income areas around the city, pointing to environmental injustice. This study does not present evidence that proves injustice, but it uncovers the geographical patterns of unjust placement of GI and reveals the necessity for more equitable changes.

6.2. Limitations and Sources of Error

The limitations of this project include data constraints, dataset gaps, time, and the fact that the data collected is secondary data. This study explores several different issues including spatial inequality in the number of GI projects in low- and high-income areas, and GI implementation and location suitability. However, it is only able to scratch the surface of each issue. As GI becomes a more popular climate change mitigation strategy, issues of "Green gentrification" are a growing concern and low-income alone does not provide enough evidence to classify these residents as vulnerable to flooding. For this study, vulnerability was used to define the vulnerability of low-income communities to flood risks and to economic disproportions of GI locations. Although this study investigated the general small-scale GI, there are several types of projects could be explored further. Each type of GI functions differentially and therefore, the functions need to be considered when implementing these projects into the cityscape. There is potential to investigate each issue more specifically through a qualitative approach that would integrate community perspectives on ways GI has impacted their communities.

Most of the data used in the suitability map were beneficial in illuminating the most suitable sites where GI would have the highest impact for mitigating against flood hazards. The impervious cover layer and flood zones layer presented some challenges. There were some areas of data in the impervious cover layer that would define the cells as a spectrum of impervious cover when the area was in fact not the type of cover. This issue is common with

NLCD imagery as the images have the potential to capture reflective surfaces that cause incorrect output. In the future, it would be beneficial to reclassify to correct any imperfections. As for the flood zone layer, finding the data was a treasure hunt. The City of Austin open access data portal did not provide necessary data to create such a layer and the TWDB provided no metadata, making it a strenuous process to find the right pieces of waterbodies data to retrieve and stitch together. In future studies, ground truthing would be a beneficial source of correcting or making sure data is accurate.

7. Conclusion

The findings of this study highlight the need for, and opportunities associated with a shift towards small-scale GI initiatives in low-income communities in Austin, Texas. Although there needs to be a deeper investigation into the causes of spatial inequality in the location of these projects around the city, there is evidence of such a pattern occurring. Low-income communities are among the most vulnerable populations and climate change hazards exacerbate their vulnerabilities even further. A shift in policies and implementation initiatives of GI needs to be addressed to allow for low-income communities to fight against flood hazards and mitigate the extra vulnerability. Furthermore, the suitability model revealed suitable GI sites within the city of Austin -- 5 out of 10 of which were in vulnerable areas. This demonstrates even further the need to push for more GI implementation in these areas.

Although this study does not prove environmental injustice through the placement of GI, there is evidence illuminating the issue of disproportionate numbers of GI projects in higher-income neighborhoods, drawing attention to the need for justice and change through targeted outreach to implement GI projects in low-income neighborhoods.

7.1. Next Steps

Future research has the possibility to take this study in several directions. Vulnerability is defined differently depending on the type of study, the perspective of the author, and the different literatures on the subject. This study bases "vulnerability" on both low-income and susceptibility to flood hazards. To take this study further, adding a layer of demographics such as age, race and ethnicity, sex, property value, education level, and lot size could be used to investigate green gentrification. To further the study even more, temporal scales could be explored to show a change in the city demographics and GI development – another look into green gentrification. Studying the temporal changes of these factors could play a role in predicting targeted areas of the city that are next for gentrification efforts and possibly the effects of these actions on surrounding communities.

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