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# Habitat Suitability Assessment for Urban Beavers in Metro Atlanta, GA, and Charlotte, NC

Alisha Guglielmi
*Georgia State University*

# Habitat Suitability Assessment for Urban Beavers in Metro Atlanta, GA, and Charlotte, NC

by

Alisha Guglielmi

Under the Direction of Sarah Ledford, PhD

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ABSTRACT

Degradation in urban streams results from expansive impervious surface cover channeling stormflow directly to streams, lessening water storage ability. To slow velocity and decrease peak flow in urban watersheds, stormwater management ponds can be effective in alleviating the impact of flooding but require resources for establishment and maintenance. Urban beaver ponds also effectively store large quantities of water, while offering ecological and geomorphic benefits. Conflicts between beavers and humans arise when dams cause localized flooding and unexpected landscape changes. Lessening conflict requires a spatial understanding of habitat suitability, which this study attempted by modelling key habitat characteristics using GIS. I found that employing input parameters typical of models built for forested catchments resulted in outputs not specific enough to highlight beaver-preferred landscape in an urban setting. After adjusting inputs to reflect patterns at urban beaver sites, the output was better at emphasizing beaver locations.

INDEX WORDS: Suitability assessment, Beavers, Suitability modeling, Urban streams

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by

Alisha Guglielmi

Committee Chair: Sarah Ledford

Committee: Luke Pangle

Lawrence Kiage

Chetan Tiwari

Electronic Version Approved:

Office of Graduate Services

College of Arts and Sciences

Georgia State University

August 2023

## DEDICATION

This work is dedicated to my parents, Domenic Guglielmi and Mary Anne Gray, and my fiancée Alex Webb. Dad: your support, encouragement, and belief in me on this journey has been the driving force in my successful completion of this project. Thank you for always being there and showing me that through a strong work ethic I can achieve anything. Mom: although you aren't physically here to witness this milestone, I know you're always with me giving me strength and guidance. Thank you for reminding me that I'm resilient and worthy. Webb: you are my rock. You have spent the last two years taking care of me and asking for nothing in return as I complete my research and this degree. You constantly remind me to take a step back and slow down. Thank you for always keeping me feeling grounded and safe. I love you all and promise to make you proud.

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# 1 INTRODUCTION

A river or stream's natural flow regime is defined as the unique pattern of its flow magnitude, timing, and variability. Flow conditions naturally vary over time and the hydrograph includes characteristics such as the magnitude of discharge and the duration, timing, rate of change, frequency, and predictability of specific discharge levels. This natural variation is critical for healthy streams and biodiversity, as there are many aquatic species that rely on dynamic habitat conditions to complete their life cycles (Poff et al., 1997). However, urbanization is a major driver of hydrological, ecological and geomorphological degradation of streams and rivers.

In the Late Holocene, intense changes in fluvial systems have been observed as populations increase (A.G. Brown et al., 2018) and humans continue to alter rivers and streams through practices such a dam-building, rapid changes in land use, and disconnection from major rivers from their flood plains (Poff et al., 1997). Walsh et al. (2005) coined the term "urban stream syndrome" to describe common symptoms exhibited by urban streams, which can include loss of flow attenuation, streambank incision, and decreased water quality. Similarly, Bilotta et al. (2010) relay that urbanization deteriorates a rivers' natural flow regime, causing intense soil erosion and flood discharge events. An increase in total catchment imperviousness in urban watersheds decreases soil infiltration and increases stormwater runoff, causing hydrographs in urban settings to be flashier, with an increase in timing, volume, and unpredictability of storm discharge, which can lead to dangerous flooding. Water quality also decreases due to increased concentrations of contaminants, pollutants, and nutrients from wastewater treatment plants, combined sewer overflows, overland non-point sources, and legacy pollutants. Many different approaches have been tried to address these changes in water quantity and quality.

Currently, stormflow is often regulated through concrete and steel piped drainage systems known as grey infrastructure (Chen et al., 2021; Dong et al., 2017; Liu et al., 2019) and through green infrastructure which includes both planned and unplanned green spaces, native vegetation, biofilters, and parks (Norton et al., 2015). Also known as best management practices (BMPs), these designs are used to redirect, decontaminate, and retain stormwater in manmade structures on the landscape such as storm drains, bioswales, and stormwater management ponds (SWMPs) before water reaches streams and rivers. During a storm event, drains and bioswales can direct stormwater to SWMPs, which can be lined on the bottom with an impermeable layer to decrease the amount and rate of infiltration (Kaushal et al., 2015). This process allows for temporary water storage; once a predetermined depth is reached, the water drains from the pond (Kaushal & Belt, 2012), and this can aid in the regulation of water behavior in the stream (i.e., slowing velocity or decreasing peak flow). BMPs tend to be expensive and deliver unreliable results (Palmer et al., 2014). However, there may be additional ways of retaining water on the landscape, such as through beaver ponds.

There is evidence in recent literature that beaver ponds may function similarly to SWMPs in their ability to slow velocity, with the added potential of providing ecological and geomorphic benefits to the streams they dam, such as aiding in nutrient cycling and the restoration of incised banks (Bailey et al., 2018; Brazier et al., 2020; Pollock et al., 2014; Puttock et al., 2017, 2020). Allowing beavers to engineer the landscape is affordable, because they take care of labor and maintenance, as well as effective because they provide positive feedback loops throughout the development of their local habitats. Auster et al. (2021), Crowley et al. (2017), and Gaywood et al. (2015) point out the importance of informed policy and management in intensively managed landscapes with a high population density. In areas undergoing rapid development, like Atlanta, beavers' land management capabilities often fall in direct opposition of other municipal priorities, so the effectiveness and affordability of a beaver-managed stream system depends heavily on informed planning, which leads to better expectation management as beavers are allowed to restore the most appropriate streams (Levine & Meyer, 2014).

Known for their dam building and resulting pond and wetland formation, beavers are commonly referred to as keystone species because of their ability to considerably modify their habitat and impact the rest of their local ecology. They are also generally regarded as ecosystem engineers, as they transform their surrounding environment to meet their preferred habitat predilections (Bailey et al., 2018). When beavers establish a dam in a landscape, the land immediately upstream of the dam becomes flooded resulting in the formation of a pond or wetland. These areas store sediment and nutrients and provide unique ecosystem services for a variety of aquatic species. Some of the significant ecological and geomorphic advantages of beavers managing a landscape include the morphologic restoration of incised stream banks through sediment deposition, attenuation of flow during high and low flow periods, and altering biogeochemical cycling of nutrients (Brazier et al., 2020). Collectively, these resulting factors allow for an increase in beaver presence, further perpetuating the positive feedback loops.

Beaver dams, canals, and burrows help with the lateral reconnection of the floodplain and an increase in cross-sectional complexity. Their dams decrease flow velocity, which allows sediment to settle out of the water column and increases aggradation rates, which then leads to an abundance of riparian vegetation and floodplain connectivity. Pollock et al. (2014) state that beaver dams located along incised streams contribute to the development of a series of positive feedback loops, starting the stream's timely journey back toward a geomorphic dynamic equilibrium.

Beaver ponds attenuate flow, increase water storage, reduce hydrological connectivity, and increase lateral connectivity. Their ponds help to recharge groundwater and increase the stream's sinuosity. Puttock et al. (2017) found 22% more water entering a site upstream of a beaver dam versus downstream during storm discharge events. These sites experienced lower magnitudes of total and peak discharge values and longer lag times between peak rainfall and peak streamflow. This reveals the ability of beaver-engineered landscapes successfully attenuate flow. This study also showed that catchments containing beaver ponds displayed an overall increase in water storage, especially during wet seasons. A subsequent study by Puttock et al. (2020) focused on high flow events found that the presence of beaver dams resulted in an overall decreasing trend in the flashiness of flow regimes due to an increase in stream baseflows during dry periods, an increase in lag time, a decrease in peak flow, and a decrease in overall storm flow.

Beaver ponds can contribute to improving downstream water quality by aiding in the process of nutrient cycling. The unique ecosystem that is created from a beaver pond contributes to the successful lifecycles of an array of aquatic vegetation, invertebrates, amphibians, and fish (Brazier et al., 2020). Ponds can act as a sink for nutrients and pollutants. There can be greater concentrations of suspended solids, total organic nitrogen, and phosphates, and lower concentrations of dissolved organic carbon upstream of a beaver dam than downstream. Water upstream was also found to be slightly more acidic than water being discharged from the dam (Puttock et al., 2017).

The idea of allowing beavers to restore local habitat is not a new one and records from as far back as the 1930's show that beavers were being relocated to degraded areas in an attempt to restore natural wetlands (Scheffer, 1938). A common practice today involves the usage of beaver dam analogs, manmade structures designed to replicate the effects beaver dams have on streams

(Pollock et al., 2014). Ecological design practices have become increasingly integrated into urban development with three main goals: recreational use, provision of ecosystem services to urban environments, and use of restoration design to "create and enhance urban habitat" (Jackson & Sinclair, 2012). Focusing on the third goal, incorporating the work of beavers into design practices may help lead urbanized landscapes back towards their natural hydrological regimes. Due to natural variability, ecological site design must be dynamic, and some processes simply cannot be recreated anthropogenically.

In urban environments, beaver dam presence generally leads to changes in local hydrology, removal of vegetation, and flooding of the nearby landscape. These factors, combined with their tendency to incorporate manmade infrastructure into their dam design and increasing populations throughout North America, have led to a rise in conflicts between beavers and humans (Bailey et al., 2018; Touihri et al., 2018). Through three case studies in Washington state, Bailey et al. (2018) found that beavers cause the least amount of nuisance and ecological designs are the most beneficial in parks and restoration areas when site designs require the presence of beavers to perform optimally. When a site is designed without the consideration of beavers moving in, there tends to be an overall loss of function for the site's intended purpose(s), unwanted clearing of vegetation, and flooding of roads and pathways. Management of these sites includes a continuous cycle of beaver trapping and recolonization. This leads to public trapping fatigue and the potential need for a complete site redesign, which ultimately wastes time and money. When site designs implement elements such as tree fencing to prevent the loss of vegetation and flow devices to limit flooding, this allows beavers to inhabit an area with a low chance of beaver-human conflict. Sites that are designed to perform optimally with beaver interference were found to be particularly successful in serving the site's purposes and providing the multitude of ecosystem services that beaver-managed landscapes can deliver (Bailey et al., 2018).

An initial step for planning to utilize beavers in landscape designs requires the knowledge of where beavers are likely to be drawn to in a location. Beavers have relatively simple habitat requirements and even in stressful environments they tend to get by with only two reliable and accessible landscape requirements: a water source, and nearby woody vegetation. Their populations are most commonly found in wadable streams and the side channels of major rivers (Müller- Schwarze & Sun, 2003). Since the 1940's, existing and potential beaver habitat was evaluated in multiple studies (Atwater, 1940; Packard, 1947) and in the 1980's the first quantitative beaver habitat suitability index (HSI) was produced (Allen, 1982). Allen et al. (1982) based their suitability on key environmental factors including stream gradient, average water fluctuation, and vegetation specifics. A later report found that HSI based models can accurately categorize habitat as suitable or unsuitable for beavers "within a short temporal window," (McComb et al., 1990), but a subsequent study in Kansas revealed that HSIs generally don't have the potential to be used in watersheds dissimilar to the catchments they were developed for (Robel et al., 1993).

Maps of potential beaver distribution have recently been created for a number of primarily forested catchments through the use of habitat suitability models and beaver capacity models developed from combining nationally available hydrological geospatial datasets and remotely sensed images (Anderson & Bonner, 2014; Dittbrenner et al., 2018; Graham et al., 2020; Macfarlane et al., 2017; Maringer & Slotta-Bachmayr, 2006; Stringer et al., 2018). Four consistent factors commonly used to determine beaver habitat suitability in forested catchments are: (1) a reliable an accessible water source, (2) a stream that is not too large, (3) a stream that has a shallow enough slope, and (4) woody vegetation accessible within proximity to the water's edge.

Although there are many studies that involve forested catchments in North America and Europe, there is a lack of research and informed management resources for heavily urbanized watersheds. Developing a tool for the purpose of quickly assessing the likelihood of beaver dam establishment for a given location will require proper identification of existing and potential beaver dam locations in metro Atlanta. This may be accomplished using remotely sensed imagery to highlight the presence of woody riparian vegetation and hydrologic data to identify perennial water flow, stream gradient, and stream order. Since past studies were performed in predominantly forested catchments, and this study's focus is in the highly urbanized watersheds, differences in stream behavior must be accounted for. Natural streams are not subject to the symptoms of urban stream syndrome, such as increased average velocity and storm discharge variation. This means that it may be possible for beavers to establish dams at steeper gradients and in larger streams in forests compared to urbanized watersheds. In forested watersheds, the maximum slope that a beaver dam is able to withstand is about 15% (Graham et al., 2020; Macfarlane et al., 2017; Maringer & Slotta-Bachmayr, 2006; Touihri et al., 2018) but I hypothesize that beavers prefer a shallower gradient in urban streams due to an increased stream power caused by urban stream syndrome. Similarly, although beavers in natural watersheds can successfully maintain and build dam complexes in streams as large as fourth order (Graham et al., 2020; Macfarlane et al., 2017; Maringer & Slotta-Bachmayr, 2006; Touihri et al., 2018), I predict that in urban watersheds, they prefer smaller streams.

Using remote sensing images and hydrologic data that are freely available to the public, this study aims to develop a habitat suitability model to represent the relative likelihood of beaver preference on stream reaches throughout metro Atlanta, GA and Charlotte, NC. This study aims to answer the question: Are the habitat preferences of beaver significantly altered by unique features of the urban landscape in contrast to the landscapes they occupy in non-urban environments? In other words, it is hypothesized that beaver habitat suitability models for highly urbanized watersheds will require adjustments to the physical criteria of stream order, slope, and land use categories because urban streams behave differently than streams in predominantly forested catchments.

# 2 METHODS

## 2.1 Site Descriptions

### *2.1.1 Piedmont Province*

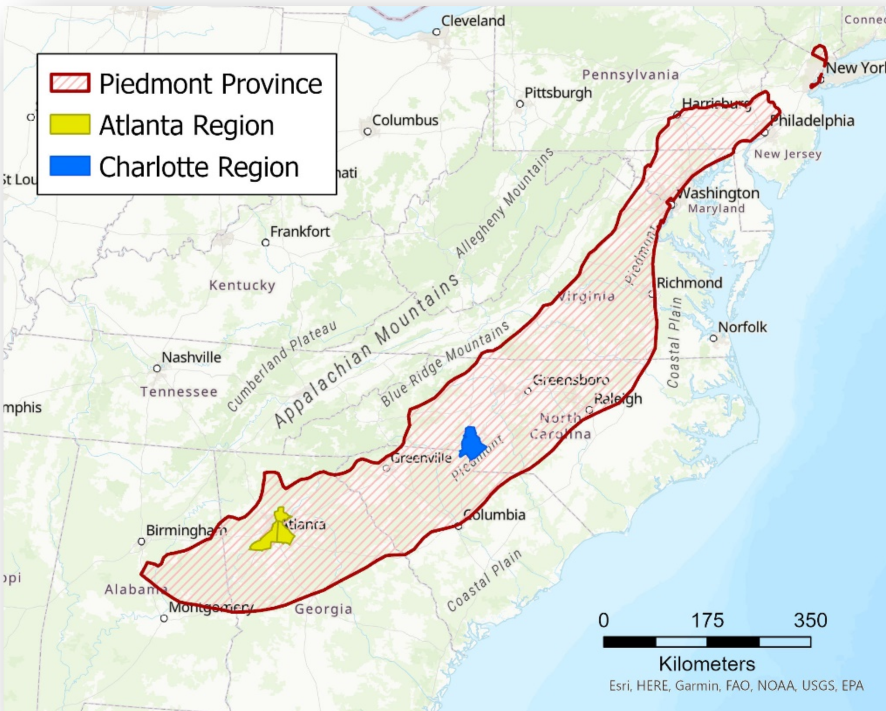


*Figure 1. Map of the Piedmont Province in the United States with Atlanta and Charlotte marked.*

The southern Piedmont Province of the United States (Figure 1) is characterized by distinctive environmental factors due to its placement between the Coastal Plain and Appalachian Mountains. Rolling hills and eroded ridges make up the generally forested landscape which is underlain by Paleozoic metamorphic rocks covered by a layer of alluvium, soil, and saprolite. The streams cutting through the topography tend to have sandy bottoms and deeply incised banks (Putnam, 1972; Rose & Peters, 2001). The southern Piedmont ecoregion encompasses two major metropolitan cities of the United States, Atlanta and Charlotte, that receive an average of 1,276 mm and 1,107 mm of annual precipitation, respectively (US Department of Commerce, 2023). As urbanization and population increases in cities like these, the impact of flood events becomes more extreme and affects larger populations of people.

### *2.1.2 Atlanta, Georgia*

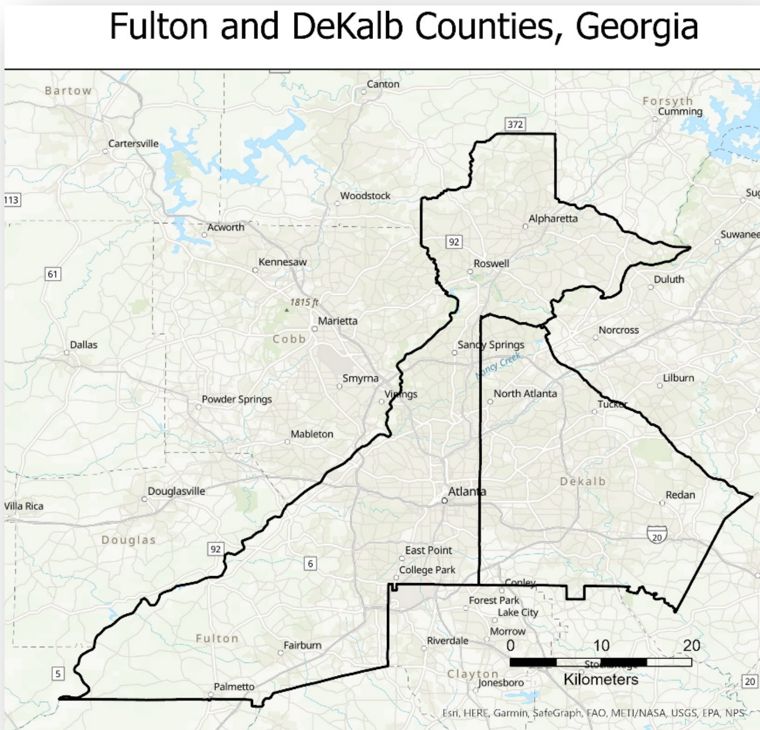


*Figure 2. Map of Fulton and DeKalb Counties in Georgia, location of metro Atlanta, GA.*

Located in north-central Georgia, this study focuses on Fulton and DeKalb counties (Figure 2), henceforth referred to as metro Atlanta, not to be confused with the Atlanta Metropolitan Area. The area encompasses approximately 2,080 square kilometers, and land use distribution throughout the two counties is ~64% trees/shrubs, ~29% urban land, ~6% open green space or exposed rock, and ~2% water (Table 1, Atlanta Regional Commission, 2012). There are about

2,285 km of surface stream length in the two counties (U.S. Geological Survey, 2018). Metro Atlanta is unique from many other highly urbanized areas because of the area's high tree density (~64%) and its location within the southern Piedmont region. It is important to note that tree density includes areas classified as "forest," "park lands," "parks," "residential- low density", and "residential- high density." The LandPro2009 classification system defines low density residential as having a "significant mix of forested… landcover," and medium density residential as being "with or without a significant mix of forested… landcover" (Atlanta Regional Commission, 2012). Built as a railroad town, the city sits at a high elevation ranging from 225-330 meters above sea level (U.S. Geological Survey, 1995), with many headwater rivers cutting through the landscape.

*Table 1. Metro Atlanta Land Cover Reclassification. LandPro2009 data was reclassified based on definitions in its classification system (Atlanta Regional Commission, 2012). Classes such as RES_LOW and RES_MED, containing a mix of forested land, were included in the Trees/Shrubs category.*

| Original Classification (LandPro2009) | Pixel Count | Reclassification | Percent of total area |
|---|---|---|---|
| AGRICULTURE | 826 | Open Green Space | 6% |
| CEMETERIES | 79 | | |
| EXPOSED_ROCK | 16 | | |
| GOLF_COURSES | 346 | | |
| QUARRIES | 79 | | |
| | | | |
| FOREST | 4215 | Trees/Shrubs | 64% |
| PARK_LANDS | 578 | | |
| PARKS | 219 | | |
| RES_LOW | 1402 | | |
| RES_MED | 8099 | | |
| | | | |
| COMMERCIAL | 1639 | Urban | 28% |
| IND/COM | 807 | | |
| INDUSTRIAL | 89 | | |
| INST_EXTENSIVE | 264 | | |
| INST_INTENSIVE | 701 | | |
| LTD_ACCESS | 317 | | |
| RES_HIGH | 506 | | |
| RES_MOBILE | 9 | | |

| | | | |
|---|---|---|---|
| RES_MULTI | 1086 | | |
| TCU | 241 | | |
| TRANSITIONAL | 624 | | |
| URBAN_OTHER | 151 | | |
| | | | |
| RESERVOIRS | 137 | Water | 2% |
| RIVERS | 61 | | |
| WETLANDS | 238 | | |

### *2.1.3 Charlotte, North Carolina*

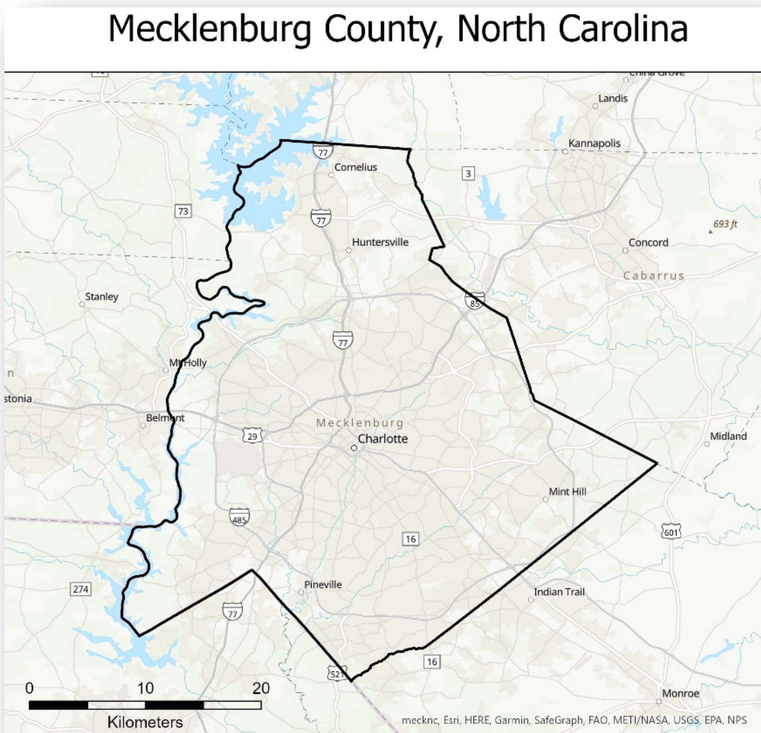


*Figure 3. Map of Mecklenburg County, location of Charlotte, North Carolina, used to validate the model.*

Located in south-central North Carolina, Mecklenburg County (Figure 3), henceforth referred to as Charlotte, is used to validate the suitability model for Atlanta. The area encompasses approximately 1,410 square kilometers, and land use distribution throughout this county is ~59% trees/shrubs, ~27% urban land, ~12% open green space, and ~2% water (Table 2, U.S. Department of the Interior, 2022) There are about 2,473 km of surface stream length in the county (U.S. Geological Survey, 2018).

*Table 2. Charlotte Land Cover Reclassification. LANDFIRE landcover data was reclassified based on definitions in its classification system (U.S. Department of the Interior, 2022).*

| Original Classification (LANDFIRE) | Pixel Count | Reclassification | Percent of total area |
|---|---|---|---|
| Developed- Upland Herbaceous | 104896 | Open Green Space | 12% |
| NASS- Vineyard | 23 | | |
| NASS-Row Crop-Close Grown Crop | 93 | | |
| NASS-Row Crop | 12905 | | |
| NASS-Close Grown Crop | 32 | | |
| NASS-Wheat | 210 | | |
| Herb Cover (10%-73%) | 64625 | | |
| | | | |
| Developed- Upland Deciduous Forest | 65160 | Trees/Shrubs | 59% |
| Developed- Upland Evergreen Forest | 91452 | | |
| Developed- Upland Mixed Forest | 38470 | | |
| Developed- Upland Shrubland | 28787 | | |
| Developed- Low Intensity | 187810 | | |
| Developed- Medium Intensity | 106064 | | |
| Tree Cover (15%-87%) | 348532 | | |
| Shrub Cover (10%-64%) | 1507 | | |
| | | | |
| Developed- High Intensity | 68006 | Urban | 27% |
| Developed- Roads | 322491 | | |
| Quarries-Strip Mines-Gravel Pits | 1940 | | |
| | | | |
| Open Water | 34384 | Water | 2% |

## 2.2 Model Overview

*Table 3. Data sources for all Atlanta suitability model inputs.*

| Factor | Dataset | Resolution | Publication Date |
|---|---|---|---|
| Stream Type<br>Stream Order<br>Stream Slope | NHDPlus HR | 6.36 meters | 2018 |
| Vegetation (Land Use) | LandPro2009 | 7 meters | 2012 |
| Culverts | NHDPlus / TIGER | 6.36 meters / 26.5 meters | 2018 / 2021 |

Suitability models in past studies have been developed to indicate potential suitable beaver habitat by using GIS data about physical features thought to be required by beavers (Anderson & Bonner, 2014; Dittbrenner et al., 2018; Graham et al., 2020; MacFarlane et al., 2017; Maringer & Slotta-Bachmayr, 2006). The suitability models created for this study combined hydrological and land use data to determine the spatial distribution of stream characteristics in metro Atlanta (Table 3). The *Suitability Modeler* Spatial Analyst tool in ArcGIS Pro was used to automate manual pixel classification, and based on predefined criteria for stream type, order, slope, and land use, this tool combined the raster images for each feature to create suitability maps that highlight the intersections of multiple habitat characteristics.

Three datasets were used for building the suitability models in metro Atlanta. Using the USGS National Map Downloader, National Hydrography Dataset Plus High Resolution (U.S. Geological Survey, 2018) data were obtained for 4-digit hydrologic units 0307, 0313 and 0315 to retrieve USGS-defined stream types (e.g. perennial, intermittent), and USGS-calculated stream order and average stream reach slope throughout metro Atlanta. The resolution of NHDPlus HR data is 6.36 meters. Land use data were acquired through the Atlanta Regional Commission's LandPro2009 database, which classifies land use using "on-screen photointerpretation and digitizing ortho-rectified aerial photography" which results in a 7-m pixel resolution. (Atlanta Regional Commission, 2012). The NHDPlus HR flowline data were combined with TIGER/Line

Shapefiles (U.S. Census Bureau, 2022) to find intersections between flowlines and roads as a proxy for road culvert locations.

Raster images with 30-meter resolution were created from the NHDPlus data for stream type, stream order, and stream slope, and LandPro2009 data for land use or vegetative cover (Figure 4). Transformation was performed on each parameter using a binary scale of 0 to 1, marking presence or absence of beaver-preferred landscape variables depending on if the model is for a predominantly forested or an urbanized watershed (Tables 4 and 5), and all parameter inputs were given the same weight.

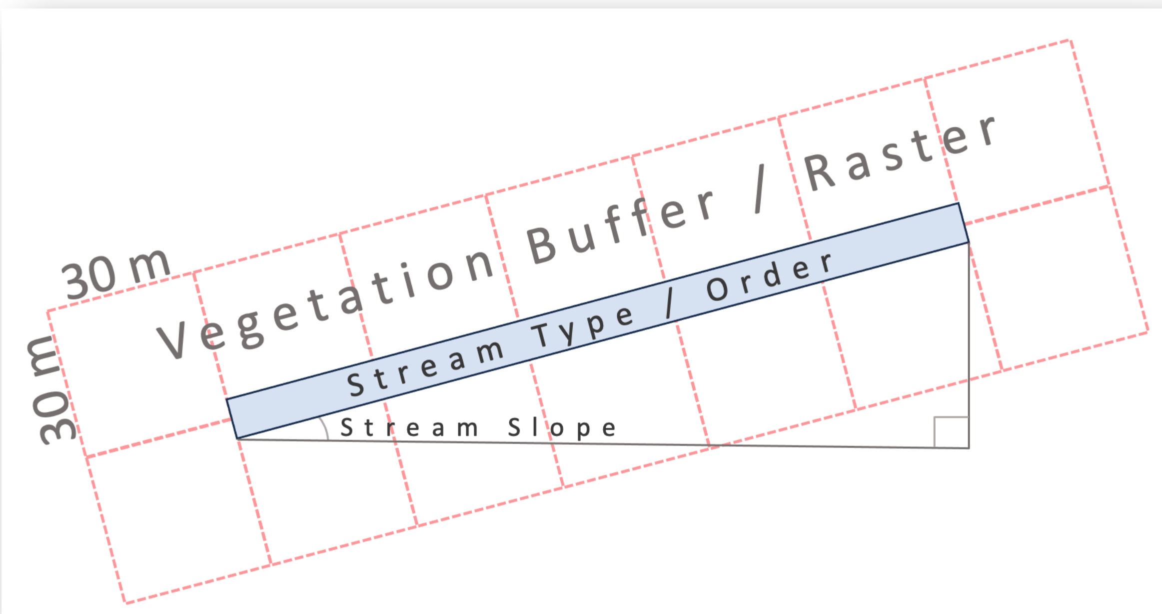


*Figure 4. Hydrologic data used for suitability model inputs.*

*Table 4. Raster transformation suitability scale assignments for the forested suitability model. All residential categories were given an input value of 0 in the forested model.*

| Stream Type | Forested Model Input | Stream Order | Forested Model Input | Stream Slope (avg) | Forested Model Input | Land Use Category | Forested Model Input |
|---|---|---|---|---|---|---|---|
| Connector | 0 | 1 – 4 | 1 | 0 – 15 % | 1 | Forested | 1 |
| Pipeline | 0 | >4 | 0 | > 15% | 0 | Park Lands | 1 |
| Intermittent | 0 | | | | | Wetlands | 1 |
| Perennial | 1 | | | | | All Others | 0 |
| Artificial Path | 0 | | | | | | |

*Table 5. Raster transformation suitability scale assignments for the urbanized suitability model. Changes in input values reflect land use patterns observed surrounding beaver sites in Atlanta.*

| Stream Type | Urban Model Input | Stream Order | Urban Model Input | Stream Slope (avg) | Urban Model Input | Land Use Category | Urban Model Input |
|---|---|---|---|---|---|---|---|
| Connector | 0 | 1 – 2 | 1 | 0 – 1 % | 1 | Forested | 1 |
| Pipeline | 0 | >2 | 0 | > 1% | 0 | Park Lands | 1 |
| Intermittent | 0 | | | | | Wetlands | 1 |
| Perennial | 1 | | | | | Parks | 1 |
| Artificial Path | 0 | | | | | Reservoir | 1 |
| | | | | | | Res-Medium | 1 |
| | | | | | | Urban-Other | 1 |
| | | | | | | All Others | 0 |

## 2.3 Habitat Suitability Configuration: Comparing Landcover Datasets

At 0.5-meter resolution, National Agricultural Imagery Program (NAIP, 2021) remote sensing data have the finest spatial resolution when compared to other free, nationally available data. ENVI® image analysis software was used to perform a classification with manual training data to create four regions of interest: (1) water, (2) urban, (3) open green space, and (4) trees/shrubs, for six known beaver sites in Atlanta (Table 7).

*Table 6. Locations of six known beaver sites around metro Atlanta used to compare land cover approximations across datasets of varying resolutions.*

| Site Name | Latitude | Longitude |
|---|---|---|
| 400 | 33°50'24.86" N | 84°21'38.48" W |
| BH | 33°51'49.60" N | 84°22'33.17" W |
| Candler | 33°46'12.53" N | 84°20'14.04" W |
| Graves | 33°53'46.33" N | 84°13'27.00" W |
| MC | 33°54'42.12" N | 84°19'25.51" W |
| Shoal | 33°46'00.34" N | 84°16'31.18" W |

Shadows, or features with very low reflectance, were consistently misclassified as water even after multiple attempts at manual reclassification. The inability to manually classify images that encompass the entirety of Fulton and DeKalb Counties due to time constraints led to the decision to compromise spatial resolution for land use classification accuracy. NAIP images for each of the six known beaver sites in Atlanta was compared to three landcover datasets of varying resolution: (1) LANDFIRE: 30-meter resolution (U.S. Department of the Interior, 2022), (2) Sentinel-2: 10-meter resolution (European Space Agency, 2022), and (3) LandPro2009: 7-meter resolution (Atlanta Regional Commission, 2012) within the same areal extent.

Images from these three datasets were clipped to the same extent as the NAIP images and land cover assignments were compared. Since land cover datasets vary in class labeling, all classes were categorized into one of the four groups ((1) water, (2) urban, (3) open green space, (4) trees/shrubs) used to classify the NAIP images (Appendix A shows reclassifications for all six sites using LANDFIRE and LandPro2009 data). Note that Sentinel-2 imagery for these areas have four land use categories where "Water" represents water, "Built Area" represents urban, "Rangeland" represents open green space, and "Trees" represents trees/shrubs, therefore no reclassification was required.

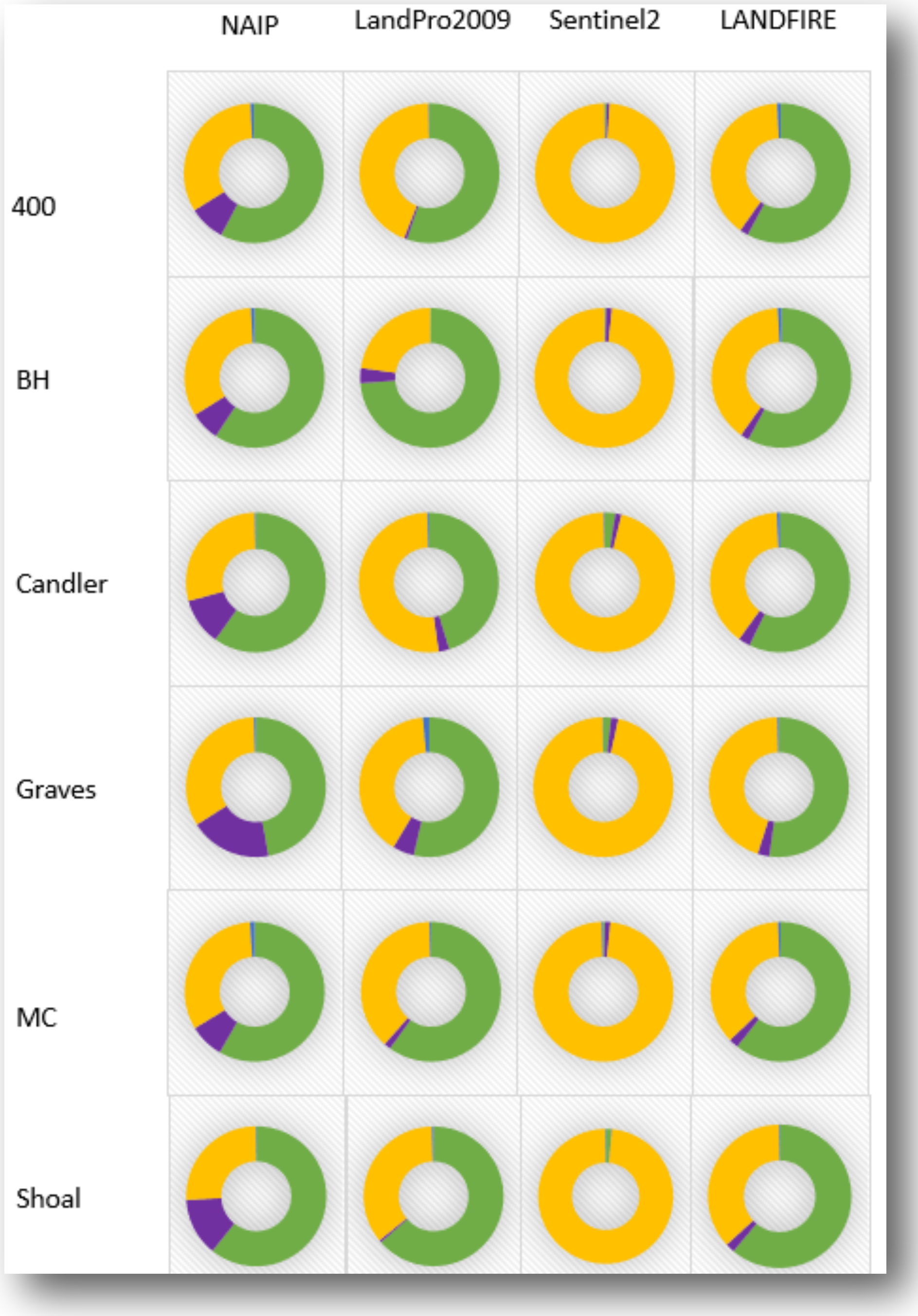


*Figure 5. Land use comparison between six known beaver sites using four datasets of varying resolution. Note: blue= water, yellow= urban, purple= open green space, green= trees.*

Land use approximations generated from these remote sensing data at varying spatial resolutions were compared to one another to determine which is the most like NAIP data (Figure

6 and Table 12). NAIP data are the finest resolution aerial imagery available for land use classification, and analysis of imagery for six beaver sites around Atlanta resulted in an average of <1% water, ~31% urban, ~11% open green space, and ~57% tree cover. LandPro2009 is a 7-meter resolution landcover and land use dataset exclusive to the Atlanta area, and when evaluating the same six sites as defined by the NAIP imagery, it was found to be comprised of an average of <1% water, ~39% urban, ~2% open green space, and ~58% tree cover. The Sentinel-2 program provides 10-meter resolution spatial data, and with this data, the six sites reflected an average of ~<1% water, ~98% urban, ~1% open green space, and ~1% tree cover. The coarsest resolution data used in land use comparison were LANDFIRE 30-meter resolution landcover classification. These data classify the six control sites as an average of ~1% water, ~39% urban, ~2% open green space, and ~58% tree cover. LandPro2009 data were most like NAIP results while having the finest-scale resolution (Table 12 and Figure 6), so this was used for the rest of the analyses in Atlanta.

*Table 7. Land use percentages (approximated) represented by each landcover dataset for six known beaver sites around Atlanta. W= water, U= urban, O= open green space, T= trees.*

| | NAIP | | | | LandPro2009 | | | | Sentinel-2 | | | | LANDFIRE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | W | U | O | T | W | U | O | T | W | U | O | T | W | U | O | T |
| **400** | 1% | 33% | 8% | 58% | 0% | 43% | 1% | 55% | 0% | 99% | 1% | 0% | 1% | 39% | 2% | 58% |
| **BH** | 1% | 33% | 7% | 59% | 0% | 23% | 4% | 74% | 0% | 98% | 1% | 0% | 1% | 39% | 2% | 58% |
| **Candler** | 0% | 29% | 11% | 60% | 0% | 52% | 2% | 45% | 0% | 96% | 1% | 2% | 1% | 39% | 3% | 57% |
| **Graves** | 0% | 34% | 19% | 47% | 1% | 40% | 5% | 54% | 0% | 96% | 2% | 2% | 0% | 45% | 3% | 51% |
| **MC** | 1% | 33% | 8% | 58% | 0% | 38% | 2% | 60% | 0% | 98% | 1% | 0% | 1% | 37% | 2% | 61% |
| **Shoal** | 0% | 26% | 13% | 60% | 0% | 36% | 1% | 64% | 0% | 98% | 0% | 1% | 0% | 37% | 2% | 61% |

## 2.4 Model Testing

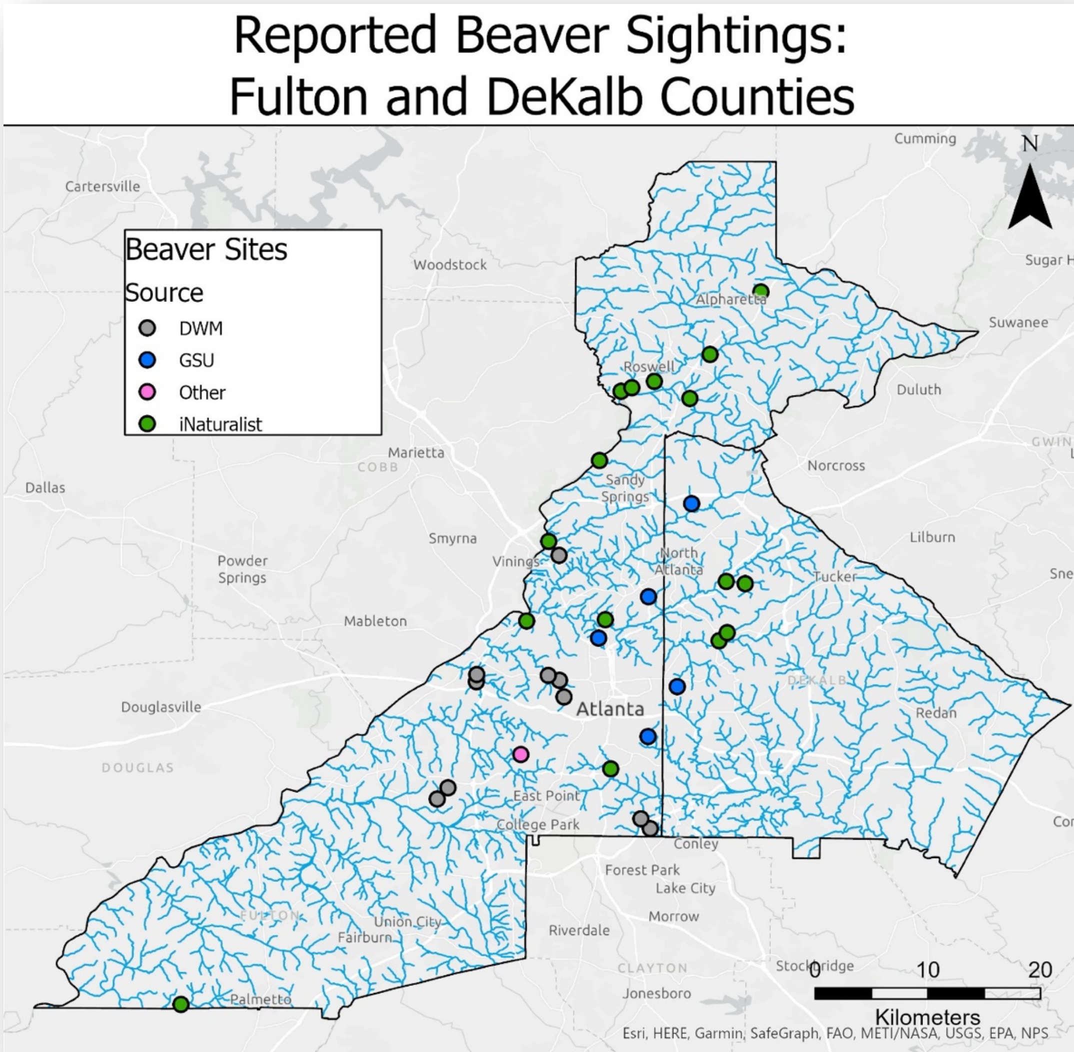


*Figure 6. Beaver sites in metro Atlanta, by source (2016-2022).*

To test the accuracy of model outputs, known beaver locations (Figure 5) were compared against model outputs. Beaver locations in this context include evidence of beaver (e.g., chewings, tree felling, lodge or dam). The beaver location data were crowd-sourced from multiple sources: the City of Atlanta Department of Watershed Management (DWM), the iNaturalist mobile application (GBIF.org, 2023), site visits from the Geosciences Department at Georgia State

University (GSU) during biweekly field sampling, and activity reported to our group by the public. All reported beaver sightings (n=32) in Fulton and DeKalb counties from 2018 to 2022 were used for these comparisons.

## 2.5 Model Validation

The suitability models developed for Atlanta (as described in section 1.2 above) was validated by testing its accuracy at predicting know beaver pond locations in Charlotte. These beaver sites (n=146) were known from the Watershed Protection Agency. Validating at this remote location did require the use of alternative land cover data from LANDFIRE (U.S. Department of the Interior, 2022), since data from LandPro2009 (Atlanta Regional Commission, 2021) were not available for Charlotte (Table 8). Tables 9 and 10 show the input values assigned for both models in Charlotte.

*Table 8. Data sources for all Charlotte suitability model inputs*

| Factor | Dataset | Resolution | Publication Date |
|---|---|---|---|
| Stream Type<br>Stream Order<br>Stream Slope | NHDPlus HR | 6.36 meters | 2018 |
| Vegetation | LANDFIRE | 30 meters | 2022 |

*Table 9. Raster transformation suitability scale assignments for the forested suitability model validation in Charlotte.*

| Stream Type | Forested Model Input | Stream Order | Forested Model Input | Stream Slope | Forested Model Input | Land Use Category | Forested Model Input |
|---|---|---|---|---|---|---|---|
| Connector | 0 | 1 – 4 | 1 | 0 – 1 % | 1 | Tree Cover (All) | 1 |
| Pipeline | 0 | >4 | 0 | 1 – 15% | 1 | Shrub Cover (All) | 1 |
| Intermittent | 0 | | | >15% | 0 | All Others | 0 |
| Perennial | 1 | | | | | | |
| Artificial Path | 0 | | | | | | |

*Table 10. Raster transformation suitability scale assignments for the urbanized suitability model validation in Charlotte.*

| Stream Type | Forested Model Input | Stream Order | Forested Model Input | Stream Slope | Forested Model Input | Land Use Category | Forested Model Input |
|---|---|---|---|---|---|---|---|
| Connector | 0 | 1 – 2 | 1 | 0 – 1 % | 1 | Developed-Upland Deciduous | 1 |
| Pipeline | 0 | >2 | 0 | 1 – 15% | 0 | Developed-Upland Evergreen | 1 |
| Intermittent | 0 | | | >15% | 0 | Developed-Upland Mixed | 1 |
| Perennial | 1 | | | | | Developed-Low Intensity | 1 |
| Artificial Path | 0 | | | | | Developed-Med Intensity | 1 |
| | | | | | | Tree Cover (All) | 1 |
| | | | | | | Shrub Cover (All) | 1 |
| | | | | | | All Others | 0 |

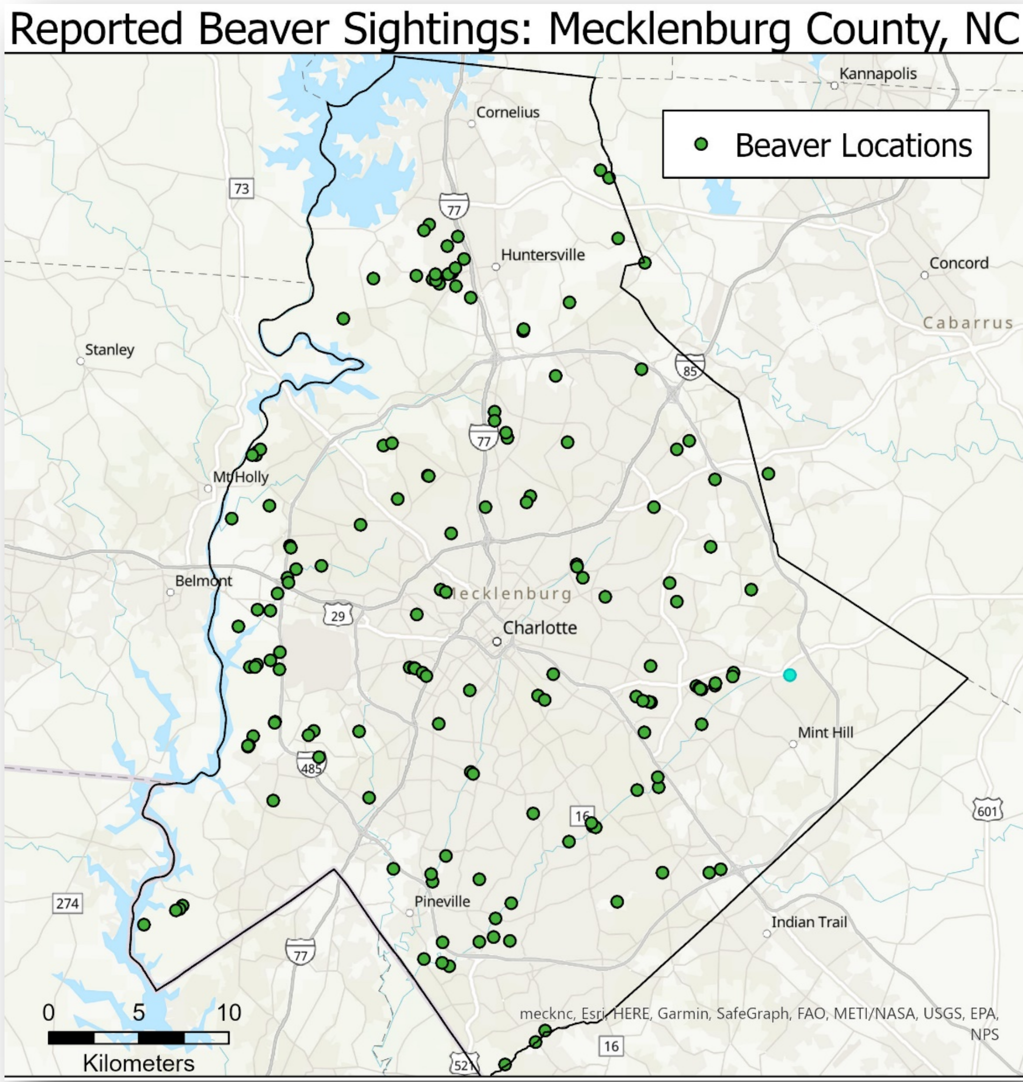


*Figure 7. Reported beaver activity in Mecklenburg County, North Carolina. Beaver location data were sourced from the Watershed Protection Agency.*

## 2.6 Statistical Analysis

Differences in model results were compared using a Student's t-test. Comparisons with p-values below 0.05 are considered statistically different. If the model of all stream reaches has the same mean value as the model representing known beaver sites, this indicates the model is not specific enough to identify the key driving characteristics of beaver sites. However, if the mean value of the beaver model is higher than all stream reaches, this would indicate the model is able to predict habitat characteristics that beaver prefer.

# 3 RESULTS

## 3.1 Forested Model Results

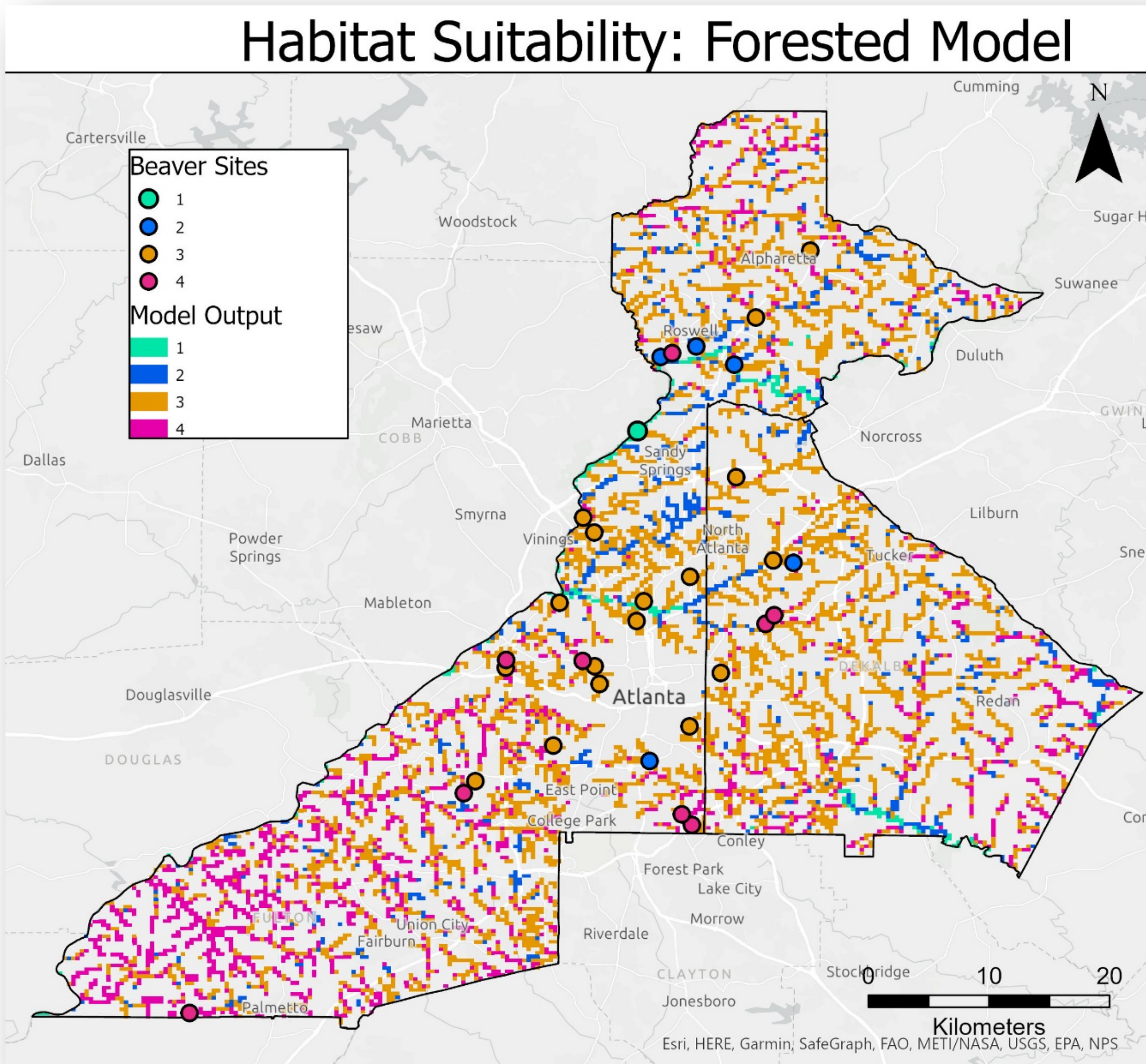


*Figure 8. Forested model output map for metro Atlanta. Output values correspond to the number of key habitat features present. Beaver site symbology represents model output values.*

A beaver habitat suitability model (Figure 8) for forested characteristics was created for all mapped streams in Fulton and DeKalb Counties. A total of 7,583 stream segments were evaluated and ranked from 1 through 4 based on the presence or absence of landscape features preferred by beavers, which include perennial flow, stream order <4, slope <15%, and woody riparian vegetation, represented in this study by land use categories containing tree or shrub cover (Graham et al., 2020; Macfarlane et al., 2017; Maringer & Slotta-Bachmayr, 2006; Touihri et al., 2018). A stream segment with a model output value of 4 represents habitat with all four necessary parameters present for successful dam and lodge building per previous models. A segment with three of the four parameters has an output value of 3, and so on.

*Table 11. Forested model outputs, means, and Student's t-test result for the entire study area and for known beaver sites in Atlanta.*

| Forested Model Output | Study Area | Beaver Locations |
|---|---|---|
| 1 | 179 (2%) | 1 (3%) |
| 2 | 862 (11%) | 5 (16%) |
| 3 | 4723 (62%) | 17 (53%) |
| 4 | 1819 (24%) | 9 (28%) |
| | Mean: 3.08 | Mean: 3.06 |
| | p=0.45 | |

Table 13 shows that after running the model, it was found that about 2% of all stream segments (n=179) in metro Atlanta resulted in an output value of 1 and are missing many of the key parameters to provide ideal beaver habitat. 11% of all stream segments (n=862) expressed a model output of 2. This forested model shows that 62% of all metro Atlanta stream reaches (n=4723) received a model value of 3, and finally, 24% of stream segments (n=1819) received an output of 4. For all streams in Atlanta, the mean output value of the forested model was 3.08.

The output values for the beaver habitat suitability model in forested watersheds for all stream reaches in metro Atlanta, when compared to known beaver locations (n=32) in the area, show that there is a similar distribution of model output values (Figure 9). The mean value output at known beaver sites was 3.06, with 3% of all known beaver locations (n=1) in stream reaches with a model output value of 1, or unlikely. 16% of beaver reports (n=5) are in stream segments with an output value of 2, 53% of beaver sightings in metro Atlanta (n=17) can be found on stream segments that received a model output of 3, and 28% of beaver locations (n=9) are in stream reaches with an output of 4. The forested model output shows that in metro Atlanta most fluvial landscape (86%) exhibits at least 3 of the 4 key landscape features required by beavers, and the distributions of output values among all stream reaches and the beaver locations are similar. A Student's t-test was performed to compare mean output values between all streams (3.08) and beaver sites (3.06) and the resulting p-value was 0.45.

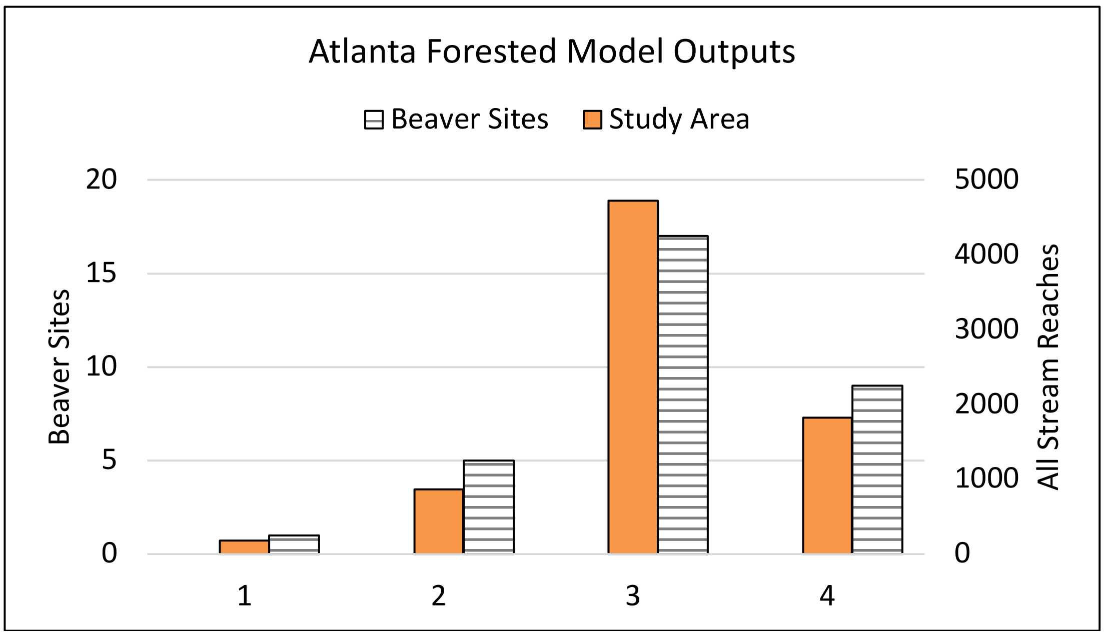


*Figure 9. Histograms of forested model outputs for all stream reaches in metro Atlanta (solid bar) and at the 32 beaver sites in Atlanta (striped bar). The mean reach score for the entire study area is 3.08 while the mean score for beaver sites is 3.06 (p=0.45).*

## 3.2 Known Beaver Location Parameters

To determine input adjustments needed for an urbanized model, I analyzed patterns found in the stream type, order, slope, and vegetation/land use at 32 known beaver sites in metro Atlanta.

### *3.2.1 Stream Type*

The study area is comprised of 64% 'Perennial,' streams, whereas 100% of beaver sites are found on 'Perennial' stream segments (Figures 10 and 11, Table 14).

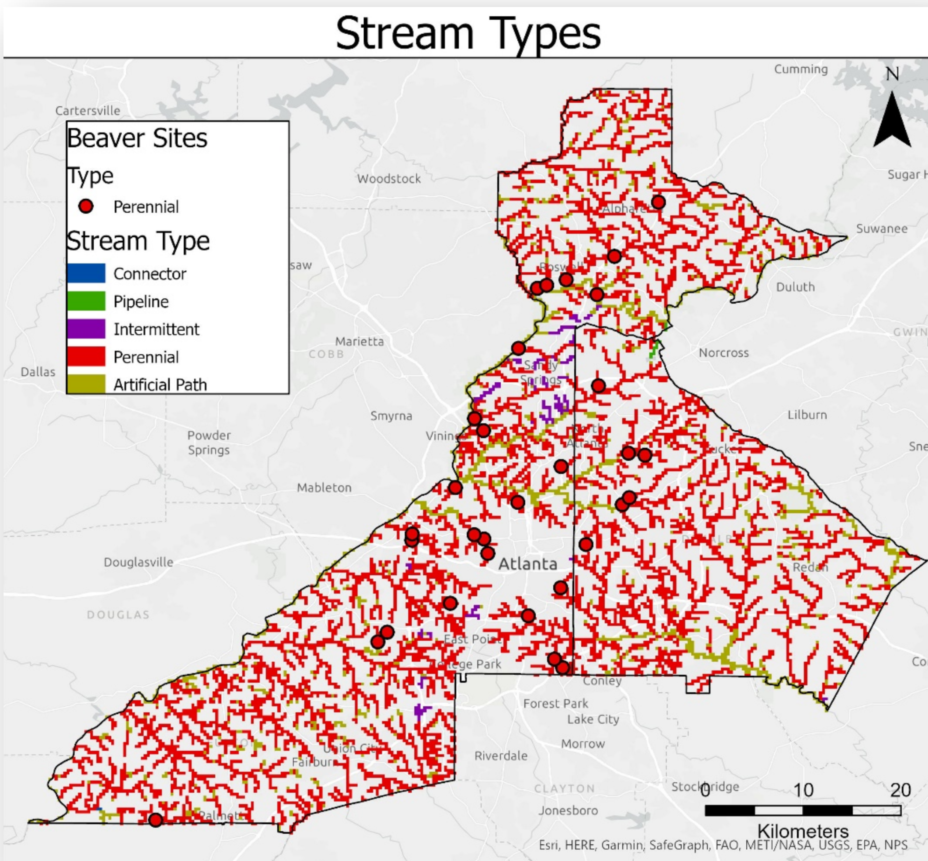


*Figure 10. Flowlines in Fulton County and DeKalb County categorized by stream type.*

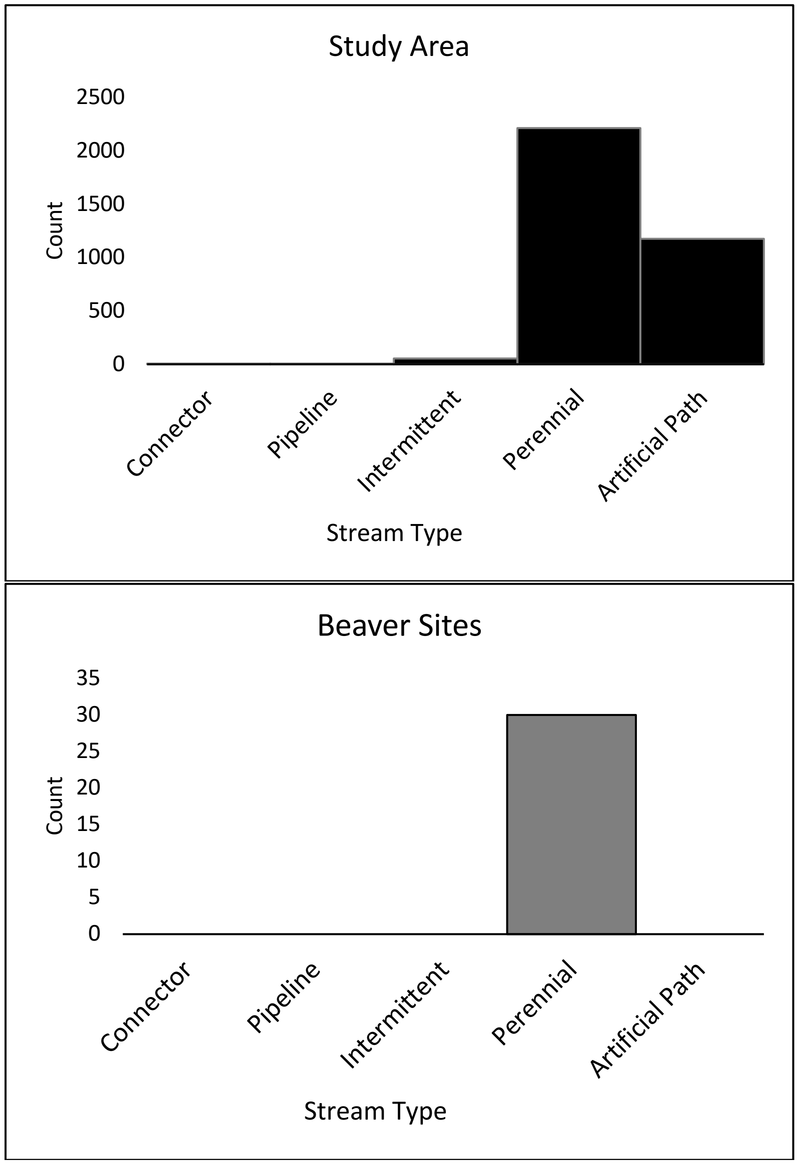


*Figure 11. Histograms showing stream types throughout metro Atlanta (top) compared to stream types found at beaver sites (bottom).*

*Table 12. Stream types throughout metro Atlanta and stream types found at beaver sites.*

| Stream Type | Study Area | Beaver Sites |
|---|---|---|
| Connector | 1 (0%) | 0 (0%) |
| Pipeline | 3 (0%) | 0 (0%) |
| Intermittent | 56 (2%) | 0 (0%) |
| Perennial | 2216 (64%) | 32 (100%) |
| Artificial Path | 1179 (34%) | 0 (0%) |

### *3.2.2 Stream Order*

As shown in Figures 12, 13, and Table 15, stream orders range from 1 to 7 throughout the study area. About 59% of streams in metro Atlanta are first order, ~21% are second order, ~11% are third order, ~4% are fourth order, and about 5% are greater than fourth order. Comparatively, beavers have been reported in stream orders ranging from 1 to 6. 38% of beaver sites are within first order streams and 31% are in second order streams. Four beaver sightings were reported on third order streams, comprising 13% of all beaver sites.

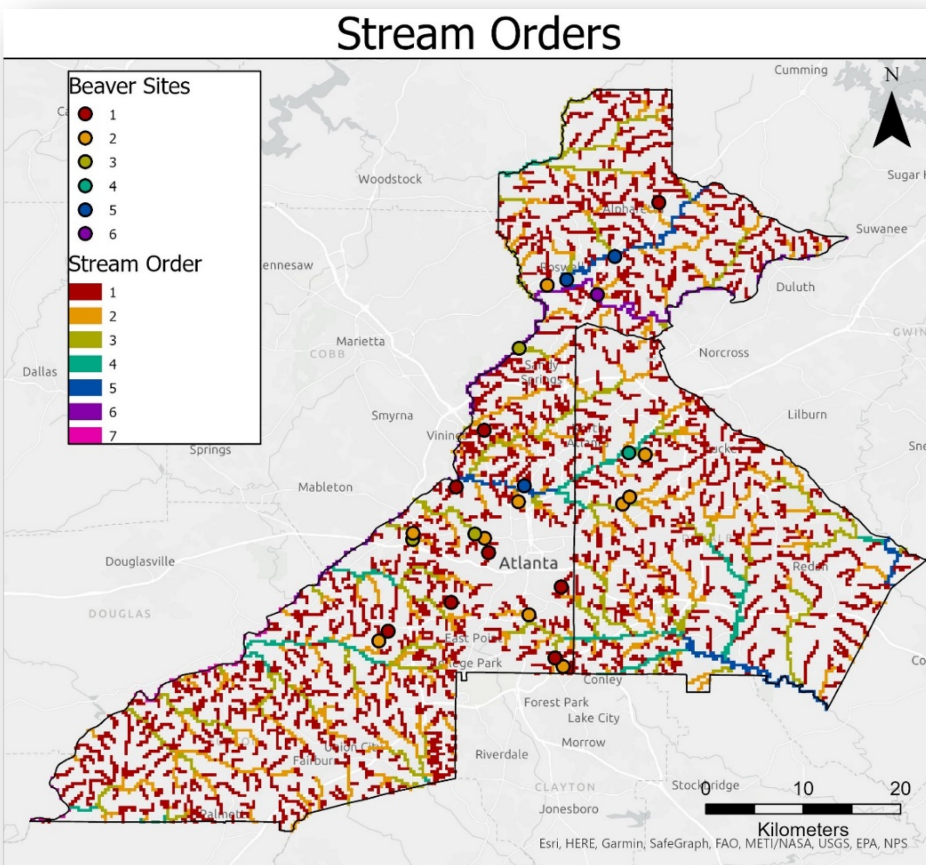


*Figure 12. Flowlines in Fulton County and DeKalb County categorized by stream order.*

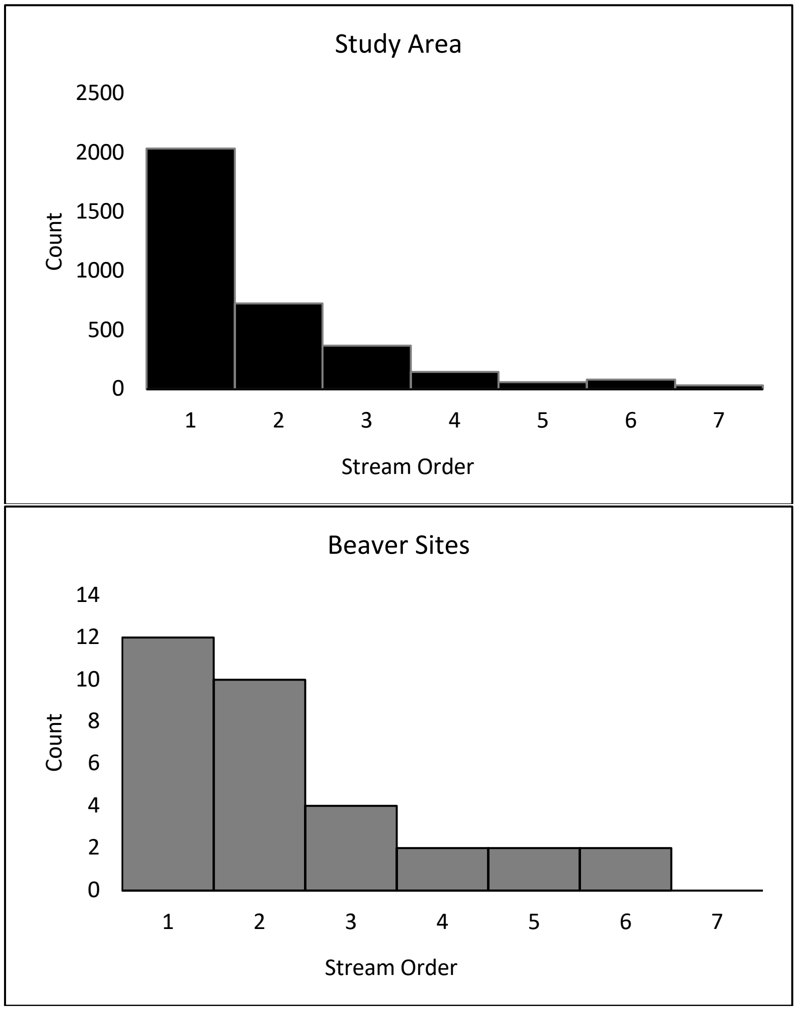


*Figure 13. Histograms of stream orders throughout metro Atlanta (top) and stream orders at beaver sites (bottom).*

*Table 13. Stream orders throughout metro Atlanta compared to stream orders found at beaver sites.*

| Stream Order | Study Area | Beaver Sites |
|---|---|---|
| 1 | 2035 (59%) | 12 (38%) |
| 2 | 725 (21%) | 10 (31%) |
| 3 | 368 (11%) | 4 (13%) |
| 4 | 145 (4%) | 2 (6%) |
| 5 | 61 (2%) | 2 (6%) |
| 6 | 84 (2%) | 2 (6%) |
| 7 | 35 (1%) | 0 (0%) |

### *3.2.3 Stream Slope*

In metro Atlanta, ~54% of all streams have a gradient between 0 and 1%, ~22% of all streams have a 1-2% slope, ~12% have a slope between 2-3%, and 3% of streams have a gradient from 3-4%. About 8% of all metro Atlanta stream reaches have a slope >4%. Of the beaver sites, 27 out of 32 (84%) can be found in a stream with a gradient no greater than 1%. Two of the sites (6%) have a slope between 1-2% and two have a slope from 2-3%. No beavers have been reported in stream reaches with a slope between 3-4%, and just one report comes from a stream with a gradient >4%. Most beaver sites are in streams with a slope of less than 1% (Figures 14 and 15, Table 16).

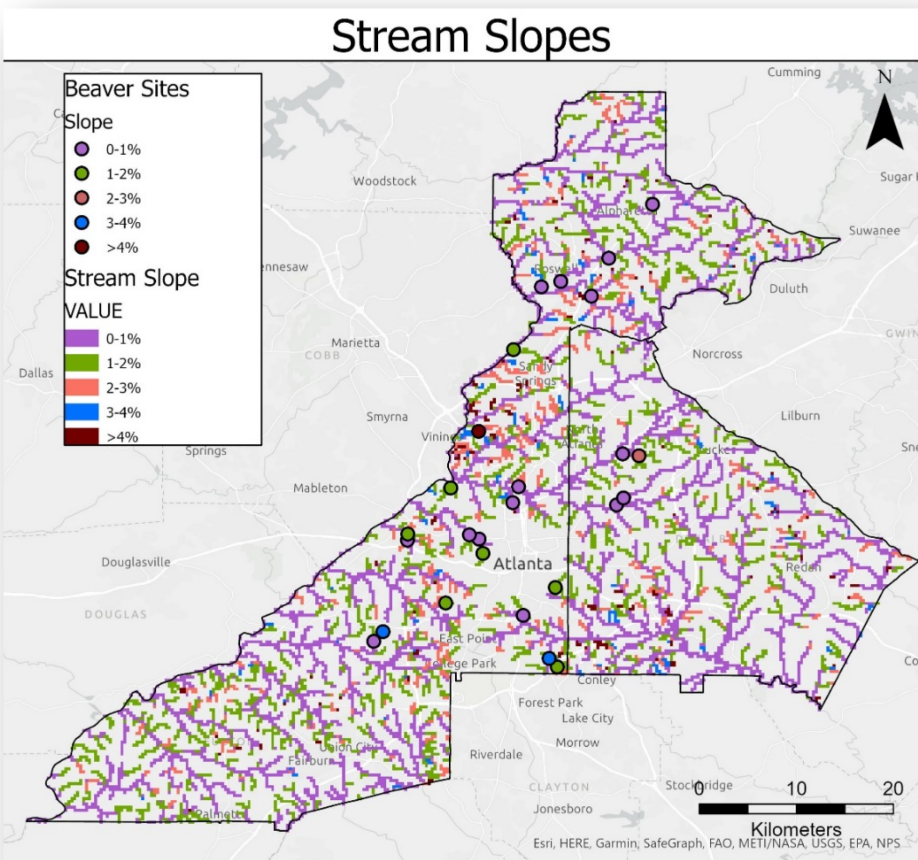


*Figure 14. Flowlines in Fulton County and DeKalb County categorized by stream slope.*

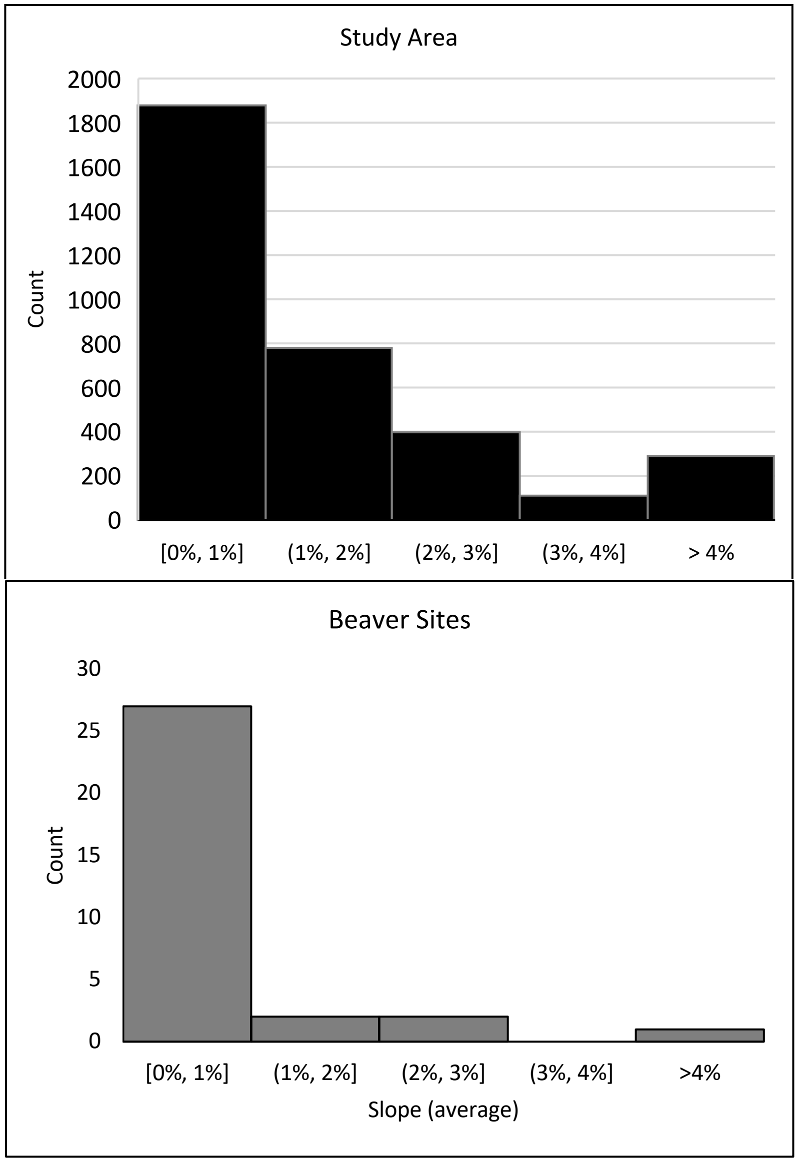


*Figure 15. Histograms showing stream slopes throughout metro Atlanta (top) compared to stream slopes found at beaver sites (bottom).*

*Table 14. Stream slopes throughout metro Atlanta and stream slopes at beaver sites.*

| Slope | Study Area | Beaver Sites |
|---|---|---|
| 0-1% | 187 (54%) | 27 (84%) |
| 1-2% | 778 (22%) | 2 (6%) |
| 2-3% | 397 (12%) | 2 (6%) |
| 3-4% | 110 (3%) | 0 (0%) |
| >4% | 290 (8%) | 1 (3%) |

### *3.2.4 Land Use Classification*

Buffers of 30 meters on each site were used for all stream reaches to determine land use variation as categorized by LandPro2009 data (Figures 16, 17, and Table 17). The categories are distributed as follows: 27% residential- medium density, 26% forest, 6% wetland, 5% park land, 4% each of residential- multifamily, agriculture, reservoirs, and residential- low density; 3% each of commercial and golf course; 2% each of transitional, rivers, institutional- extensive, parks, industrial/commercial; 1% each of institutional- intensive, limited access, residential- high density, urban- other; and 0% each of cemetery, exposed rock, industrial, quarries, residential- mobile, and transportation, communication and utilities (TCU). At the 32 beaver sites, 30-meter buffers were also used and at these reported locations, the land is comprised of 29% park lands, 24% residential- medium density, 12% forest, 9% reservoir, 7% urban- other, 6% parks, 3% each of residential- multi family, industrial/commercial, golf course; 2% wetlands, 1% commercial, and 0% transitional, agriculture, residential- low density, river, institutional- intensive, institutional extensive, limited access, residential- high density, transportation, quarry, cemetery, industrial, residential- mobile, and exposed rock.

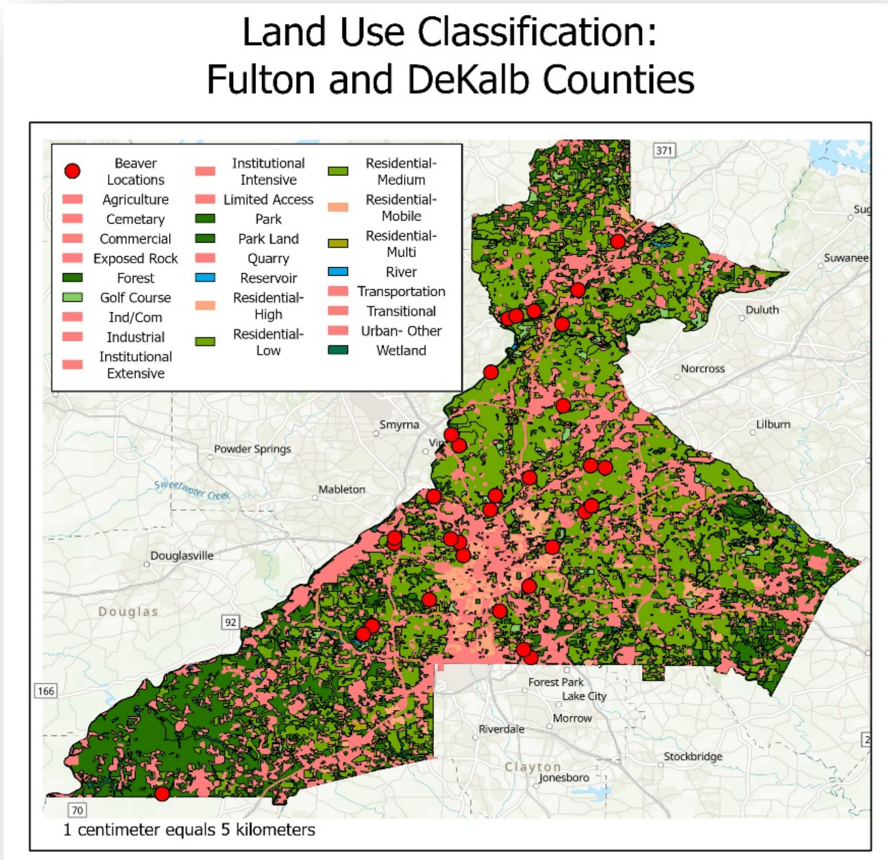


*Figure 16. LandPro2009 land use classification for Fulton County and DeKalb County.*

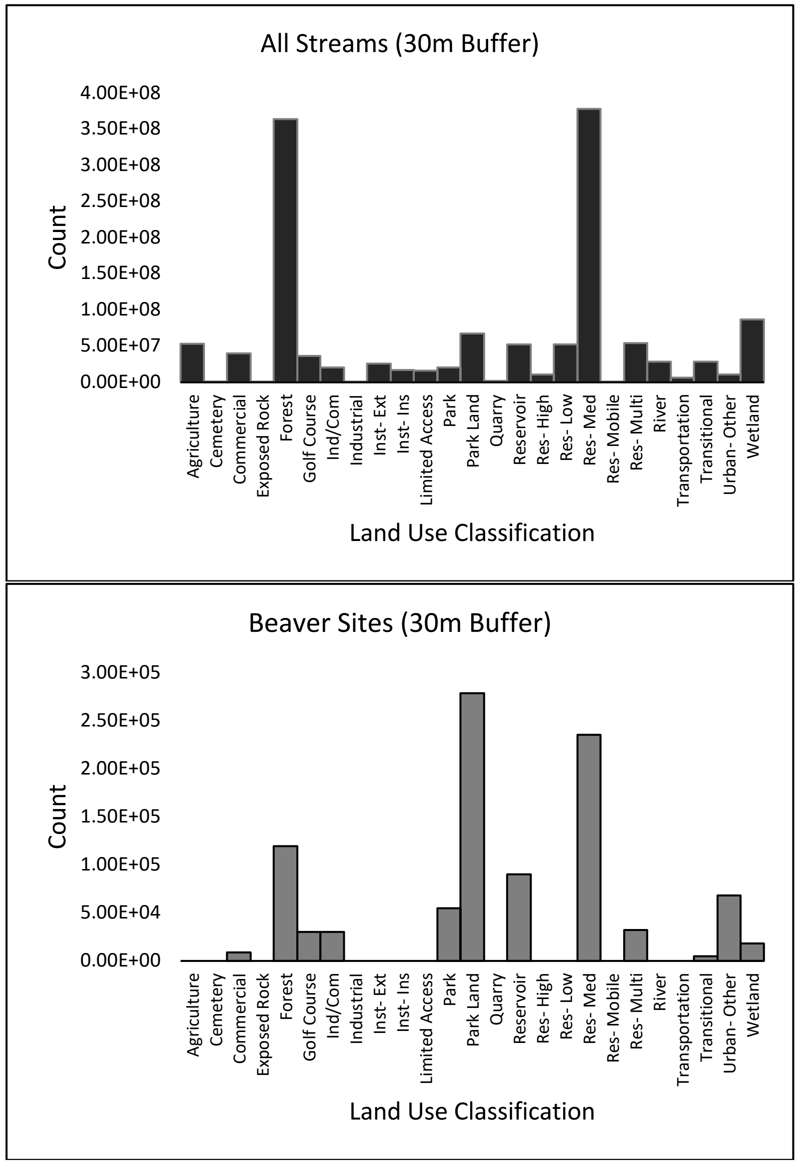


*Figure 17. Histograms showing land use within a 30-m buffer of all streams (top), and at beaver sites (bottom) in Atlanta.*

*Table 15. LandPro2009 land use classification within a 30-m buffer of all streams in the study area and at beaver sites in metro Atlanta.*

| Land Use Classification | Study Area (30m buffer) | Beaver Sites (30m buffer) |
|---|---|---|
| Agriculture | 53536382 (4%) | 0 (0%) |
| Cemetery | 1070788 (0%) | 0 (0%) |
| Commercial | 40250892 (3%) | 8990 (1%) |
| Exposed Rock | 49408 (0%) | 0 (0%) |
| Forest | 363741841 (26%) | 119263 (12%) |
| Golf Course | 36703560 (3%) | 30406 (3%) |
| Ind/Com | 20637743 (2%) | 30409 (3%) |
| Industrial | 614651 (0%) | 0 (0%) |
| Inst- Ext | 26028447 (2%) | 0 (0%) |
| Inst- Ins | 17288530 (1%) | 0 (0%) |
| Limited Access | 16472524 (1%) | 0 (0%) |
| Park | 20732557 (2%) | 55224 (6%) |
| Park Land | 67401870 (5%) | 279247 (29%) |
| Quarry | 1960420 (0%) | 0 (0%) |
| Reservoir | 52411972 (4%) | 90122 (9%) |
| Res- High | 10848824 (1%) | 0 (0%) |
| Res- Low | 51931463 (4%) | 0 (0%) |
| Res- Med | 377376919 (27%) | 235580 (24%) |
| Res- Mobile | 522873 (0%) | 0 (0%) |
| Res- Multi | 53927134 (4%) | 32489 (3%) |
| River | 28445127 (2%) | 0 (0%) |
| Transportation | 5957257 (0%) | 0 (0%) |
| Transitional | 28597298 (2%) | 4813 (0%) |
| Urban- Other | 10544661 (1%) | 68310 (7%) |
| Wetland | 87156824 (6%) | 18199 (2%) |

### *3.2.5 Additional Criteria: Culverts*

In consideration of additional physical criteria beavers may prefer in urbanized catchments, I analyzed the proximity of each beaver site to its nearest road culvert. Of the 32 beaver sites, ~31% (n=10) are within 200 meters of a culvert, 25% (n=8) are 200-400 meters from a culvert, about 19% (n=6) are 400-600 meters from a culvert, and 25% (n=8) are greater than 600 meters (Figure 18, Table 18).

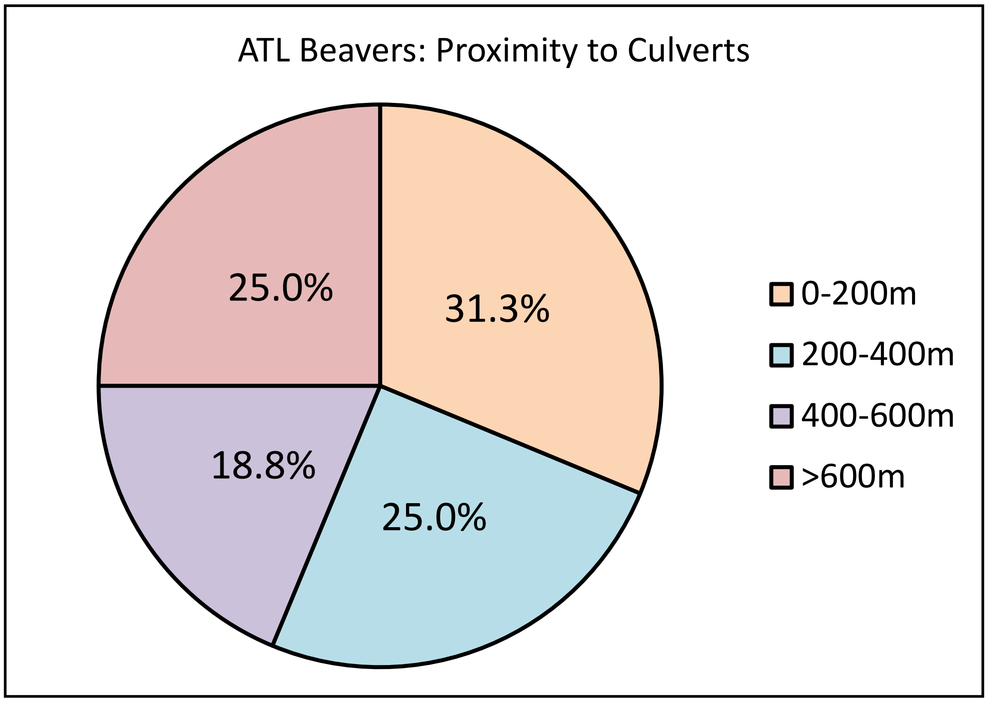


*Figure 18. Proximity of beaver sites to culverts in metro Atlanta.*

*Table 16. Distance from reported beaver sites in Atlanta to the nearest culvert.*

| Proximity to Culvert (m) | Count | Percentage |
|---|---|---|
| 0-200 | 10 | 31% |
| 200-400 | 8 | 25% |
| 400-600 | 6 | 19% |
| >600 | 8 | 25% |

## 3.3 Urban Model

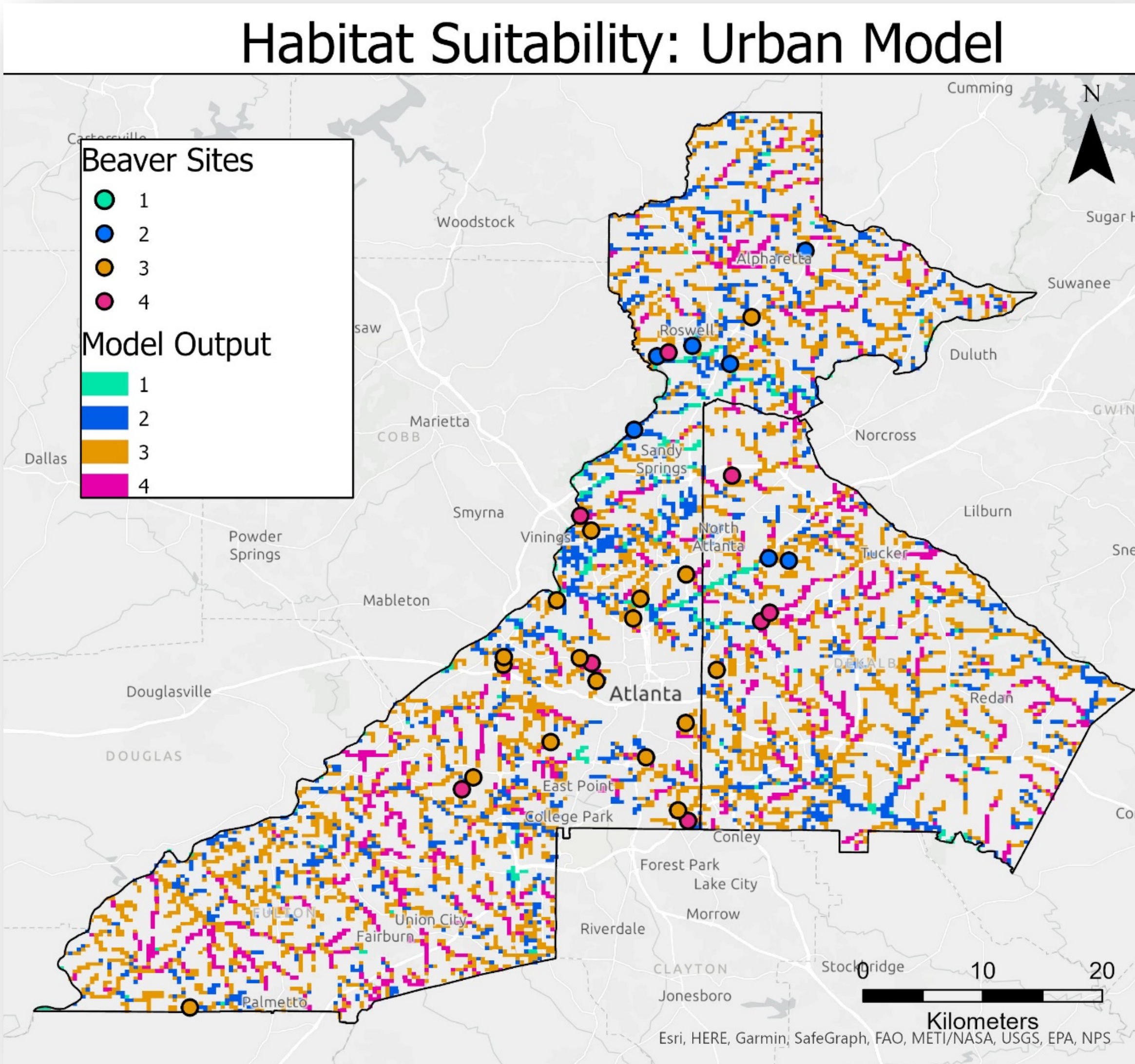


*Figure 19. Urban model output map for metro Atlanta. Output values correspond to the number of key habitat features present. Beaver site symbology represents model output values.*

The 7,583 stream segments in Fulton and DeKalb Counties were input into an adjusted urbanized model (Figure 19) based on the landscape parameters found at reported beaver sites in our study area. Beavers in metro Atlanta are mainly found in perennial streams (100%) with a stream order <=2 (80%) and a slope <=1% (54%). The land use within a 30m buffer of all reported beaver sites is generally classified as forest (12%), park land (29%), or medium-density residential (24%) in LandPro2009 data.

*Table 17. Urban model outputs, means, and Student's t-test result for the entire study area and for known beaver sites in Atlanta.*

| Urban Model Output | Study Area | Beaver Locations |
|---|---|---|
| 1 | 272 (4%) | 0 (0%) |
| 2 | 1959 (26%) | 7 (22%) |
| 3 | 4019 (53%) | 17 (53%) |
| 4 | 1333 (18%) | 8 (25%) |
| | Mean: 2.85 | Mean: 3.03 |
| | p= 0.07 | |

As shown in Table 19 and Figure 20, the urbanized model resulted in output values of 1 in 4% of all stream segments (n=272), 26% of segments (n=1959) received a model output of 2, 53% of stream reaches (n=4019) obtained an output value of 3, and 18% of all streams in metro Atlanta (n=1333) were given an output of 4. The distribution of output values for the urban model in all stream reaches were used to extract output values at beaver locations (n=32) with the following results. 0% of beaver locations (n= 0) in metro Atlanta received an urban habitat suitability value of 1. 22% of beaver sightings (n=7) occurred in stream reaches that have a suitability value of 2 in the urbanized index. 53% of beaver locations (n=17) are in stream reaches that received an output of 3. 25% of all beaver sightings (n=8) in the study area were found to be inhabiting areas containing all 4 physical parameters. The urbanized suitability model exhibits that approximately 71% of all stream reaches received a 3 or 4 output value, and this model assigned ~78% of beaver sites an output value of 3 or 4. A Student's t-test comparing the mean reach scores to all streams (mean: 2.85) versus at known beaver sites (mean: 3.03) yielded a p-value of 0.07.

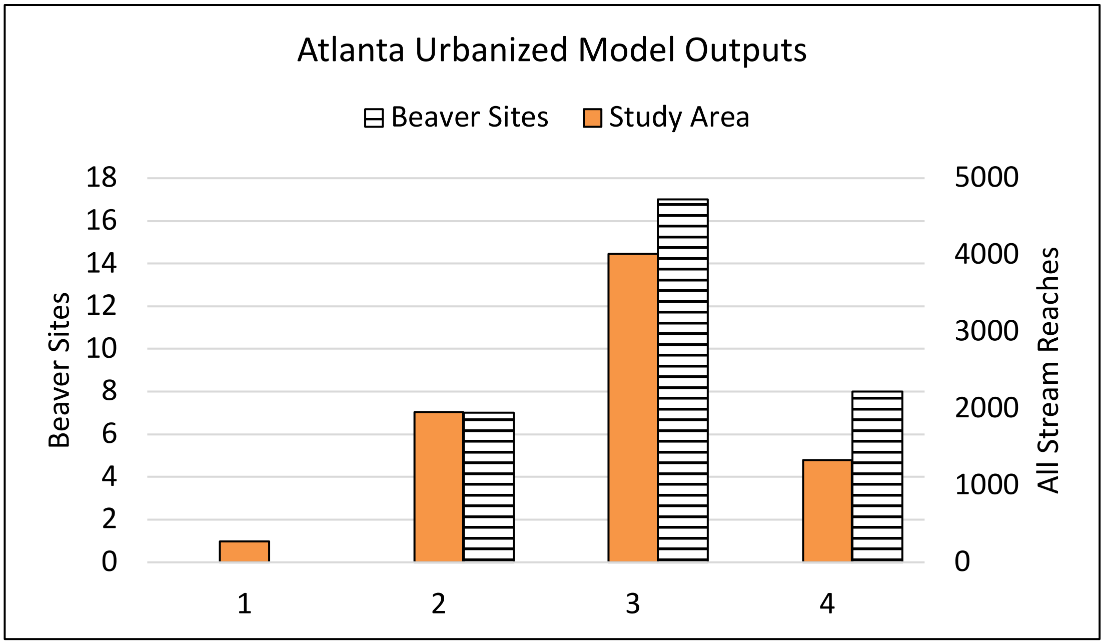


*Figure 20. Histograms of urban model outputs for all stream reaches in metro Atlanta (solid orange bar) and at the 32 beaver sites in Atlanta (striped, gray bar). The mean reach score for the entire study area is 2.85 while the mean score for beaver sites is 3.03 (p=0.07).*

### 3.4 Validation in Charlotte: Forested Model

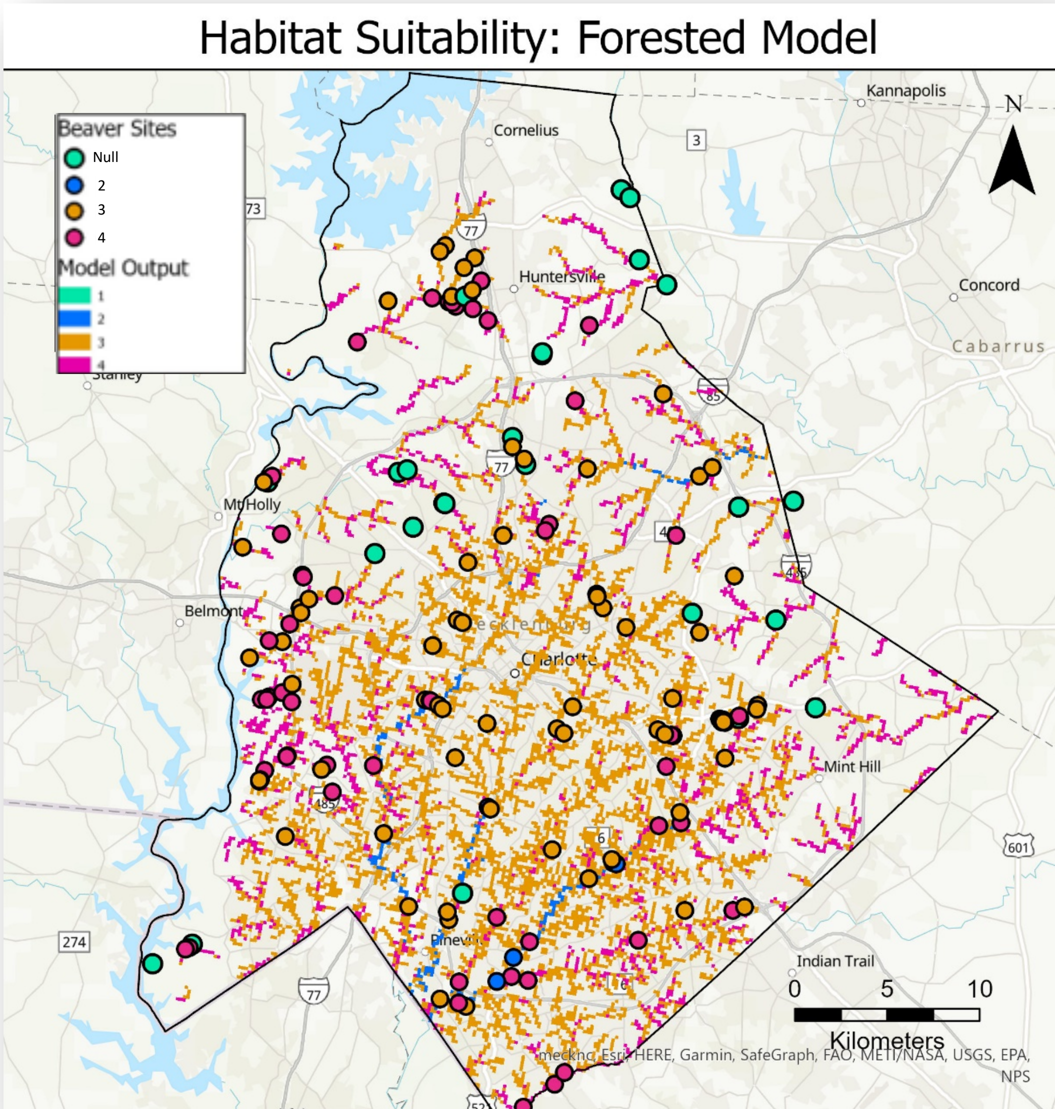


*Figure 21. Forested model output map for Charlotte. Output values correspond to the number of key habitat features present. Beaver site symbology represents model output values. Null values are beaver reports outside the 30m raster buffer built around stream reaches.*

The habitat suitability model (Figures 21 and 22, Table 20) for forested characteristics created for Charlotte resulted in a total of 10,111 stream segments being evaluated. Model inputs and outputs were ranked the same way as the Atlanta model. This model resulted in 0% of all stream segments (n=0) in Charlotte having output values of 1. 2% of all stream segments (n=252) received a model output of 2, missing two of the four required beaver habitat parameters. 73% of all stream reaches (n=7429) obtained an output value of 3 and the remaining 24% of stream segments (n=2430) were given an output of 4. The mean output value of the forested model for all stream reaches in Charlotte is 3.21.

*Table 18. Forested habitat suitability model outputs, means, and Student's t-test result for the entire study area and beaver sites in Charlotte, NC.*

| Forested Model Output | Study Area | Beaver Locations |
|---|---|---|
| 1 | 0 (0%) | 0 (0%) |
| 2 | 252 (2%) | 5 (3%) |
| 3 | 7429 (73%) | 81 (55%) |
| 4 | 2430 (24%) | 61 (41%) |
| | Mean: 3.21 | Mean: 3.38 |
| | p= 2.60E-4 | |

Model outputs at beaver sites in Charlotte received a mean value of 3.38, with 0 beaver sites occurring in stream reaches with a model output value of 1. 3% of beaver reports (n=5) are in stream segments with an output value of 2. Stream segments that received a model output of 3 comprised 55% of all beaver sites (n=81), and 41% of beaver locations (n=61) are in stream segments with an output of 4. The forested model for Charlotte resulted ~96% of all streams receiving a 3 or 4 output. The mean value of beaver sites (3.38) using this model is significantly higher than the mean output for all stream reaches (3.21), with a Student's t-test resulting in a p-value of 2.60E-4.

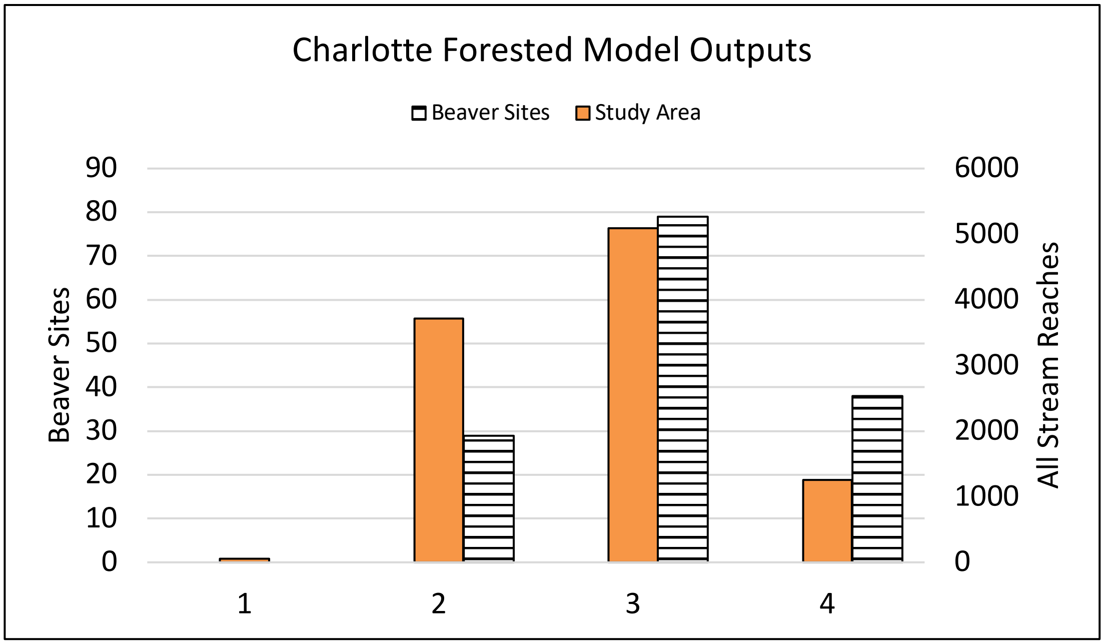


*Figure 22. Histograms of forested model outputs for all stream reaches in Charlotte (solid orange bar) and at the 146 beaver sites in Charlotte (striped, gray bar). The mean reach score for the entire study area is 3.21 while the mean score for beaver sites is 3.28 (p=2.60E-4).*

### 3.5 Validation in Charlotte: Urbanized Model

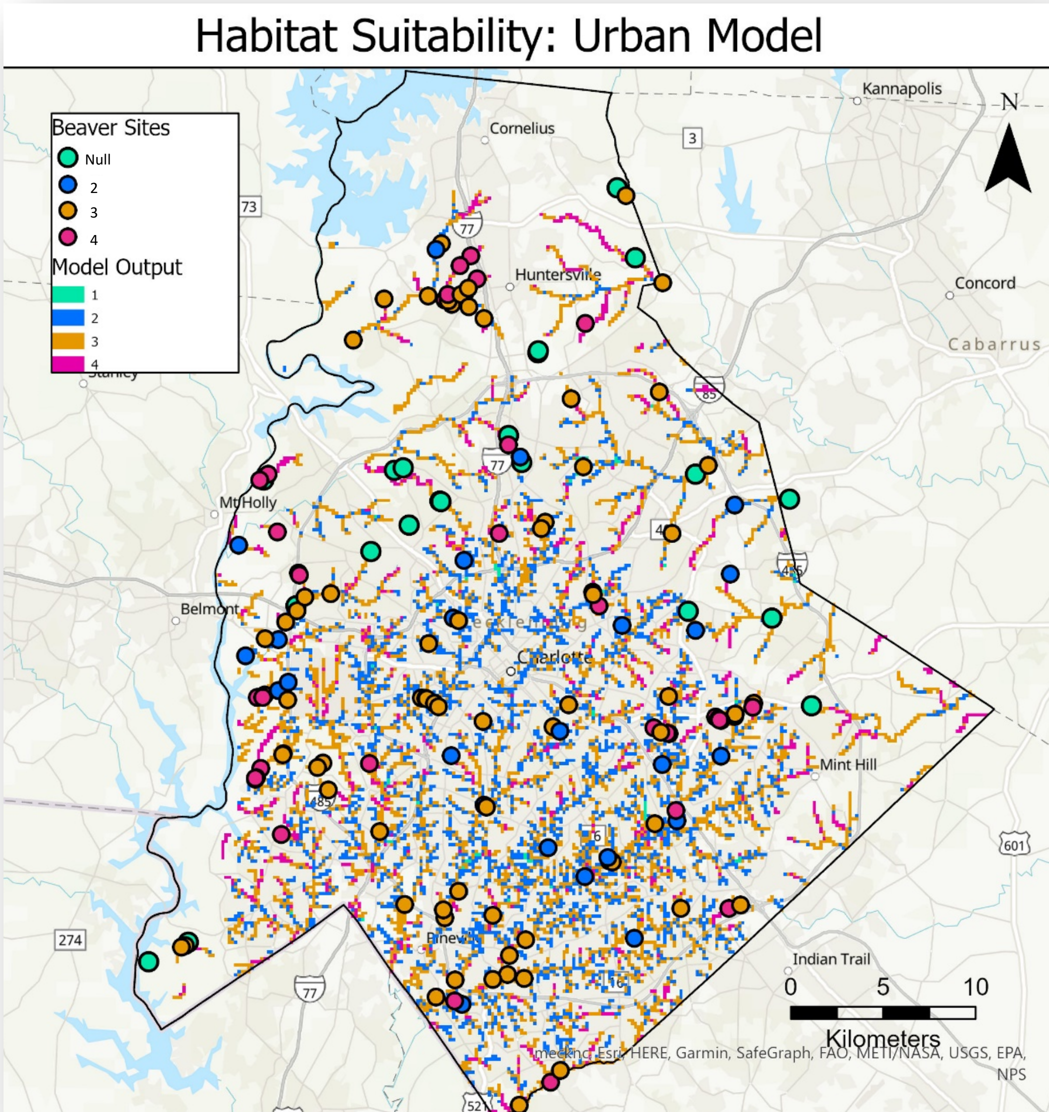


*Figure 23. Urban model output map for Charlotte. Output values correspond to the number of key habitat features present. Beaver site symbology represents model output values. Null values are beaver reports outside the 30m raster buffer built around stream reaches.*

When run in Charlotte, the urbanized model (Figures 23 and 24, Table 21) shows that 1% (n=58) of all stream segments received a model output of 1. 37% of all stream segments (n=3714) received a score of 2 out of 4. 50% of all stream segments (n=5087) had an output of 3 and 12%

(n=1259) of all stream segments received an output of 4, so a total of 62% of all streams in Charlotte received a 3 or 4 output after model adjustments were made. The mean values reported for all streams in the Charlotte urbanized model is 2.74.

*Table 19. Urban habitat suitability model outputs, means, and Student's t-test result for the entire study area and beaver sites in Charlotte, NC.*

| Urban Model Output | Study Area | Beaver Locations |
|---|---|---|
| 1 | 58 (1%) | 0 (0%) |
| 2 | 3714 (37%) | 29 (20%) |
| 3 | 5087 (50%) | 79 (54%) |
| 4 | 1259 (12%) | 39 (27%) |
| | Mean: 2.74 | Mean: 3.06 |
| | p=4.43E-8 | |

Zero beaver sites in Charlotte received an urbanized model output score of 1, and 20% of the beaver locations (n=29) were found in stream reaches with outputs of 2. 50% of all beaver sites in Charlotte contain 3 of the specified parameters for this model (n=79), and 27% of the beaver sites (n=39) were found in stream reaches with model values of 4. Of all the beaver sites, about 77% lie within stream reaches that received an output value of 3 or 4, and the mean output value was 3.06. Performing a Student's t-test on the mean values at all streams versus beaver sites in Charlotte resulted in a p-value of 4.43E-8, indicating the mean value at known beaver sites is higher than that for all stream reaches (mean= 2.74) in Charlotte.

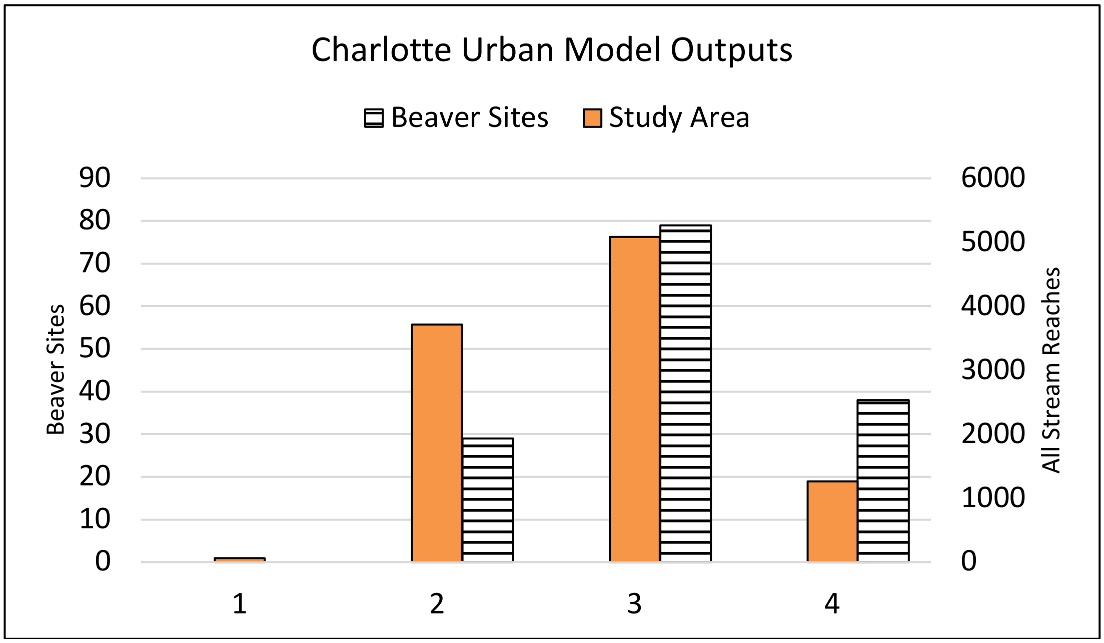


*Figure 24. Histograms of the urban model outputs for all stream reaches in Charlotte (solid orange bar) and at the 146 beaver sites in Charlotte (striped, gray bar). The mean reach score for the entire study area is 2.74 while the mean score for beaver sites is 3.06 (p=4.43E-8).*

# 4 DISCUSSION AND CONCLUSIONS

In highly urbanized watersheds, the abundance of impervious surface cover contributes to decreased infiltration and increased runoff during storm events, resulting in unnatural quantities of water being discharged through the landscape, causing flooding and stream degradation. Stormwater management efforts include urban infrastructure designs such as stormwater management ponds that provide water storage and regulation by mimicking natural landscape features. These designs are expensive and time consuming to design, build, and maintain. Studies show that in forested watersheds, beaver dams and ponds greatly contribute to the overall ecosystem health of streams, including their water quality (Brazier et al., 2020; Law et al., 2016; Pollock et al., 2014; Puttock et al., 2017) and beaver dams built on urban streams can slow water during high flow periods and store water during dry periods (Auster et al., 2022; Law et al., 2017; Ledford et al., 2023).

The increased prevalence of beavers in highly urbanized watersheds shows they have adapted to the stressed environmental conditions like flashy storm discharges and lack of choice in stemmed vegetation, but as their populations increase, so does the potential for conflict to arise. Urban beavers can cause unwanted flooding of roadways and walkways, as well as rapid change in vegetation cover. To lessen conflict with beavers as their populations increase, it is necessary to understand habitat availability in urbanized watersheds.

Previous studies have narrowed down the minimum habitat characteristics required for beavers in forested watersheds: a water source with perennial flow, flow that is not strong enough to blow out dams during a storm event (i.e., streams of lower order and slope), and nearby stemmed vegetation for eating and building (Graham et al., 2020; Macfarlane et al., 2017; Maringer & Slotta-Bachmayr, 2006; Touihri et al., 2018). Graham et al. (2020) differentiates between tree types in their modelling of a forested catchment, but I chose a generalized approach for this model based on evidence that beavers' preferences in food source become less particular as resources are stressed (Fustec et al., 2001; Vorel et al., 2015).

After building a forested model for metro Atlanta using inputs of 1) perennial flow, 2) stream order <=4, stream slope <=15%, and presence of woody riparian vegetation, this model shows that ~86% of all fluvial landscape in metro Atlanta exhibited at least 3 of the 4 landscape features required by beavers while 81% of known beaver sites had a score of 3 or 4 (Figure H and Table 11). This indicates that most of the metro Atlanta area could be habitable, even though beavers are not currently living in most of these areas. Working under the assumption that the habitat model should highlight particular characteristics that are not present in the entire study area, I argue that the models should not result in the same mean reach value, and the beaver sites should have a higher mean value than the entire area, nor should the model have the same percent of known beaver sites falling into high scores as all stream reaches. Looking at the habitat of known beaver occupancy locations, the mean (3.06) habitat ranking of known beaver locations using this model is about the same as the mean (3.08) of all reaches in Atlanta ($p=0.45$). The similar mean reach value and distribution in output values between all stream reaches and the beaver locations (Figure I) indicate that the forested model is not specific enough to differentiate between likely and unlikely beaver habitat.

After the model inputs were adjusted to reflect parameters at known beaver sites (Tables 14, 15, 16, and 17), henceforth referred to as the urban model (Figure 19 and Table 19), the mean (2.85) 30-m reach score in the whole metro Atlanta area was less than the mean (3.03) of scores found at known beaver locations ($p=0.07$). Although $p>0.05$, we can infer that the urban model is more effective at differentiating suitable from unsuitable urban beaver habitat than the forested model because this p-value is much closer to the threshold of 0.05 than the p-value comparing the forested model outputs to beaver sites (p=0.45). In addition, the number of known beaver sites with a score of 4 was 25%, while there were only 18% of total stream reaches that scored 4 (Table 17). Therefore, it can be stated that making urban adjustments to the model did increase the likelihood of the model accurately differentiating the habitat of urban beaver locations.

To validate the model, I built the same two models for the streams of Charlotte, NC, with a different landcover dataset because LandPro2009 is only available for Atlanta. Justification for substituting LANDFIRE data for LandPro2009 data stems from the landcover comparison in Atlanta (Table 12). At 30-meter resolution, LANDFIRE more closely resembles the land cover distribution of the 0.5-meter resolution NAIP data than the Sentinel-2 data with resolution of 10 meters. The forested model for Charlotte resulted in ~98% of all stream reaches containing at least 3 of the 4 required landscape features and 96% of known beaver sites (Figure 21 and Table 20). When the forested model outputs for all Charlotte streams was compared to the forested model outputs for Charlotte beaver sites (n=146, all streams: 3.21; beaver sites: 3.38) they are significantly different, with beaver site scoring higher (p=2.6E-04). This indicates that forested model seems to be less biased in highlighting potential beaver activity in Charlotte than it was in Atlanta, potentially due to the larger dataset of beaver locations. When the model was adjusted for urban beavers in Charlotte (Figure 23 and Table 21), the t-test also showed that all streams and beaver sites do not have the same mean score (p=4.4E-08), with beaver sites having a higher mean suitability (3.06) than all sites (2.74). The smaller p-value than the forested characteristic model indicates that the urban model is better than the forested model at differentiating beaver sites from non-beaver sites in Charlotte. However, the final urban model mean scores in known beaver sites of 3.03 in Atlanta and 3.06 in Charlotte show that, while better than the forested model, the urban model still misses key habitat characteristics.

## 4.1 Missing Habitat Characteristics?

Beavers that reside in urban environments are subject to stressors on their food and habitat preferences, but since these animals are highly adaptable, they have been observed utilizing man-made infrastructure in their ecosystem engineering designs (Curtis & Jensen, 2004; Jensen et al., 2001; Touihri et al., 2018). Overall, the fact that our urban-adapted model still had mean rankings of 3.03 and 3.06 for known beaver sites in Atlanta and Charlotte respectively does show that the urban model is better than the forested but also clearly points to missing characteristics in the model. Stressors for beavers come from, but are not limited to, predation and competition with other beavers for suitable habitat in forested areas, while urban beavers have the added stress of rapid land use changes and human-beaver conflict (Auster et al., 2020; Campbell-Palmer et al., 2016; Swinnen et al., 2015, 2017). Since road culverts in urban areas channel and direct water through a relatively small opening, these structures are ideal for beavers to clog with their dams if they want to raise the water level upstream of where it discharges and I thought they would be a potential parameter. In metro Atlanta, beavers have been reported as close as 30 meters and as far as 1300 meters from the nearest culvert (Figure R and Table 18). Just over half of the sites were found within 400 meters of a culvert, but 25% of beavers were not found within 600 meters of one. These findings suggest that although convenient for dam building, the presence of a nearby culvert does not tend to influence the behavior of beavers to inhabit a section of a stream, therefore culvert proximity was not considered as an input to add to my urbanized model. When considering conflict management (Campbell-Palmer et al., 2016; Swinnen et al., 2015, 2017) this finding is key to framing conversations with residents and stakeholders. Field observations further suggest that in lieu of damming free-flowing water in urban catchments, beavers may utilize small bodies of ponded water in their habitat design, however at 7-meter-resolution, the landcover dataset used is not fine enough spatial resolution to pick out waterbodies smaller than that size. Additional work is needed to continue to refine the urban model with missing landscape characteristics.

## 4.2 Biases in Datasets

The habitat suitability models presented in this study depend on crowd-sourced beaver location data for model calibration, while the validation dataset was collected by a municipality. With resources, education, and verification, crowd-sourced wildlife observations can be an effective tool in conservation and research, the accuracy and the validity of such reporting is impacted by the reporters' ages, time spent residing in the area, education, and personal experience with the species (G. Brown et al., 2018; Jacobs, 2016). In addition to there being a limited number of resources to report beavers in Atlanta, there is no database for all beaver reports and minimal communication between organizations to combine knowledge into such a database. This creates unreliability in my calibration technique, where I compared model outputs to existing beaver habitat locations reported since 2016.

Natural seasonal variability in preferred beaver habitat (Law et al., 2014; Vorel et al., 2015) and stressors like urban development lead to a transience in beaver habitat selection, where they move in and out of landscapes over extended periods of time. Model validation would benefit greatly from a larger dataset of beaver sites in the study area, and specific characteristics should be noted in the dataset. In addition to dam building, conflict with beavers can be caused by other activity such as burrowing and destroying crops (Auster et al., 2020; Campbell-Palmer et al., 2015;

Crowley et al., 2017). As the inventory expands, the model can be run with various categories of beaver presence, including a dam or lodge structure, clues such as tree felling and chewings, beaver sightings, and eventually keeping track of population expansion.

These models were also limited by the temporal and spatial resolution of the land cover datasets. Using 7-meter-resolution LandPro 2009 data was the first step in trying to understand potential beaver habitat hotspots in Atlanta, but next, these models should be run with more recent 0.5-meter-resolution NAIP imagery to compare and further evaluate the effectiveness of using the lower resolution data for vast areas (e.g., across counties). With the use of higher resolution data, beaver sites should also be analyzed based on their proximity to small ponds only visible in finer-scale aerial imagery.

### 4.3 Conclusions

The findings of this research suggests that the habitat preferences of beaver are significantly altered by unique features of the urban landscape in contrast to the landscapes they occupy in non-urban environments. The beaver habitat suitability model for Atlanta and Charlotte required adjustments to the physical criteria of stream order, slope, and land use categories to more accurately highlight potential beaver habitat. This study demonstrated the lack of understanding of beaver-preferred landscape parameters in urban settings because ideally most or all beaver sites should be found in pixels with urban model outputs of 4, and that was not the case in either city. Both urban models resulted in beaver sites yielding larger means than the study area, with p-values showing these differences are statistically significant. A more sophisticated input criteria with more logical input variables is necessary to refine the models. For example, instead of using the average slope values for stream segments given by the NHD+HR data, the slopes of predefined reach lengths can be calculated. Additionally, the same land use dataset can be used for both cities during validation to eliminate the possibility of extraneous influence of different land cover data.

Predicting the spatial variability of suitable habitat in urban areas is necessary because there is a gap in understanding what drivers dictate beaver activity and preference when natural resources are stressed, or nonexistent, and this study's modeling procedures provide a novel approach to quickly approximate the relative likelihood of a stream reach's ability to support beaver. Future models can be further refined through usage of higher resolution remote sensing datasets to (1) evaluate a more fine-tuned vegetation distribution, and (2) analyze finer-scale features, like ponds, that beavers might be drawn to in urban settings. The urbanized beaver habitat suitability model introduced by this study is a crucial first step in identifying key beaver habitat features in urban landscapes and can serve as a valuable tool for planners, managers, and researchers to determine where their restoration and investigative efforts can be most beneficial.

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# APPENDICES

## Appendix A

### *Appendix A.1 LANDFIRE reclassification*

*Table 20.Reclassification of LANDFIRE land use data for Site 400.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 1132 | Eastern Cool Temperate Urban Herbaceous | Open Green Space |
| 20 | Eastern Cool Temperate Developed Herbaceous | |
| 1 | Eastern Cool Temperate Row Crop | |
| 78 | Eastern Cool Temperate Pasture and Hayland | |
| 9 | Southeastern Ruderal Grassland | |
| 8119 | Developed-Low Intensity | Trees/Shrubs |
| 7538 | Developed-Medium Intensity | |
| 178 | Southern Piedmont Mesic Forest | |
| 347 | Southern Piedmont Dry Pine Forest | |
| 455 | Southern Piedmont Dry Oak Forest | |
| 432 | Southern Piedmont Dry Oak-(Pine) Forest | |
| 662 | Eastern Cool Temperate Urban Deciduous Forest | |
| 11814 | Eastern Cool Temperate Urban Evergreen Forest | |
| 1497 | Eastern Cool Temperate Urban Mixed Forest | |
| 204 | Eastern Cool Temperate Urban Shrubland | |
| 833 | Eastern Cool Temperate Developed Deciduous Forest | |
| 1651 | Eastern Cool Temperate Developed Evergreen Forest | |
| 2299 | Eastern Cool Temperate Developed Mixed Forest | |
| 65 | Southern Piedmont Small Floodplain and Riparian Forest | |
| 517 | Southeastern Native Ruderal Forest | |
| 76 | Southeastern North American Temperate Forest Plantation | |
| 1 | Southeastern Ruderal Shrubland | |
| 5340 | Developed-High Intensity | Urban |
| 19614 | Developed-Roads | |
| 532 | Open Water | Water |

*Table 21. Reclassification of LANDFIRE land use data for Site BH.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 1417 | Eastern Cool Temperate Urban Herbaceous | Open Green Space |
| 25 | Eastern Cool Temperate Developed Herbaceous | |
| 2 | Eastern Cool Temperate Row Crop | |
| 304 | Eastern Cool Temperate Pasture and Hayland | |
| 1 | Southern Piedmont Small Floodplain and Riparian Herbaceous | |
| 21 | Southeastern Ruderal Grassland | |
| 7617 | Developed-Low Intensity | Trees/Shrubs |
| 5160 | Developed-Medium Intensity | |
| 539 | Southern Piedmont Mesic Forest | |
| 988 | Southern Piedmont Dry Pine Forest | |
| 1278 | Southern Piedmont Dry Oak Forest | |
| 1672 | Southern Piedmont Dry Oak-(Pine) Forest | |
| 851 | Eastern Cool Temperate Urban Deciduous Forest | |
| 13412 | Eastern Cool Temperate Urban Evergreen Forest | |
| 2072 | Eastern Cool Temperate Urban Mixed Forest | |
| 261 | Eastern Cool Temperate Urban Shrubland | |
| 1619 | Eastern Cool Temperate Developed Deciduous Forest | |
| 2655 | Eastern Cool Temperate Developed Evergreen Forest | |
| 4339 | Eastern Cool Temperate Developed Mixed Forest | |
| 244 | Southern Piedmont Small Floodplain and Riparian Forest | |
| 1294 | Southeastern Native Ruderal Forest | |
| 97 | Southeastern North American Temperate Forest Plantation | |
| 1 | Southeastern Ruderal Shrubland | |
| 2791 | Developed-High Intensity | Urban |
| 13808 | Developed-Roads | |
| 946 | Open Water | Water |

*Table 22. Reclassification of LANDFIRE land use data for Site Candler.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 1453 | Eastern Cool Temperate Urban Herbaceous | Open Green Space |
| 16 | Eastern Cool Temperate Developed Herbaceous | |
| 1 | Eastern Cool Temperate Row Crop - Close Grown Crop | |
| 12 | Eastern Cool Temperate Row Crop | |
| 251 | Eastern Cool Temperate Pasture and Hayland | |
| 31 | Southeastern Ruderal Grassland | |
| 8795 | Developed-Low Intensity | Trees/Shrubs |
| 7349 | Developed-Medium Intensity | |
| 425 | Southern Piedmont Mesic Forest | |
| 443 | Southern Piedmont Dry Pine Forest | |
| 1022 | Southern Piedmont Dry Oak Forest | |
| 554 | Southern Piedmont Dry Oak-(Pine) Forest | |
| 1008 | Eastern Cool Temperate Urban Deciduous Forest | |
| 9683 | Eastern Cool Temperate Urban Evergreen Forest | |
| 2332 | Eastern Cool Temperate Urban Mixed Forest | |
| 341 | Eastern Cool Temperate Urban Shrubland | |
| 1012 | Eastern Cool Temperate Developed Deciduous Forest | |
| 909 | Eastern Cool Temperate Developed Evergreen Forest | |
| 1526 | Eastern Cool Temperate Developed Mixed Forest | |
| 1 | Eastern Cool Temperate Orchard | |
| 265 | Southern Piedmont Small Floodplain and Riparian Forest | |
| 16 | Southeastern Native Ruderal Flooded & Swamp Forest | |
| 685 | Southeastern Native Ruderal Forest | |
| 59 | Southeastern North American Temperate Forest Plantation | |
| 2 | Southeastern Ruderal Shrubland | |
| 5271 | Developed-High Intensity | Urban |
| 19757 | Developed-Roads | |
| 466 | Open Water | Water |

*Table 23. Reclassification of LANDFIRE land use data for Site Graves.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 1027 | Eastern Cool Temperate Urban Herbaceous | Open Green Space |
| 35 | Eastern Cool Temperate Developed Herbaceous | |
| 9 | Eastern Cool Temperate Row Crop | |
| 614 | Eastern Cool Temperate Pasture and Hayland | |
| 1 | Eastern Cool Temperate Wheat | |
| 37 | Southeastern Ruderal Grassland | |
| 9633 | Developed-Low Intensity | Trees/Shrubs |
| 8378 | Developed-Medium Intensity | |
| 295 | Southern Piedmont Mesic Forest | |
| 356 | Southern Piedmont Dry Pine Forest | |
| 658 | Southern Piedmont Dry Oak Forest | |
| 234 | Southern Piedmont Dry Oak-(Pine) Forest | |
| 644 | Eastern Cool Temperate Urban Deciduous Forest | |
| 7354 | Eastern Cool Temperate Urban Evergreen Forest | |
| 938 | Eastern Cool Temperate Urban Mixed Forest | |
| 325 | Eastern Cool Temperate Urban Shrubland | |
| 781 | Eastern Cool Temperate Developed Deciduous Forest | |
| 818 | Eastern Cool Temperate Developed Evergreen Forest | |
| 1510 | Eastern Cool Temperate Developed Mixed Forest | |
| 2 | Eastern Cool Temperate Developed Shrubland | |
| 425 | Southern Piedmont Small Floodplain and Riparian Forest | |
| 12 | Southeastern Native Ruderal Flooded & Swamp Forest | |
| 758 | Southeastern Native Ruderal Forest | |
| 130 | Southeastern North American Temperate Forest Plantation | |
| 10374 | Developed-High Intensity | Urban |
| 18131 | Developed-Roads | |
| 206 | Open Water | Water |

*Table 24. Reclassification of LANDFIRE land use data for Site MC.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 1229 | Eastern Cool Temperate Urban Herbaceous | Open Green Space |
| 40 | Eastern Cool Temperate Developed Herbaceous | |
| 108 | Eastern Cool Temperate Pasture and Hayland | |
| 26 | Southeastern Ruderal Grassland | |
| 8266 | Developed-Low Intensity | Trees/Shrubs |
| 7438 | Developed-Medium Intensity | |
| 435 | Southern Piedmont Mesic Forest | |
| 463 | Southern Piedmont Dry Pine Forest | |
| 649 | Southern Piedmont Dry Oak Forest | |
| 511 | Southern Piedmont Dry Oak-(Pine) Forest | |
| 1037 | Eastern Cool Temperate Urban Deciduous Forest | |
| 10875 | Eastern Cool Temperate Urban Evergreen Forest | |
| 1800 | Eastern Cool Temperate Urban Mixed Forest | |
| 207 | Eastern Cool Temperate Urban Shrubland | |
| 1411 | Eastern Cool Temperate Developed Deciduous Forest | |
| 1268 | Eastern Cool Temperate Developed Evergreen Forest | |
| 2551 | Eastern Cool Temperate Developed Mixed Forest | |
| 1 | Eastern Cool Temperate Developed Shrubland | |
| 343 | Southern Piedmont Small Floodplain and Riparian Forest | |
| 90 | Southeastern Native Ruderal Flooded & Swamp Forest | |
| 983 | Southeastern Native Ruderal Forest | |
| 120 | Southeastern North American Temperate Forest Plantation | |
| 2 | Southeastern Ruderal Shrubland | |
| 4022 | Developed-High Intensity | Urban |
| 19188 | Developed-Roads | |
| 351 | Open Water | Water |

*Table 25. Reclassification of LANDFIRE land use data for Site Shoal.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 1073 | Eastern Cool Temperate Urban Herbaceous | Open Green Space |
| 35 | Eastern Cool Temperate Developed Herbaceous | |
| 5 | Eastern Cool Temperate Row Crop | |
| 184 | Eastern Cool Temperate Pasture and Hayland | |
| 32 | Southeastern Ruderal Grassland | |
| 8236 | Developed-Low Intensity | Trees/Shrubs |
| 5522 | Developed-Medium Intensity | |
| 215 | Southern Piedmont Mesic Forest | |
| 604 | Southern Piedmont Dry Pine Forest | |
| 716 | Southern Piedmont Dry Oak Forest | |
| 421 | Southern Piedmont Dry Oak-(Pine) Forest | |
| 1234 | Eastern Cool Temperate Urban Deciduous Forest | |
| 13598 | Eastern Cool Temperate Urban Evergreen Forest | |
| 2508 | Eastern Cool Temperate Urban Mixed Forest | |
| 216 | Eastern Cool Temperate Urban Shrubland | |
| 984 | Eastern Cool Temperate Developed Deciduous Forest | |
| 1594 | Eastern Cool Temperate Developed Evergreen Forest | |
| 1847 | Eastern Cool Temperate Developed Mixed Forest | |
| 6 | Eastern Cool Temperate Developed Shrubland | |
| 1 | Eastern Cool Temperate Orchard | |
| 1 | Eastern Cool Temperate Bush fruit and berries | |
| 298 | Southern Piedmont Small Floodplain and Riparian Forest | |
| 32 | Southeastern Native Ruderal Flooded & Swamp Forest | |
| 752 | Southeastern Native Ruderal Forest | |
| 132 | Southeastern North American Temperate Forest Plantation | |
| 5 | Southeastern Ruderal Shrubland | |
| 3778 | Developed-High Intensity | Urban |
| 19529 | Developed-Roads | |
| 127 | Open Water | Water |

***Appendix A.2 LandPro2009 reclassification***

*Table 26. Reclassification of LandPro2009 land use data for Site 400.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 4 | GOLF_COURSES | Open Green Space |
| 12 | FOREST | Trees/Shrubs |
| 2 | RES_LOW | |
| 290 | RES_MED | |
| 12 | PARKS | |
| 95 | COMMERCIAL | Urban |
| 5 | TCU | |
| 7 | IND/COM | |
| 5 | URBAN_OTHER | |
| 9 | TRANSITIONAL | |
| 95 | RES_MULTI | |
| 14 | INST_INTENSIVE | |
| 5 | RES_HIGH | |
| 16 | LTD_ACCESS | |
| 1 | RESERVOIRS | Water |

*Table 27. Reclassification of LandPro2009 land use data for Site BH.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 5 | AGRICULTURE | Open Green Space |
| 14 | GOLF_COURSES | |
| 1 | CEMETERIES | |
| 5 | PARK_LANDS | Trees/Shrubs |
| 10 | FOREST | |
| 50 | RES_LOW | |
| 348 | RES_MED | |
| 9 | PARKS | |
| 35 | COMMERCIAL | Urban |
| 1 | TCU | |
| 10 | IND/COM | |
| 1 | TRANSITIONAL | |
| 47 | RES_MULTI | |
| 27 | INST_INTENSIVE | |
| 1 | RES_MOBILE | |
| 8 | LTD_ACCESS | |

*Table 28. Reclassification of LandPro2009 land use data for Site Candler.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 12 | GOLF_COURSES | Open Green Space |
| 2 | CEMETERIES | |
| 16 | PARK_LANDS | Trees/Shrubs |
| 35 | FOREST | |
| 8 | RES_LOW | |
| 183 | RES_MED | |
| 17 | PARKS | |
| 36 | COMMERCIAL | Urban |
| 2 | INDUSTRIAL | |
| 11 | TCU | |
| 27 | IND/COM | |
| 2 | INST_EXTENSIVE | |
| 6 | TRANSITIONAL | |
| 35 | RES_MULTI | |
| 46 | INST_INTENSIVE | |
| 128 | RES_HIGH | |
| 4 | LTD_ACCESS | |
| 2 | RESERVOIRS | Water |

*Table 29. Reclassification of LandPro2009 land use data for Site Graves.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 7 | GOLF_COURSES | Open Green Space |
| 3 | FOREST | Trees/Shrubs |
| 71 | RES_MED | |
| 1 | PARKS | |
| 11 | COMMERCIAL | Urban |
| 18 | IND/COM | |
| 17 | RES_MULTI | |
| 2 | INST_INTENSIVE | |
| 8 | LTD_ACCESS | |
| 2 | RESERVOIRS | Water |

*Table 30. Reclassification of LandPro2009 land use data for Site MC.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 9 | GOLF_COURSES | Open Green Space |
| 3 | PARK_LANDS | Trees/Shrubs |
| 17 | FOREST | |
| 1 | RES_LOW | |
| 310 | RES_MED | |
| 12 | PARKS | |
| 102 | COMMERCIAL | Urban |
| 6 | TCU | |
| 9 | TRANSITIONAL | |
| 41 | RES_MULTI | |
| 28 | INST_INTENSIVE | |
| 6 | RES_HIGH | |
| 26 | LTD_ACCESS | |
| 2 | RESERVOIRS | Water |

*Table 31. Reclassification of LandPro2009 land use data for Site Shoal.*

| Count | Land Use Category | Reclassification |
|---|---|---|
| 3 | CEMETERIES | Open Green Space |
| 4 | PARK_LANDS | Trees/Shrubs |
| 23 | FOREST | |
| 5 | RES_LOW | |
| 333 | RES_MED | |
| 7 | PARKS | |
| 55 | COMMERCIAL | Urban |
| 5 | TCU | |
| 24 | IND/COM | |
| 2 | URBAN_OTHER | |
| 2 | INST_EXTENSIVE | |
| 3 | TRANSITIONAL | |
| 53 | RES_MULTI | |
| 29 | INST_INTENSIVE | |
| 16 | RES_HIGH | |
| 6 | LTD_ACCESS | |
| 1 | RESERVOIRS | Water |
| 1 | WETLANDS | |