USING GIS TO IDENTIFY SUITABLE AREAS FOR SUSTAINABLE DRAINAGE SYSTEMS FOR FLOODPLAIN AND STREAM CHANNEL MITIGATION IN STILLWATER, OKLAHOMA

By

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USING GIS TO IDENTIFY SUITABLE AREAS FOR SUSTAINABLE DRAINAGE SYSTEMS FOR FLOODPLAIN AND STREAM CHANNEL MITIGATION IN STILLWATER, OKLAHOMA

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Major Field: ENVIRONMENTAL SCIENCE

Abstract: Urbanized areas require proper management and mitigation strategies to help minimize flood risk during precipitation events. Municipal Separate Storm Sewer Systems (MS4s) work as a conveyance system to collect runoff via inlets and pipes leading to a designated discharge point. The increase of urbanization, climate change, and land-use change contributes to increased stress and deterioration of stormwater infrastructure. Stillwater, Oklahoma needs reevaluation of their outdated infrastructure to help relieve anthropogenic and precipitation pressures on the system. The City of Stillwater contracted with Oklahoma State University to conduct a holistic storm sewer assessment and stream channel characterization within city limits. We collected qualitative data of stormwater structures and stream channels in the field using Geographical Information System (GIS) software on ArcGIS Collector and an EOS Positioning Systems ARROW 100. The assessment of the storm sewers and stream channels using GIS helped identify flood-prone areas and stormwater infrastructure failures. Identifying these areas allows for prioritizing where Sustainable Drainage Systems (SuDS) can be implemented. Simulations using PCSWMM were conducted to display the environmental effects and benefits of SuDS implementation. Results included locating current stormwater infrastructure problem areas, identifying suitable areas for SuDS, and creating flood relief to the floodplains and stream channels in Stillwater, Oklahoma.

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CHAPTER I

INTRODUCTION

The City of Stillwater is located in Payne County of north-central Oklahoma (Figure 1). Stillwater and several areas across the state experienced extensive flooding in May 2019. The catastrophic event left roadways under water for several days and resulted in water damage to numerous homes, businesses, and other infrastructure within city limits (Appendix A, Figure A-1). The Stillwater Creek Watershed received an estimated 13 inches of rainfall more than the seasonal average (Appendix A, Figure A-2) (Oklahoma Climatological Survey, 2021). The precipitation caused many upstream impoundments to utilize emergency spillways. The outdated stormwater system for Stillwater and streams were not suitable for the excess amounts of flow through the city. The stormwater infrastructure did not protect the urban areas and streams from damaging flood waters.

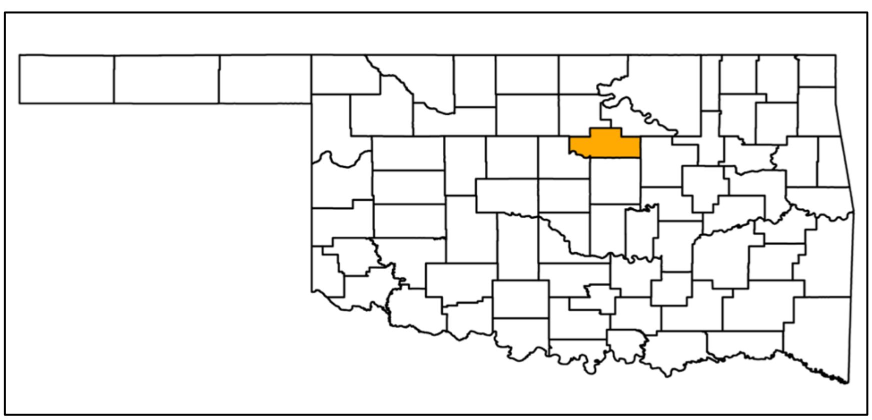

Figure 1. The state of Oklahoma with Payne County highlighted to show the location of the study area (Stillwater, Oklahoma) (U.S. Census Bureau, 2020; NRCS, 2021).

The City of Stillwater stormwater manager, Zachary Henson, and Meshek and Associates contracted with the Environmental Science Graduate Program at Oklahoma State University (OSU) to conduct an assessment on the condition of stormwater infrastructure and the characterization of the streams within city limits. Qualitative data of stormwater structures and stream channels in the field was collected using ArcGIS Collector and an EOS Positioning Systems ARROW 100. The assessment of the storm sewers and stream channels using GIS helped identify flood-prone areas and stormwater infrastructure failures. Identifying these areas allows for prioritizing where Sustainable Drainage Systems (SuDS) can be implemented. These are also referred to as Green Infrastructures. They include best management practices (BMPs) such as bioretention basins, bioswales, green roofs, permeable pavement systems and rain gardens.

Simulations using Personal Computer Storm Water Management Model (PCSWMM) were conducted to display the environmental effects and benefits of SuDS implementation. Results included locating current stormwater infrastructure problem areas, identifying suitable areas for SuDS, and creating flood relief to the floodplains and stream channels in Stillwater.

An updated inventory of stormwater sewer infrastructure and stream channel characterization assessment for the City of Stillwater is a critical step towards answering events like the May 2019 flood and the recent intensification of the hydrologic cycle (Kang and Marston, 2006; NOAA, 2020). Further preparation and adaptation for the changing climate and land use in Stillwater can be done sustainably with the help of SuDS. This study intends to show how tools in ArcGIS can be utilized by stormwater managers to identify flood hazard areas via spatial analytics technology and simulation models. Urbanized areas retrofitted with SuDS could demonstrate the alleviation of flood events, efficient use of land, protection of stream channels and water quality, better management of runoff, and decreased impervious surfaces. The PCSWMM modeling of pre- and post-SuDS integration within GIS-defined stormwater sewer infrastructure zones provides the City of Stillwater with evidence of economic, social, and environmental benefits of implementing such green infrastructure practices.

CHAPTER II

REVIEW OF LITERATURE

Background

Alterations to the natural hydrological processes and intensification of flood frequency in watersheds are caused by the major phenomenon of rapid urbanization, climate change, and land use change (Jato-Espino et al., 2016; Venkararamanan et al., 2019; Dash and Sar, 2020; Anni et al., 2020). The continuing growth of cities increases the runoff volume and decreases the peak time. A rapid discharge of precipitation through man-made and natural channels occurs, disregarding soil moisture needs and the recharging of groundwater. The capacity of these open and closed systems is exceeded, and flooding occurs (Jato-Espino et al., 2016). The reoccurrence and devastation of flooding serves as a threat to human lives and socio-economic conditions (Dash and Sar, 2020). Pollution, contributing to high suspended solids and bacteria levels, from urban flooding is also a great concern for stormwater managers due the deteriorating condition of stream channels within the catchment (Gajewar, 2005). The increasing flood risks affecting communities on a global scale is not avoidable. Implementation of proper management and mitigation strategies that account for physio-climatic, hydrodynamic, economic, social, and ecological impacts provides relief from flood risks (Dash and Sar, 2020).

Runoff in urbanized catchments is carried by stormwater sewer systems also known as Municipal Separate Storm Sewer Systems (MS4s). MS4s are designed and added as cities develop. This system of conveyances is responsible for collecting runoff (i.e., stormwater runoff, snow melt runoff, surface runoff, and drainage) through pipes, storm drains, and ditches until the runoff reaches a designated discharge point. Discharge points release water untreated into local water bodies like streams, lakes, rivers, and wetlands (Gajewar, 2005). Urban flooding in recent years has been contributed to by aging sewer systems, poor drainage, and the increasing amount of impervious surfaces (Venkararamanan et al., 2019).

Natural conditions were capable of absorbing up to 50 percent of runoff through groundwater recharge prior to urbanization. Another 40 percent of runoff was removed by evapotranspiration. The remaining 10 percent of runoff travelled across saturated pervious surface to streams. Urbanized areas today cover nearly all of the natural ground with impervious surfaces, like buildings, roofs, roads, and parking lots (Gajewar, 2005; Anni et al., 2020). The decrease in natural landscape increases the runoff rate to nearly 55 percent, because the infiltration rate is reduced (Gajewar, 2005).

One way city planners and stormwater managers in growing urban areas have found to help relieve some catastrophic flooding is reevaluating stormwater sewer systems that are contributing to the flooding of streets, homes and businesses (Venkararamanan et al., 2019). Many cities face the major challenge of locating where stormwater infrastructures and land cover are failing to mitigate flooding due to the lack of information available to run urban flood simulations (Anni et al., 2020). The utilization of Geographic Information Systems (GIS) and stormwater assessment data can provide a framework to locate hot spots for stormwater infrastructure failures (Jato-Espino et al., 2016).

GIS is a computer system that uses, interrupts, manages, calculates, and identifies data that has been geographically referenced. GIS technology makes it possible to create quality maps that displays thematic layers of data. These include stormwater infrastructure, soil types, elevation, flood frequency data, land usage, and stream channels, in order to calculate problem areas (Gajewar, 2005). Stormwater managers can also use GIS to locate where SuDS could be implemented to be a cost-effective and environmentally friendly way to mitigate flooding by identifying flood-prone areas with GIS (Jato-Espino et al., 2016; Venkararamanan et al., 2019; Anni et al., 2020; Thorsby et al., 2020).

PCSWMM is another technological advance that has proven to help engineers and planners. PCSWMM was created by Computational Hydraulics Int. (CHI). It originated from the EPA's Storm Water Management Model (SWMM). The simulation model runs single event or long-term simulations of water runoff quantity and quality in urban areas. PCSWMM allows the planning, analysis, and design associated with stormwater sewer infrastructure. SuDS can be included in the simulation.

The program works as an artificial study area for inputting data. It runs hydrologic, hydraulic, and water quality simulations. The results can be viewed quickly. The system includes color-coded drainage areas, conveyance system maps, time series graphs and tables, profile plots, and statistical frequency analyses. PCSWMM accounts for runoff reduction from SuDS implementation, time-varying precipitation and evaporation of standing surface water, rainfall infiltration into soil layer, and groundwater capabilities. Add-ins like the Climate Adjustment Tool (CAT) can be used to project future climate changes effects on stormwater infrastructure (EPA, 2016a).

The addition of SuDS in stormwater simulations like PCSWMM allows planners and engineers to determine their effectiveness before implementation. The model's capabilities provide instant information on reductions in runoff flow volume. The SuDS, or Low Impact Developments (LIDs), available in PCSWMM simulations are rain gardens, bioretention cells, vegetative swales, infiltration trenches, green roofs, rooftop disconnections, rain barrels, and permeable pavement systems (Appendix B, Figure B-1).

SuDS provide significant pollutant reduction benefits after implementation (EPA, 2016a). Geometric and hydrologic criteria must be fulfilled prior to the implementation (Table 1). Reports and manuals were used to create criteria for SuDS. These include the recommended maximum drainage area, desired Hydrologic Soil Group (HSG), maximum or minimum distance to buildings, roads, and streams, slope percentage of the land, and minimum depth to groundwater (Appendix B, Table B-1) (Jato-Espino et al., 2016).

Table 1. Criteria required for SuDS implementation in Urban catchments (Jato-Espino et al., 2016).

SuDS	Area (ha)	Hydrologic Soil Group	Building Buffer (m)	Road Buffer (m)	Stream Buffer (m)	Slope (%)	Water Table Depth (m)
Bio-retention cell	<0.4	A–D	-	<30	>30	<5	>0.6
Green roof	-	-	-	-	-	-	-
Infiltration trench	<2.0	A–B	-	-	>30	<15	>1.2
Permeable pavement	<1.2	A–B	-	-	-	<5	>0.6
Rain barrel	-	-	<9 [1]	-	-	-	-
Rain garden	<0.4	A–D	-	-	>30	<5	>0.6
Rooftop disconnection	<0.1 [2]	-	<1.5 [3]	-	-	-	-
Vegetative swale	<2.0	A–D	-	-	-	<4	>0.6

Watershed Characterization

Cities like Stillwater, Oklahoma, are experiencing a rapid transition of urbanization. Stillwater is located in Payne County, Oklahoma. The city covers 29.5 square miles. The watershed (Figure 2) surrounding the city also faces the increasing pressures of anthropogenic changes to the landscape and streams (Kang and Marston, 2006). The population of Stillwater has increased from 39,065 (2000) to 45,688 (2010). It increased to an estimated 49,939 in 2020 (Gajewar, 2005; U.S. Census Bureau, 2020).

The exurban watershed has a drainage area of 283 square miles. The land use is comprised primarily of agricultural land, pasture, woodland, and crops. Approximately 4.49 percent is impervious (Kang and Marston, 2006). The urban growth displayed in this catchment has resulted in research on the impervious areas and stormwater infrastructures over the past two decades (Gajewar, 2005; Kang and Marston, 2006).

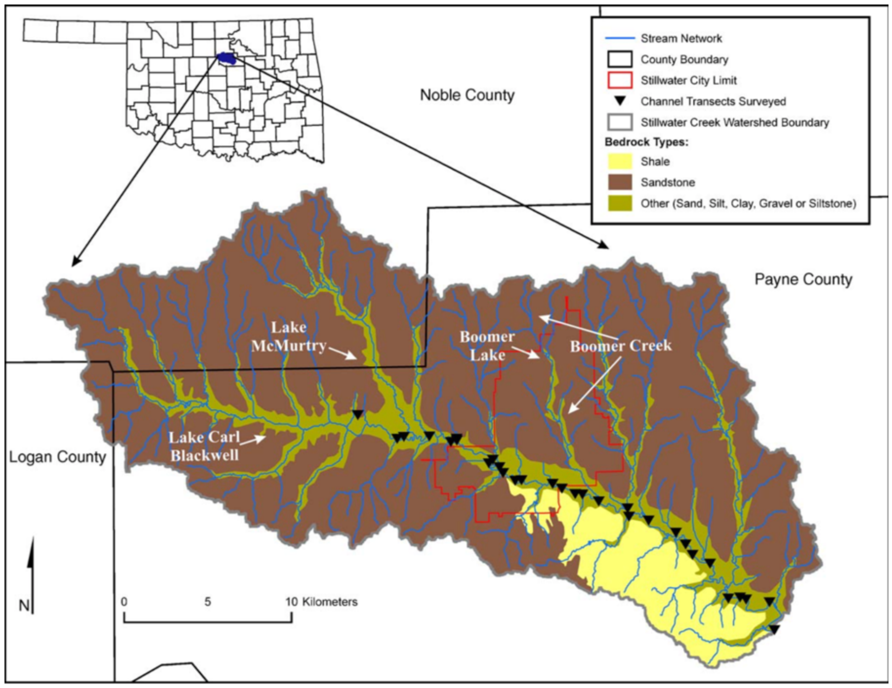

Figure 2. A map of the Stillwater Creek Watershed that surrounds Stillwater, Payne County, Oklahoma (Kang and Marston, 2006).

The Federal Emergency Management Agency (FEMA) provides Stillwater with flood hazard zones along the main streams and reservoirs traveling through city limits (Figure 3). This data provides support for the National Flood Insurance Program, helps the community know flood risk in their city, and the type of flooding throughout the area. Zone A is characterized by being within the area of 1% chance of flooding. This zone is also characterized by a 26% chance of flooding over the life of a 30-year mortgage. This means over the three decades it takes to pay the loan back there is a 74% chance of no flooding. Detailed analyses are not completed for Zone A. This means base flood elevations are not shown for this area. Zone AE is within the base floodplain. The base flood elevations are provided based on zones ranging from A1 to A30 (FEMA, 2020). Recent intensification of the hydrologic cycle and the May 2019 flood have increased the need for an updated inventory of stormwater infrastructure and stream channel characterization for the City of Stillwater (Kang and Marston, 2006; NOAA, 2020).

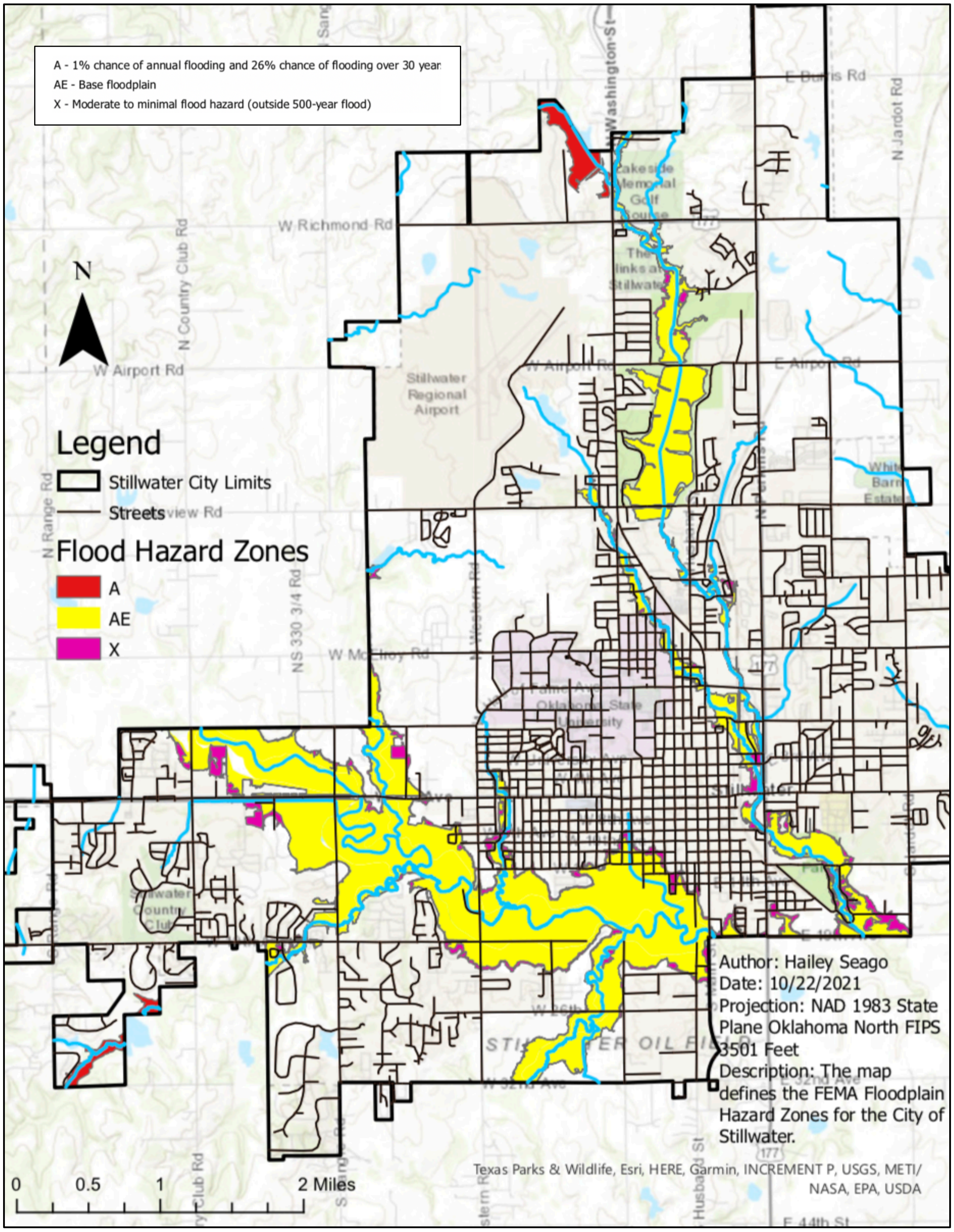

Figure 3. The FEMA floodplain and flood hazard zones for the City of Stillwater (FEMA, 2020; NRCS, 2021; USGS, 2021).

Climate

The climate in Oklahoma ranges from humid subtropical in the east to semi-arid in the west. Stillwater is located in the Central climate division of Oklahoma. This northern portion of the state experiences humidity, cloudiness, and precipitation more than the eastern and southern sections of Oklahoma. Summer is typically long and hot. Winter is shorter and less severe than northern Plains states. The average normal temperature in Oklahoma decreases from the south to the north. It also decreases from east to west (Figure 4). Temperatures above 90 degrees Fahrenheit (F) or greater happen for 65 days per year on average in Payne County. Days above 100 degrees F or greater occur approximately 15 times throughout the year. Humidity adds to the heat index value and increases the number of days that experience extreme summer temperatures. The average amount of days below 32 degrees F is eight in Payne County (Oklahoma Climatological Survey, 2021).

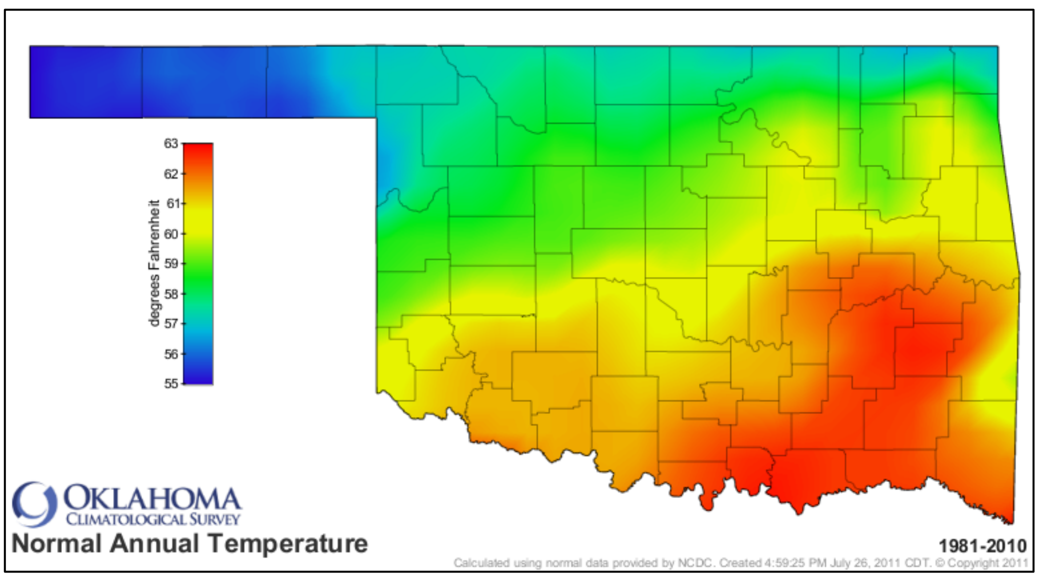

Figure 4. The average annual temperature throughout the state of Oklahoma from climate data ranging from 1981 to 2010 (Oklahoma Climatological Survey, 2021).

Precipitation and Flooding

Precipitation increases from the northwest to the southeast in Oklahoma (Figure 5). Payne County experiences an average rainfall of 38.35 inches each year. Winter weather in the area averages 7.3 inches of snowfall each year and five days of snow on the ground. The mean number of days with precipitation each year is 71. The wettest year on record for Payne County was 1959 with 61.9 inches of rainfall. August 1942 recorded 7.5 inches of rain in a 24-hour period. The average annual rainfall in a 24-hour period is less than one inch for the area (Oklahoma Climatological Survey, 2021).

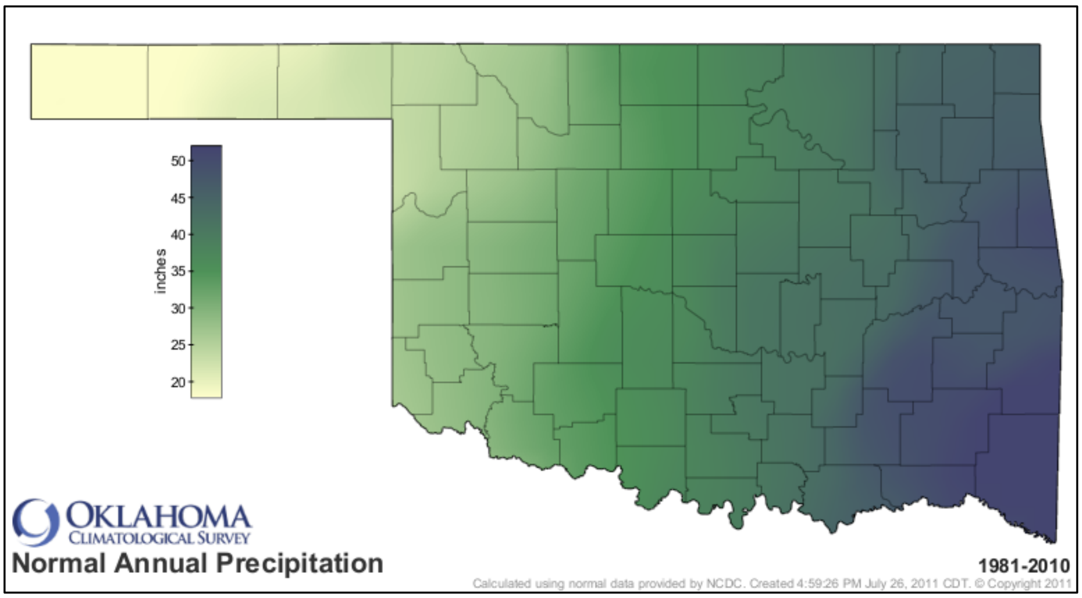

Figure 5. The average annual precipitation in Oklahoma over the timeline of 1981 to 2010 (Oklahoma Climatological Survey, 2021).

A majority of precipitation occurs during the spring and autumn months. The greater amount of rainfall during these periods is associated with the greatest frequency of flooding within major rivers and tributaries. Flood prevention programs, like the implementation of impoundments, has helped reduce flood frequency and severity since the 1950s. Flash flooding in urban and suburban areas has still remained a serious threat due to the increased development and removal of vegetation increasing the runoff in creeks and minor streams.

Stillwater experienced 17.30 inches of precipitation in May 2019 with 4.59 inches of rainfall recorded in a 24-hour period. The amount of rainfall in Payne County was 326 percent more than normal precipitation for the month of May. The amount of precipitation was the second wettest on record for Payne County and the third wettest average for the state (Oklahoma Climatological Survey, 2021).

Hydrology and Water Quality

The Boomer Lake-Stillwater Creek (HUC 110500030106) Watershed, containing Stillwater, Oklahoma, has three creeks and one lake listed impaired by the Oklahoma Department of Environmental Quality (OKDEQ). These waterbodies include Boomer Creek (Waterbody ID: OK620900040140_00), Sanborn-Hazen Lake Creek (Waterbody ID: OK620900040150_00), Stillwater Creek (Waterbody ID: OK620900040070_10), and Boomer Lake (Waterbody ID: OK620900040190_00). The main cause of impairment is degraded aquatic life. The waterbodies are also impaired for low oxygen, turbidity, chlorophyl-a, and mercury (OKDEQ, 2020; EPA, 2021).

Watersheds found upstream of these waterbodies hold impoundments, Lake Carl Blackwell (Waterbody ID: OK620900040280_00) in the Lake Carl Blackwell-Stillwater Creek Watershed (HUC 110500030102) and Lake McMurtry (OK620900040240_00) in the Lake McMurtry Watershed (HUC 110500030103). They are both impaired for chlorophyll-a, turbidity, and mercury. Cow Creek (Waterbody ID: OK620900040200_00) is impaired for degradation of aquatic life. It is in the Harrington Creek-Stillwater Creek Watershed (HUC 110500030104) and flows into Stillwater Creek upstream from the City of Stillwater.

Stillwater Creek receives flow from Boomer Creek and other natural and stormwater sewer tributaries within city limits. These waters travel southeast until meeting the Cimarron River (Waterbody ID: OK620900030010_00) north of Ripley, Oklahoma and flow into Keystone Lake (Waterbody ID: OK621200010020_00). Both bodies of water are impaired for turbidity and degraded aquatic life. The Cimarron River is additionally impaired for e. coli, which causes negative issues for aquatic life, recreation, and drinking water sources (OKDEQ, 2020; EPA, 2021).

Ecoregion

Oklahoma is comprised of 12 Level III Ecoregions and 46 Level IV Ecoregions. These ecoregions are divided based on the physiography, geology, climate, soils, land use, wildlife, fish, hydrology, and vegetation analyzed across the landscape (EPA, 2021). Ecoregions define areas relatively large units of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions. The recognition of spatial differences within these capacities and potentials of ecosystems gives researchers in state, federal, and nongovernmental agencies a critical structural component on how these areas respond to disturbance. Ecoregions are also important for how agencies will implement ecosystem management strategies (EPA, 2021).

Stillwater is located in the EPA Level III Ecoregions known as the Central Great Plains and the Cross Timbers (Figure 6). The Central Great Plains foundation consists mostly of red, Permian-age shale, siltstone, and sandstone. The land found in this region is widely used for farming with an extensive occurrence of gas and oil fields. Mixed grass prairie, mesquite-buffalograss and shinnery are the native vegetation present.

The Cross Timbers Ecoregion is a mixture of woodlands, pastureland, and rangeland. This area of low, rolling hills serves as transition zone between the moist, forested eastern

Oklahoma to the dry prairies found in western areas. Manmade impoundments are common throughout the Cross Timbers. Stream erosion is more noticeable in these ecoregions due to the release of flood-control reservoirs upstream (EPA, 2021).

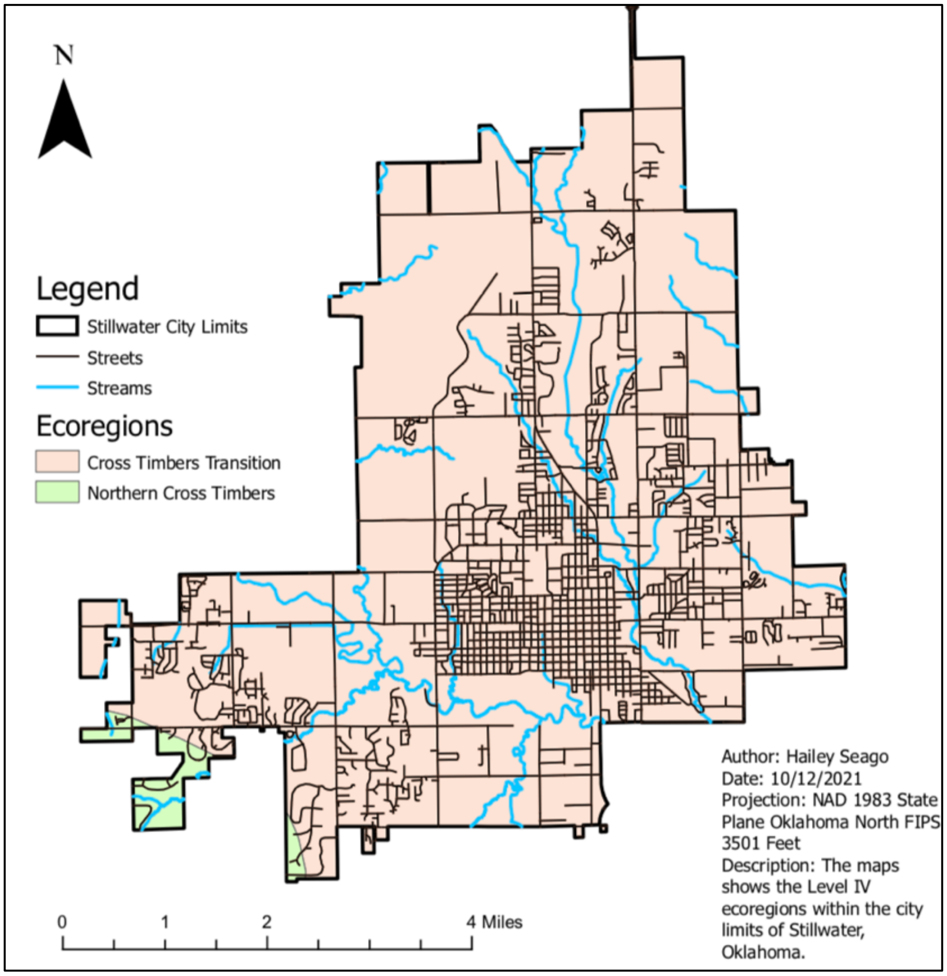

Figure 6. A map showing the EPA Level IV Ecoregions located within city limit boundaries of Stillwater, Oklahoma (EPA, 2021; NRCS, 2021; USGS, 2021).

The Level III Ecoregions are subdivided into a Level IV designation created by the EPA. The city limits of Stillwater are found in a majority of Cross Timbers Transition, which is a subdivision of the Central Great Plains. Cross Timbers Transition holds prairie grasses, eastern redcedar, oaks, and elms from rough plains in the west to tree-populated hills in the east. Fire suppression in this ecoregion has increased the number of trees. The degradation and loss of riparian forests and wetlands has increased since the early 19th century. This transition is a result of channelization and land use changes. Streams in this area typically contain rocky and muddy substrates. Less turbid waters are found here rather than streams throughout other parts of the Central Great Plains Ecoregion. Cottonwoods, willows, elm, ash, walnut, and pecan trees are common throughout riparian areas. The Cross Timber Transition Ecoregion is largely used as rangeland and cropland. Common crops are small grains, sorghum, alfalfa, and soybeans (EPA, 2021).

The small section of the southwest corner of Stillwater is composed of the Northern Cross Timbers, a branch of the Cross Timbers. This subdivision consists of porous, course-textured soils derived from sandstone across a hill- and ridge-filled landscape. The nature of the soil makes it highly erodible when disturbed. Oil and gas pads are widespread in this region. Streams have shown increased salinity due to the associated brine, drilling mud, and waste products of petroleum operations. Stream channels in this ecoregion are shallow and contain sandy substrates that form poor habitats and lack in species richness. Areas with deep pools, riffles, and other substrates show increased species richness and more pollution-and habitat-tolerant species compared to the shallower channels. Post and Blackjack Oak are common native trees found among understory grasses. Livestock farming is the main land use in this ecoregion with limited cropland due to the increased expansion of woodlands (EPA, 2021).

CHAPTER III

METHODOLOGY

Data Collection

Field data was collected using an iPad with the mobile data collection application known as ArcGIS Collector (Collector). An EOS Positioning Systems ARROW 100 (EOS) was used for collecting precise coordinate information. A geodatabase was setup before data collection with existing GIS features. Meshek and Associates created this geodatabase for stormwater sewer infrastructure inventory and stream channel characterization assessment.

Stormwater sewer infrastructure inventory layers consisted of point features for inlets, manholes, and discharge outlets. Pipes, open drains, and culverts were identified using line features. An offline map was downloaded for each field collection. Edits and additions to the map were synced to the server at Meshek and Associates at the end of each field collection event. The stormwater sewer infrastructure inventory included over 2000 sites for capturing data. This included pipe diameters, depth from the surface to the bottom of the pipe, and any obstructions or problems with the integrity of the feature. Pictures were taken to document the location and show the condition of the infrastructure. Each photo was associated with the corresponding stormwater structure being edited in Collector. The EOS also updated the location of the unit on Collector.

Stream channel characterization data was captured by walking approximately 29 miles of streams in Stillwater. Qualitative data collected during these field collection events consisted of line or point features. Erosion and bank scouring, concrete channels, rip-rap usage, sediment deposition, and channel conveyances were among the most used line features. Point features such as exposed tree roots, fallen trees, exposed sanitary sewer manholes, and discharge outlets were commonly identified and assessed during field collections. Photos were taken during each field collection to document the condition of the stream channel and verify the edits being added. Each data point or line was associated with a coordinate position using EOS. The data after each field event was uploaded to a main database server.

GIS Application

Data acquired from the May 2019 flood was prepared using conversion and intersect tools on ArcGIS Pro. The flooded streets layer was converted from a KML/KMZ file to a raster layer. Further processing was simplified by converting the raster to a polyline shapefile (Figure 7).

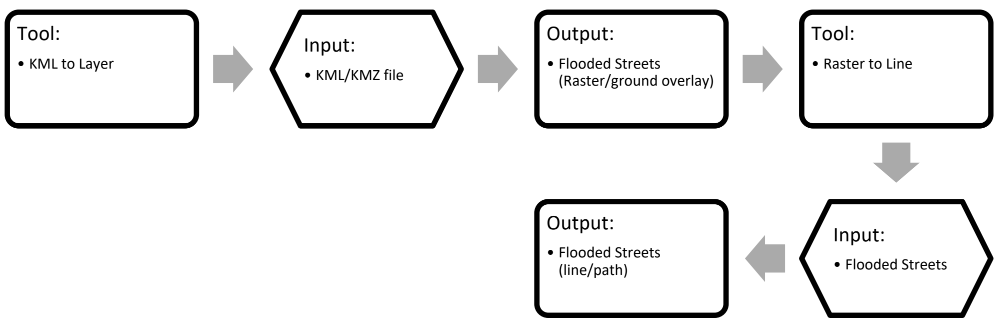

Figure 7. Converting a Google Earth file (KMZ/KML) to raster, then raster to a line.

Intersect tool was used many times for this project to identify where streets, FEMA hazard areas, and FEMA streams were located within the city limits of Stillwater. The intersection of the FEMA hazard area layer with the flooded street layer was also completed (Figure 8). Each layer's coordinate system was verified as the same by going to the layer properties and then source tab. The adjustment of symbology, also located in the layer properties, helped identify what fields to be displayed on the maps and legend. Other operations such as adding fields and calculating geometry were completed to check the sum of mileage of streams and areas affected within the City of Stillwater. Various maps were created by adding or unadding layers from the viewer to display several aspects that coincide with flooding and stormwater infrastructure. The legend was adjusted by adding and removing the components needed for each map.

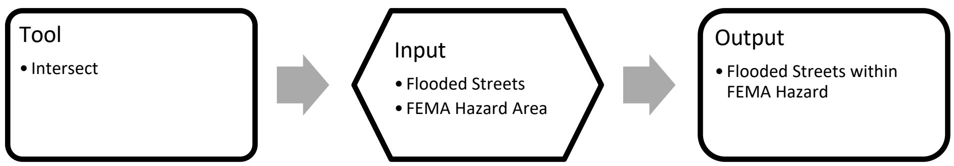

Figure 8. Intersecting multiple layers to create a layer where all features overlap.

The preparation of layers to complete the spatial analyses began with finding stream channels flowing through the city limits of Stillwater. The elevation DEM was used to help depict the natural drainage and runoff flow for the city (Figure 9). The stream flood zone type was displayed in the legend to help differentiate the types of flooding expected in the channels (Figure 10). Floodways are the part of a channel that is reserved for containing runoff during base flood events without surpassing a designated water surface elevation. The hazard zones designated by FEMA for floodplains are the same for stream designations (FEMA, 2020).

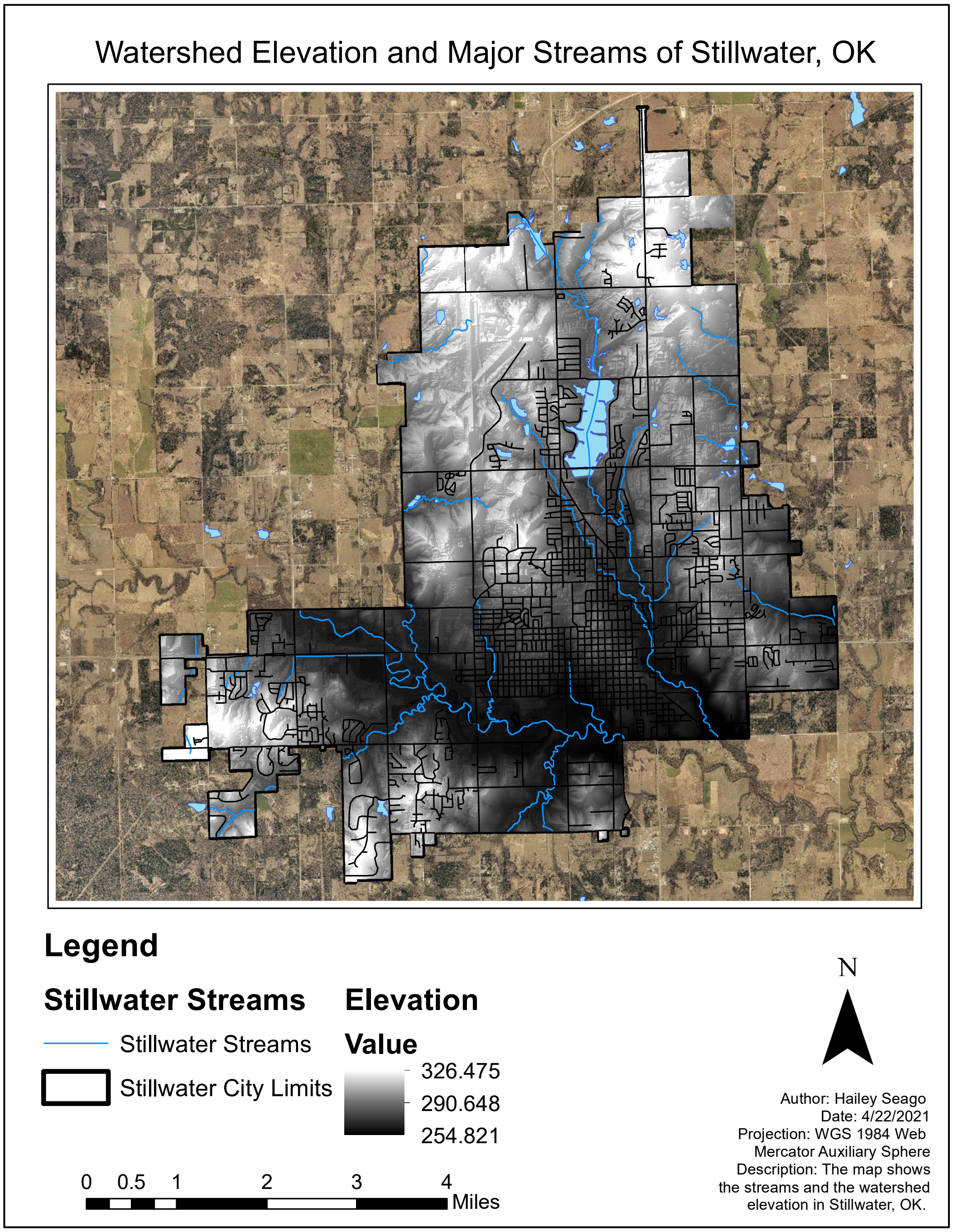

Figure 9. A watershed elevation map of Stillwater, Oklahoma. The map shows various streams flowing through the city limits (NRCS, 2021; USGS, 2021).

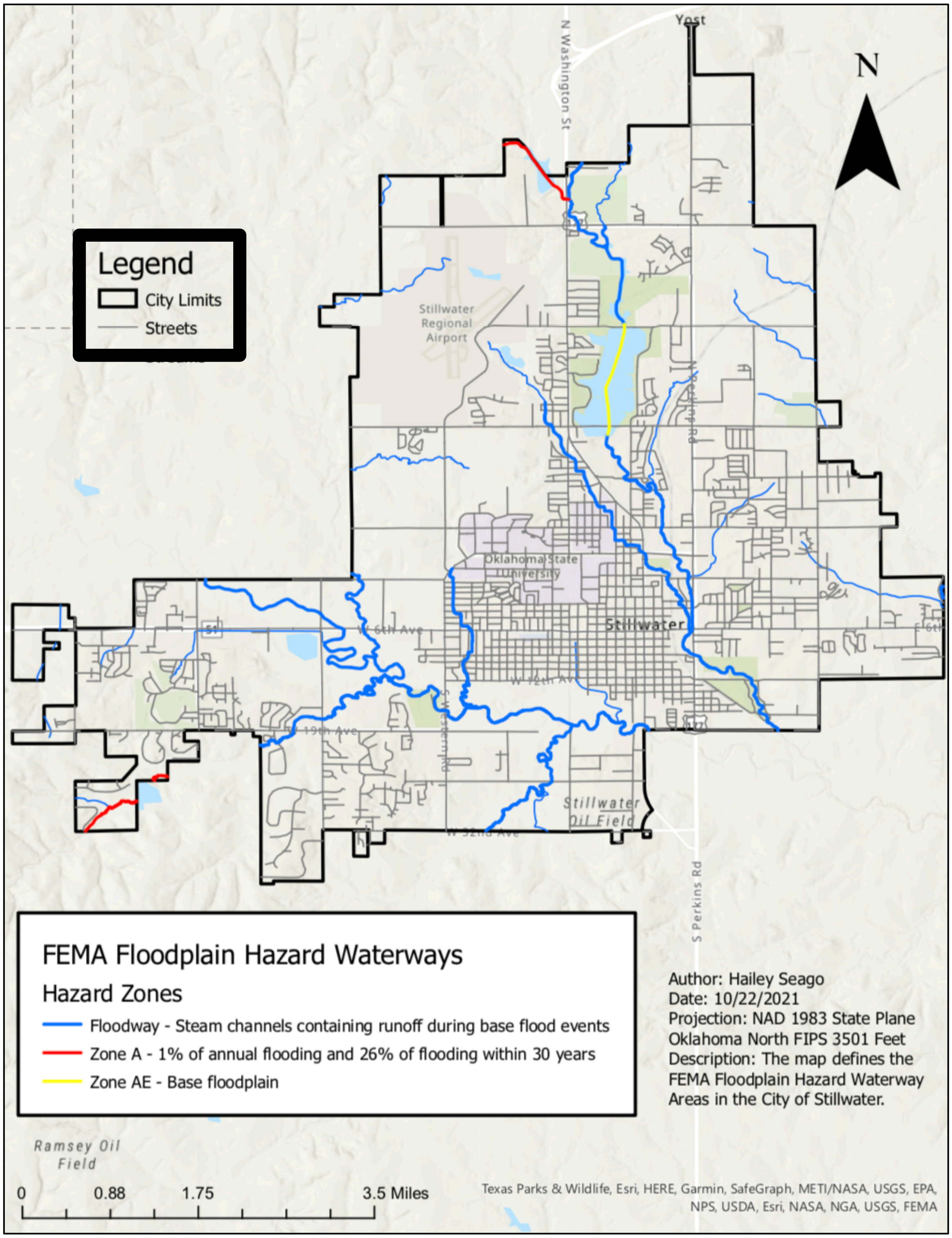

Figure 10. The map displays the designated FEMA Floodplain Hazard Waterways within the city limits of Stillwater, Oklahoma (NRCS, 2021; FEMA, 2020).

GIS layers were acquired from the USDA Geospatial Data Gateway (GDG) for the characterization of Stillwater's watershed. These included digital elevation models and soil texture classes (Appendix C, Figure C-1). Hydrological Soil groups were defined within City of Stillwater land parcels (Appendix C, C-2). They were used to fit SuDS criteria mentioned in Table 1. The DEM was converted to a slope raster. Areas with a slope less than 5 percent were found using the symbology tool and editing the classes for slope.

Additional information was acquired to fit the suitable area criteria for SuDS. The water table depth (WTD) was determined by analyzing groundwater level observations for the state of Oklahoma. The water table is the subsurface zone between unsaturated ground and saturated ground. The unsaturated zone is defined by the air and water found between particles of gravel, sand, silt, clay, and rocks. The saturated zone has voids completely filled with water. This water is referred to as groundwater. The WTD is the distance from the land surface to the zone of saturation (Winter et al., 1998). Stillwater is located in the Permian hydrogeologic basin. A report published by the OWRB shows the minimum WTD in the region is 15.24 meters (Osborn and Hardy, 1999). This clears the suitable area criteria requirement for a minimum of 0.6 meters below the surface.

The City of Stillwater land parcel layer was added to the criteria to help offer an economical option to the city (Appendix C, Figure C-3). An inlet layer from data collected from the field was created. The inlet layer and the City of Stillwater land parcel layer were processed using the Intersect tool. Inlets located on public land were prioritized for maximum cost-effectiveness and social outreach. SuDS measures can be integrated into parks or playing fields without compromising function. Implementing SuDS near recreational areas serves as an educational tool for the community (EPA, 2016b). The land use and land cover layer was added to delineate the developed and non-developed lands within city parcel lands (Appendix C, Figure C-4). Suitable areas were located by applying the Select Layer by Attribute tool to soils for HSG Soil A or B

(Appendix C, Figure C-5). All criteria were combined using the Intersect tool. This helped create a single map on ArcGIS that precisely located areas for SuDS implementation.

PCSWMM Preparation

Areas found suitable for SuDS implementation were cross-referenced with the flood-prone areas from the initial GIS analysis. These areas were prioritized for PCSWMM simulation. Babcock Park, located in southwest Stillwater, was selected as the study area for the PCSWMM simulation (Figure 11). The study area subcatchment for the current stormwater sewer infrastructure covers three acres with 50 percent impervious pavements. The drainage area allows for multiple SuDS to be implemented if needed.

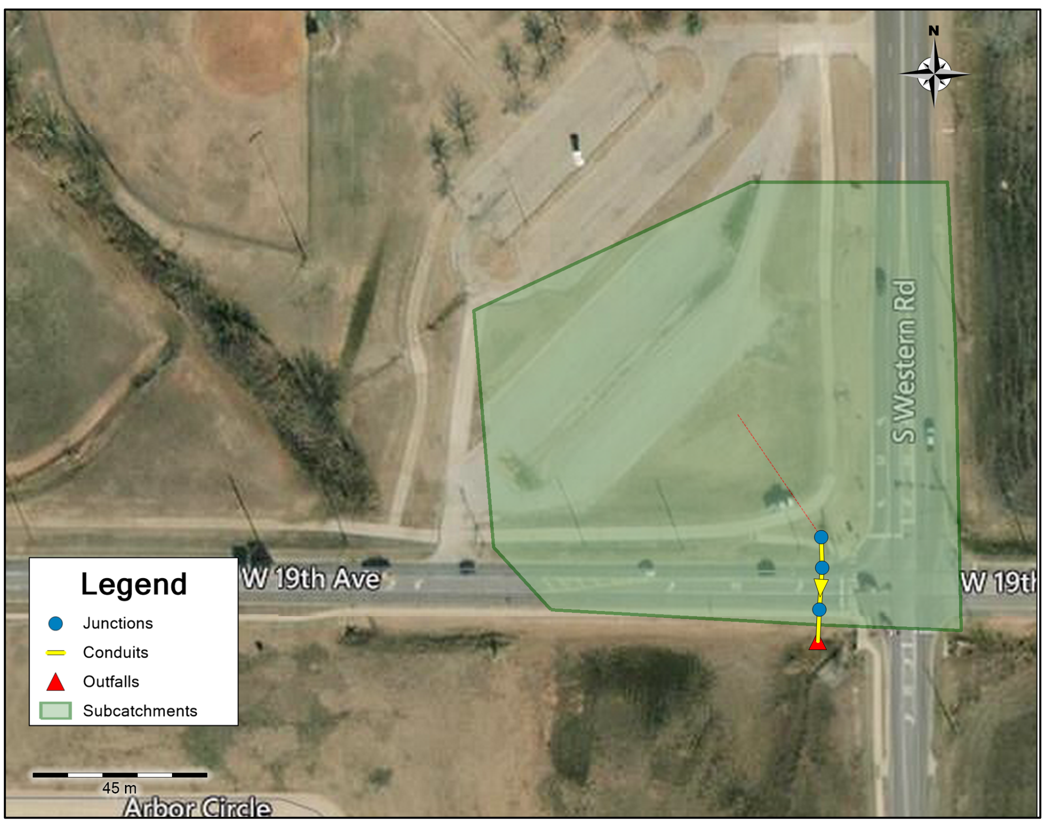

Figure 11. A map of the PCSWMM simulation study area at Babcock Park in Stillwater, Oklahoma. The subcatchment, junctions, conduits, and outfall are shown in the photo (CHI, 2021).

The discharge point, or outfall, was placed in the simulation first. Manholes and inlets, known as junctions in the software, were added next in the correct arrangement and coordinates. Pipes, known as conduits in PCSWMM, were added by clicking at the upstream junction first then the next junction downstream until connected to the discharge point. The subcatchment area was created as a polygon layer around the junctions and conduit, excluding the discharge point. Data collected from the field, including pipe diameter and depth measurement, were used for the model. A cross-section profile of the stormwater sewer infrastructure was used to edit the junction elevations (Figure 12).

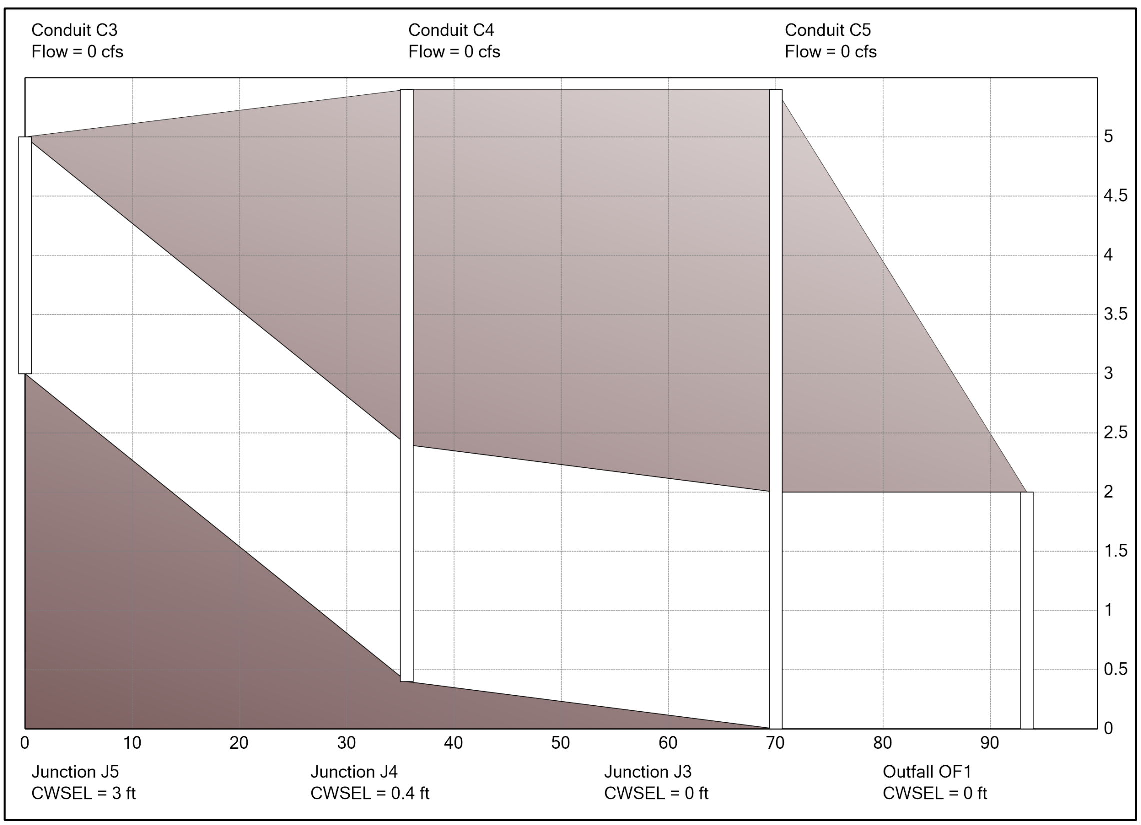

Figure 12. The profile, or cross section view of the junctions, conduits, and outfall for the PCSWMM simulation at Babcock Park in Stillwater, Oklahoma (CHI, 2021).

Climate information was added to demonstrate accurate weather conditions experienced in Stillwater. The Natural Resources Conservation Service (NRCS), formally known as Soil

Conservation Service (SCS), created hypothetical storms based on rainfall distribution across the United States. These storms were created using averages of rainfall patterns. Stillwater is located within the SCS Type II storm. Several scenarios were completed to demonstrate how the pre-SuDS implementation would react to the stormwater runoff. SCS Type II storms were designed to have increments of 1-, 2-, 3-, 4-, and 5-inch rainfall events during a 24-hour duration. The rain interval of rainfall was set to 6 minutes. The storm duration time (measured in hours and minutes) and the rainfall volume (measured in inches) were collected.

Data was inputted for the SuDS, known as LID in PCSWMM, to fit the environment found in Stillwater. Bioretention cell was selected to be used for the size of the study area. The bioretention cell was selected to receive runoff from the entire subcatchment area. Drainage areas with highly impervious areas are recommended to have one cell per two acres (ISWMM, 2009). The Babcock Park study area consists of concrete sidewalks, paved roadways, and a majority of grassed area. Surface, soil, storage, and underdrain controls were assigned data points from stormwater best management practices (BMP) (Table 2). The recommended controls were a maximum of four feet for soil thickness, a maximum of three feet for storage, and half an inch per hour for the drain coefficient (EPA, 2021). The LID was set to receive runoff from the assigned subcatchment. The same climate scenarios were completed to show post-SuDS implementation.

Table 2. Criteria for Bioretention Cell Implementation Area (ISWMM, 2009).

Properties of the Drainage Area Tributary to the Bioretention Cell	Determine the expected drainage area to be routed to the bioretention cell and the projected amount of impervious surfaces. It is recommended that the **impervious** area to each cell not exceed 2 acres. Multiple cells can be designed to treat runoff from larger areas. Surface properties required to determine time of concentration will be needed for final design (refer to Chapter 1, section 4).
Space Required	The required temporary ponding area will be approximately 3-7% of the tributary **impervious** area. Most of the ponding area must be level, so remember that additional space will be needed for slope grading to establish the overflow elevation and match surrounding grades.
Slope	Cells are easier to construct away from steep slopes, but special elements such as retaining walls can be included for sites with steep slopes. Care must be taken not to compact the soils within the bioretention area during installation of any structural features around the cell.
Minimum Head	Make sure that there is sufficient elevation difference to pond water as needed and drain the soil and aggregate layers through a subdrain and/or outlet works to a finished surface, swale, or storm sewer system.
Water Table	A separation distance of 2 feet is recommended between the bottom of the bioretention cell and expected high groundwater levels.
Existing Site Soils	No restrictions when modified soils are used. However, soils with higher infiltration rates can be used to promote infiltration and groundwater recharge, reducing post-development surface runoff volumes.

CHAPTER IV

FINDINGS

Flood-Prone Areas

The flooded streets layer was paired with the street and stream layers (Figure 13). This created a visual of where the stormwater infrastructure was being either utilized, failed, or overwhelmed with excess runoff. An additional map was created to show the problem areas located outside the designated flood hazard zone (Figure 14). Each problem area outside the FEMA hazard zone area was found near developed, residential areas containing impervious surfaces or near streams without a flood zone designation (Appendix D, Table D-1).

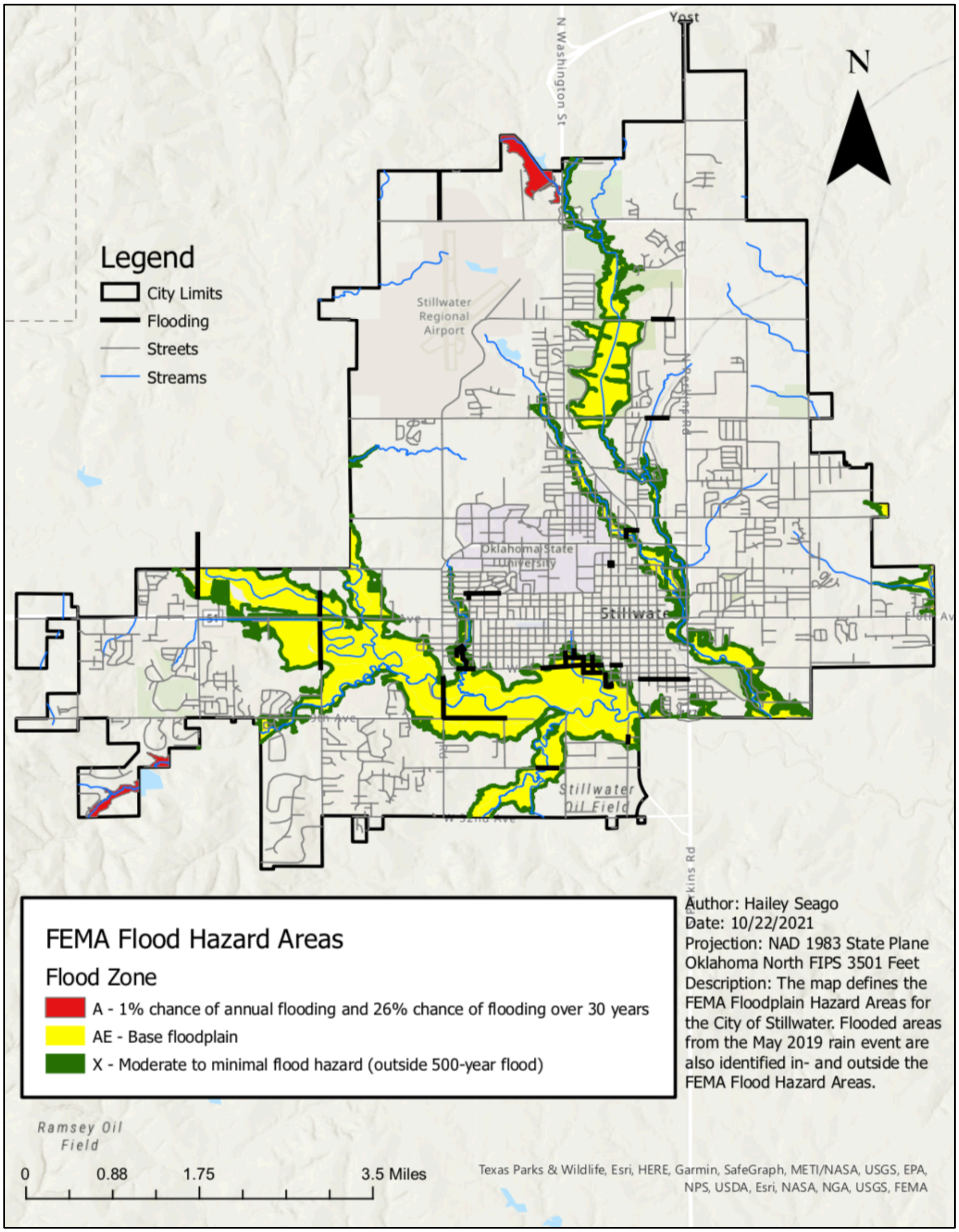

Figure 13. An aerial map of Stillwater, OK that displays the streams, FEMA hazard areas, and streets within city limits. Streets that were flooded during the May 2019 rain events are highlighted (FEMA, 2020; NRCS, 2021).

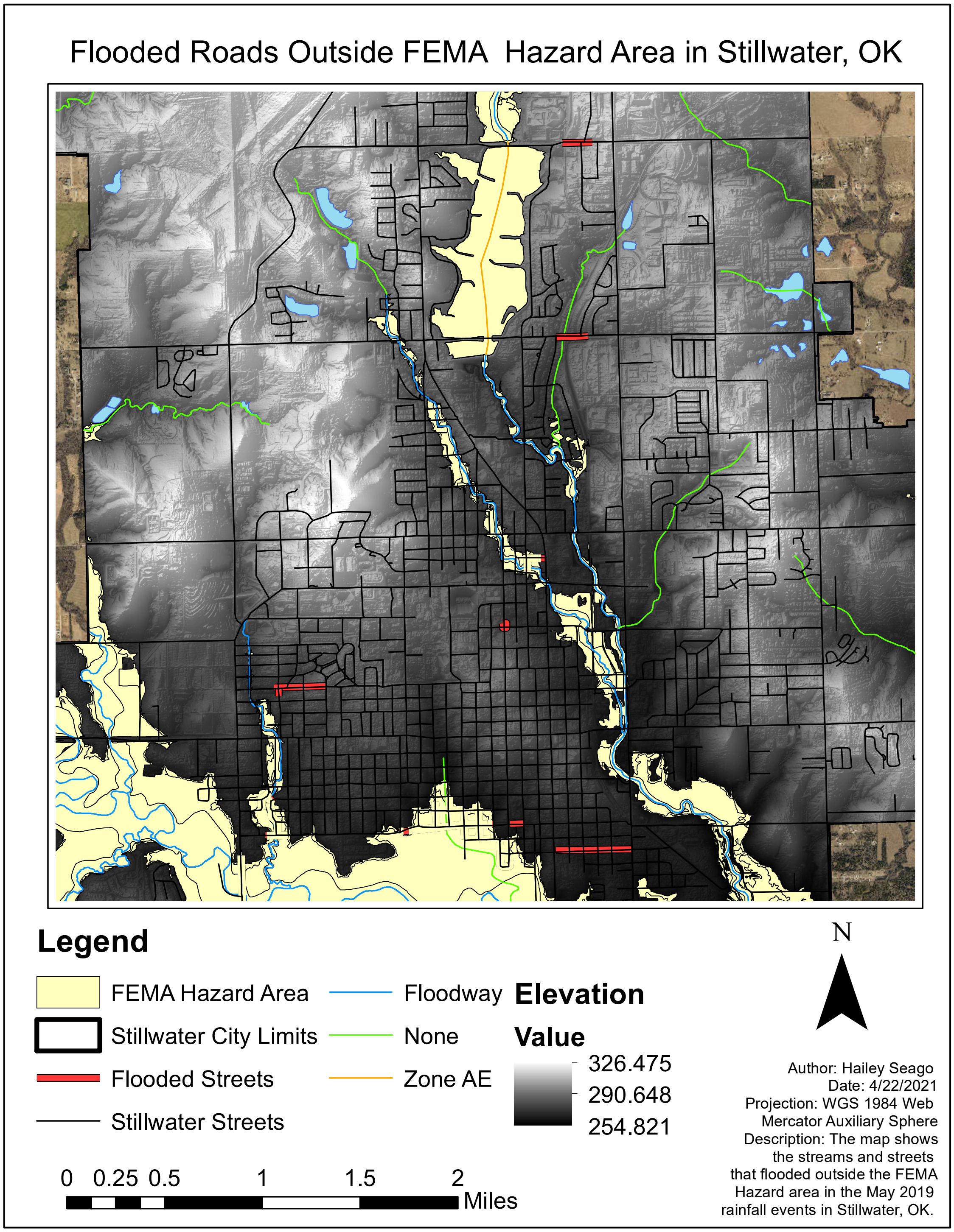

Figure 14. An elevation map of Stillwater, OK displaying flooded streets that were located outside the FEMA Hazard Area (FEMA, 2020; USGS, 2021; NRCS, 2021).

Suitable Areas for SuDS Implementation

The use of GIS helped identify suitable areas for SuDS implementation by intersecting data layers that fit the bioretention cell criteria (Figure 15). The inlet sites were used to help eliminate subcatchment areas that were not on city-owned land parcels. Suitable areas were prioritized for PCSWMM simulation. Prioritization was completed by referencing flood-prone areas with the suitable areas that met BMPs for bioretention cell implementation.

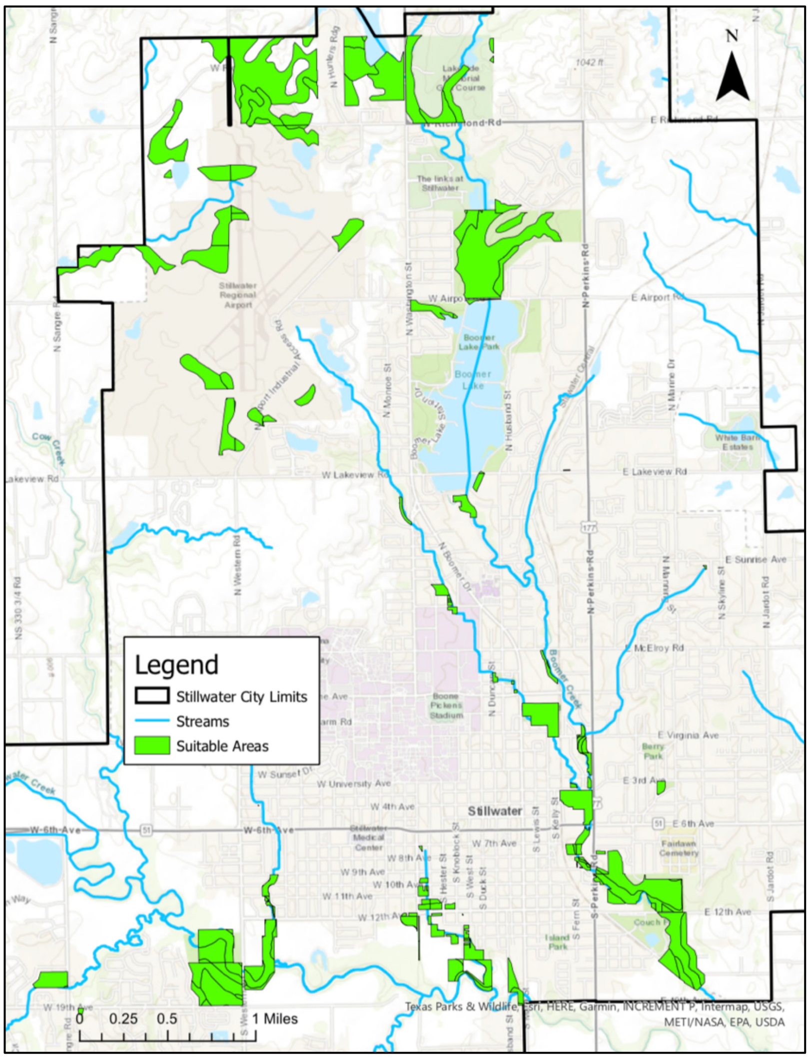

Figure 15. Sites for SuDS implementation that fit criteria. HSG, slope, public land parcel, water table depth, and buffer requirements were combined in ArcGIS to find suitable areas (NRCS, 2021).

PCSWMM Simulation

Each PCSWMM simulation on Babcock Park was an SCS Type II 24-hour storm event. The one-inch rainfall event had a maximum runoff of 2.94 cubic feet per second (cfs) and 10,460 cubic feet of total runoff through the standard stormwater sewer system present. The SuDS implementation for the one-inch rainfall event had no runoff (Figure 16). The bioretention cell was able to infiltrate all runoff from the storm event.

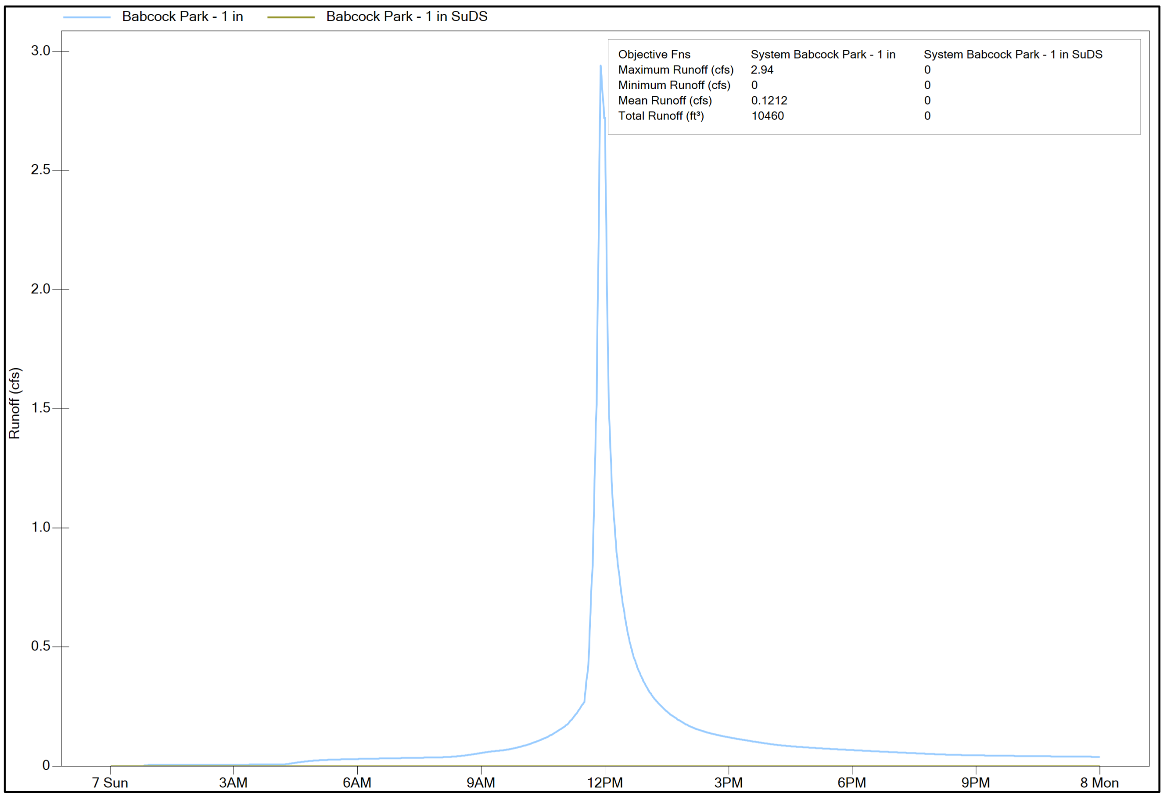

Figure 16. Hydrograph comparing the runoff (cfs) of an SCS Type II 24-hour storm event with 1 inch of rainfall before and after SuDS implementation (CHI, 2021).

The two-inch rainfall event peaked at 6.78 cfs for the current stormwater system. The total runoff was 22,510 cubic feet. The bioretention cell minimized the maximum runoff to 0.26 cfs and allow 194.1 cubic feet of runoff for the 24-hour storm event (Figure 17).

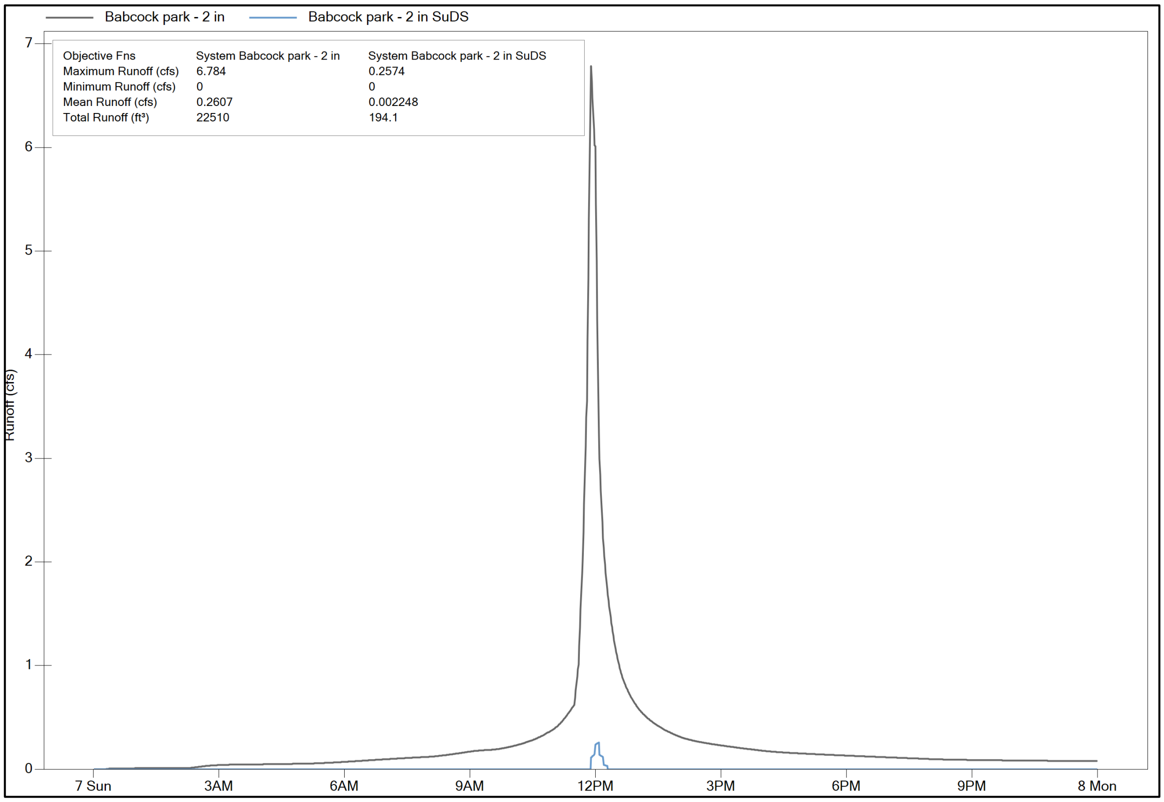

Figure 17. Hydrograph comparing the runoff (cfs) of an SCS Type II 24-hour storm event with 2 inches of rainfall before and after SuDS implementation (CHI, 2021).

The 3-inch rainfall 24-hour storm event created 28,360 cubic feet of runoff. The current stormwater system handled a maximum runoff of 10.85 cfs. The SuDS implementation reduced the peak intensity runoff to 1.26 cfs. The total runoff from the bioretention cell was 1,803 cubic feet (Figure 18).

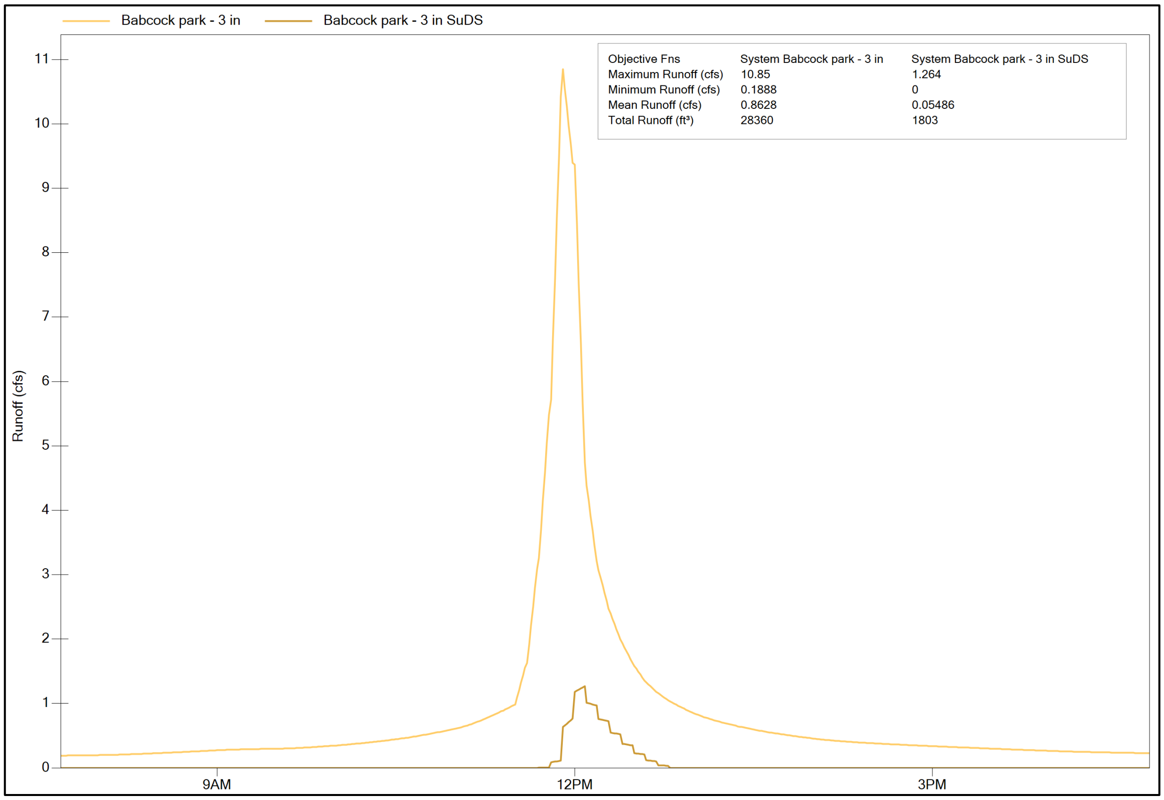

Figure 18. Hydrograph comparing the runoff (cfs) of an SCS Type II 24-hour storm event with 3 inches of rainfall before and after SuDS implementation (CHI, 2021).

The four-inch rainfall event created 15.03 cfs of runoff at the peak discharge. The total runoff from the stormwater sewer system at Babcock Park was 37,860 cubic feet. The bioretention cell allowed 5,137 cubic feet of runoff with a maximum peak runoff of 2.79 cfs (Figure 19).

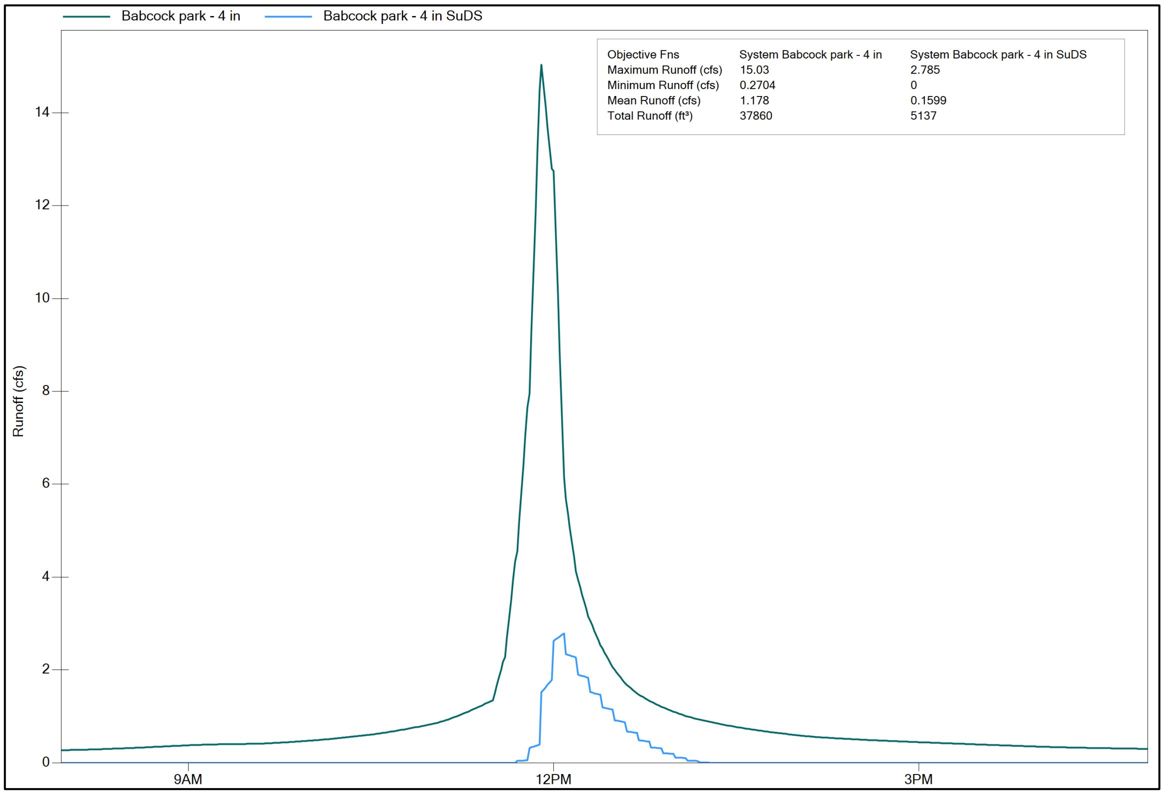

Figure 19. Hydrograph comparing the runoff (cfs) of an SCS Type II 24-hour storm event with 4 inches of rainfall before and after SuDS implementation (CHI, 2021).

The 24-hour storm event with five inches of rainfall generated 46,410 cubic feet of runoff in the pre-SuDS implementation scenario. The peak runoff discharge was 19.3 cfs. The post-SuDS implementation scenario allowed 9,853 cubic feet of runoff with a maximum runoff of 4.70 cfs (Figure 20).

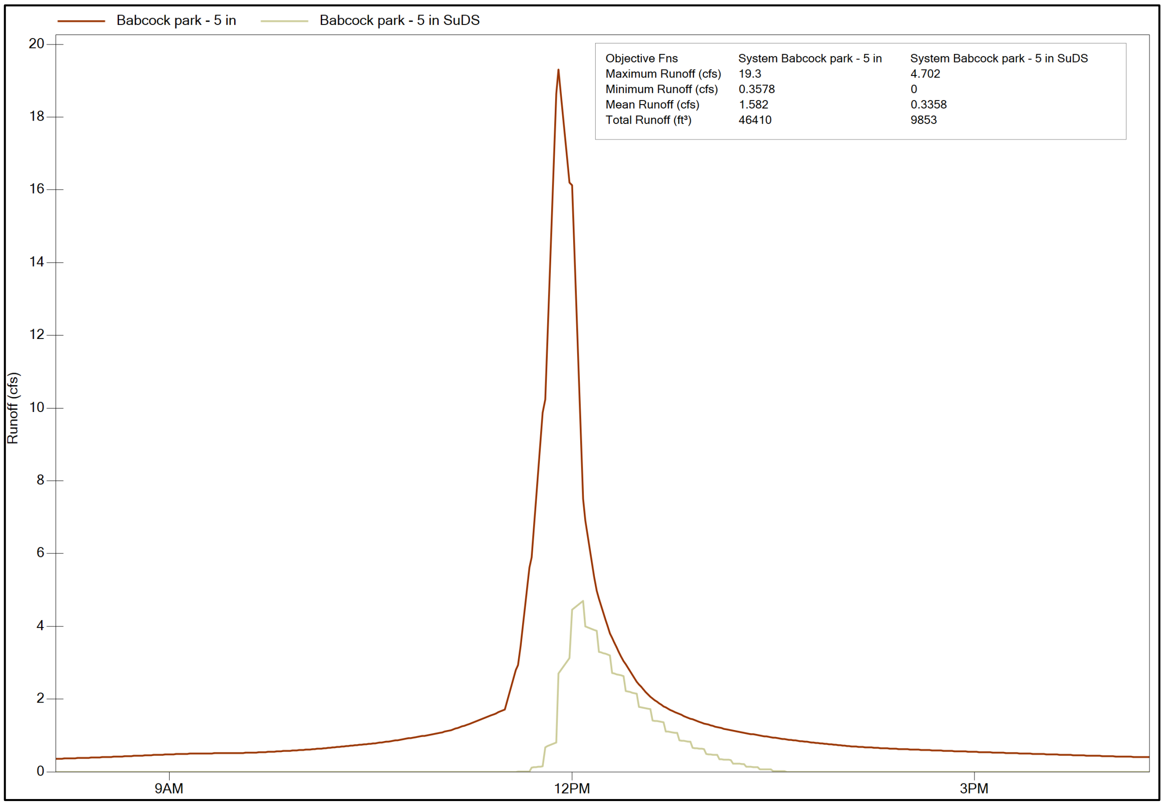

Figure 20. Hydrograph comparing the runoff (cfs) of an SCS Type II 24-hour storm event with 5 inches of rainfall before and after SuDS implementation (CHI, 2021).

Model Limitations and Recommendations

The PCSWMM software and simulations can serve as a basis for development of SuDS in the City of Stillwater. Initial parameters recommended by technical assistance reports were used for simulations in the Babcock Park study area. The SuDS implemented in the small subcatchment area could vary in runoff results during real storm events compared to the PCSWMM simulations. Final design documents for implementation are recommended to ensure project success. Bioretention cell specifications for construction would guide planning efforts (Appendix D, Table D-2). Stormwater project managers should conduct detailed subsurface investigations to verify conditions and parameters for SuDS proposed in this study. Incorporating stakeholder groups or planning consultants into the project can provide further insight for the conceptual design plans (EPA, 2016c).

Environmental Benefits

The SuDS example used for the PCSWMM simulation was a bioretention cell. They provide a wide range of benefits. Bioretention cells act as a small-scale wetland within urbanized areas. They pool water from parking lots and other impermeable surfaces. These cells are able to hold the water for longer periods of time. The soil and plants within the cells help trap silt and pollutants collected in runoff. This infiltration practice reduces stormwater runoff and mitigates flood and water quality impacts. Other benefits include increased groundwater recharge, improved air quality, reduced carbon dioxide, decreased urban heat island effect, improved habitat, and enhanced community livability (CNT, 2010).

The infiltration capabilities of the modeled bioretention cell delayed peak runoff intensity and volume. The five-inch rainfall event with SuDS implementation was 607 cubic feet less total runoff than the one-inch rainfall event with a standard stormwater sewer system. Stillwater typically faces 24-hour storm events less than one-inch of rainfall on average, but nearly five inches of rain within one day occurred during the May 2019 flood. SuDS implementation based off the PCSWMM simulation can reduce the total amount of runoff produced by a five-inch 24-hour storm event by 79 percent. Groundwater recharge can potentially increase from bioretention cells and infiltration practices directing rainfall into the ground (CNT, 2010).

The addition of more SuDS in the Stillwater city limits would significantly reduce the pollutant loading and potential for flooding in streams. Bioretention cells modeled in this study's simulation reduced runoff and consequently reduced pollutant loading into nearby streams. The City of Stillwater can record the environmental benefits of post-SuDS implementation by implementing a water quality monitoring system. Williamsville, New York collected water quality data before and after SuDS construction (Table 3). The data gathered compared the positive impacts bioretention cells have on stream health and water quality. The reduced peak discharges helped reduce the effects of erosion (EPA, 2017).

Table 3. Williamsville, NY Water Quality Data Pre- and Post- Bioretention Cell Construction (EPA, 2017).

	Pre-construction	Post-construction
Average volumetric flow rate	10,199.25 cm3 /sec	1,082.06 cm3 /sec
Average turbidity	112.11 NTU	34.7 NTU
Average TSS	57.39 mg/L	20.44 mg/L
Average TKN	0.8688 mg/L	0.7315 mg/L
Average phosphorus	0.182 mg/L	0.102 mg/L
Average N-N	0.30464 mg/L	0.33135 mg/L

This study can help identify more potential sites for SuDS projects on both privately-owned lands and other watersheds. The EPA's technical assistance program provides insight into how communities have addressed barriers while planning and implementing SuDS. The lessons learned and goals reached by urbanized cities implementing SuDS programs across the United States could serve as a guide for Stillwater to do the same (EPA, 2015).

Large urban cities have already made plans to improve community resiliency by increasing the supply of water, reducing floods, adapting to climate change, and improving water quality. Milwaukee, Wisconsin has demonstrated its plans for a sustainable stormwater future by creating the Greenseams program. Greenseams sets aside undeveloped properties located in upstream watersheds for SuDS management at the source. This program helps infiltrate rainfall onsite and mitigates downstream flooding.

Nashville, Tennessee has pursued SuDS opportunities by identifying 50 sites within the city center. Nashville leaders have also set aside 22,000 acres over the next 25 years to implement

SuDS within large-scale preserves along river bends. Both projects allow for the urban area to reduce flood risk and sewer overflows, restore impaired streams, and protect the endangered species populations (EPA, 2020).

Stillwater can further enhance flood resiliency by adopting an internal policy requiring all public street proposals to integrate SuDS concepts during the initial design phase. An example of SuDS being introduced during the design phase can be seen in Tucson, AZ. New roadways are built while existing streets are widened to accommodate the state's growing community. Their government installed SuDS concepts to collect rainwater in these projects to counteract the increased number of impermeable surfaces. The installation of bioswales, bioretention cells, permeable pavement systems, and infiltration trenches can be added to collect rainwater. The green streets work as a tool to gather runoff to augment local water supplies while simultaneously mitigating flooding, improving water quality, and reducing potable water demand (EPA, 2020).

Economic Benefits

The multiple benefits SuDS deliver to communities can also be expressed by assessing the value of these practices' outcomes (CNT, 2010). SuDS can strengthen the economy of Stillwater for years to come. Introducing SuDs reduces the cost to build storm drain infrastructure. Green spaces incorporated into urban areas can increase property values. The reduction of flooding due to SuDS implementation nearly eliminates property damage and associated costs for private and commercial landowners. The reduction of polluted runoff, eroded stream banks, and high-velocity streams make neighborhoods safer and healthier. Building and maintaining SuDS create jobs that help boost the local economy (EPA, 2015).

Stillwater can look at other cities for an idea of what monetary gains can come from environmental benefits of SuDS. A case study completed by the EPA in Lancaster, Pennsylvania showed how the implementation of SuDS in growing urban settings has economic benefits. The

Lancaster Plan accounted for a 25-year implementation period that applied an overall goal of reducing runoff by 1.053 billion gallons per year (EPA, 2014).

The runoff capture would be accomplished using SuDS instead of using a Combined Sewer System (CSS) and a wastewater treatment facility that would implement gray infrastructure storage. The estimated cost of SuDS implementation over the 25-year timeline would cost an estimated $141 million. The incorporation of SuDS into already-planned capital improvement projects would be a total marginal cost of $77 million (EPA, 2014).

The implementation of SuDS could help Lancaster avoid $661,000 in pumping and treatment costs per year and $120 million in gray infrastructure costs over 25 years (an estimated total of $136 million in the 25-year implementation period). Other calculated benefits were found in energy, air quality, and climate change. SuDS can help reduce energy costs through green roofs, tree planting, and rainwater harvesting. Energy usage reductions can be seen in decreased daily temperature changes in buildings and potable water use. Lancaster's study showed an estimated $2,368,000 reduction in energy use per year (EPA, 2014).

The incorporation of SuDS practices, like bioretention cells, green roofs, and tree planting, help reduce air pollutants through direct absorption in plants and soils used for the design. Emissions from electricity and natural gas reductions combined with the natural uptake of SuDS, helped Lancaster save $1,023,000 per year during the 25-year study. Climate change-related benefits from reducing the amount of carbon dioxide present was a savings of $786,000 per year. Carbon sequestration from trees and green roofs and reductions in energy use from SuDS implementation helped reduce carbon dioxide (EPA, 2014).

The Lancaster Plan saved an estimated annual benefit total of $4,838,000 and avoided $120 million in capital costs for unsustainable projects. The City of Lancaster saved an estimated $23 million by implementing SuDS (EPA, 2014). Stillwater could implement a similar long-term implementation plan like Lancaster. Lancaster's SuDS implementation exemplifies how Stillwater can be effective and successful in reaching environmental and economic goals that would benefit the community.

The City of Stillwater can get started with implementing SuDS with the help of EPA's Clean Water State Revolving Fund (CWSRF). The CWSRF is one of the largest sources of public financing for SuDS projects. Lancaster's long-term implementation plan was a recipient of $7 million from this program. The Illinois River Watershed near Tahlequah, Oklahoma was another CWSRF success story that incorporated the loan into 12 stream stabilization projects. CWSRF offers the City of Stillwater flexibility, affordability, and eligibility to receive funding for SuDS implementation and addressing other water quality concerns (EPA, 2017).

The City of Stillwater can seek additional funds from FEMA. SuDS projects offer flood reduction, water quality improvement, public safety, and property loss prevention. These benefits qualify Stillwater for the FEMA's funding programs. FEMA provides funding through the Hazard Mitigation Grant Program, Pre-Disaster Mitigation, and Flood Mitigation Assistance. The FEMA Local Mitigation Handbook offers resources and suggestions for SuDS implementation (EPA, 2018).

Social Benefits

Benefits from SuDS implementation are not all monetized. Research has shown that the willingness to pay for a home in a community with sustainable infrastructure and green spaces is on average higher than it is for a community without. Cities with SuDS implementation have additionally reported an increase in outdoor activity. These areas create a green space for the community to enjoy recreationally, which generally improves their overall health and well-being (EPA, 2015). A better quality of life from the addition of SuDS also includes better aesthetics and reduced noise pollution. SuDS reduce noise transmission due to the use of permeable materials (CNT, 2010).

Outreach programs could influence community cohesion and the implementation of neighborhood SuDS, like a rain garden, green roofs, or tree planting (CNT, 2010). The creation of a SuDS Team for Stillwater would help formalize the commitment to protecting the watershed and community. Leaders in Austin, Texas chose this solution in 2011 to drive the city's promise towards sustainability. The team in Austin was able to model how SuDS implementation reduced flooding and erosion, improved water quality, and helped decrease the usage of potable water for landscape irrigation. The SuDS Team also conducted outreach to private sectors to help encourage implementation in neighborhoods through development code incentives and educational opportunities at schools (EPA, 2011).

Cost of Implementation

The city of Sanford, Maine received technical assistance from the EPA to implement SuDS. Two sites were selected for this project to enhance aesthetics, improve water quality, and help drainage and road infrastructure. An initial conceptual design and cost estimate resulted from this report (Table 4). The initial design cost for a 3,000 square foot bioretention cell was $36,451. The City of Stillwater could expect to spend an estimated $12 per square foot to implement a bioretention cell based on this study. A final report completed by a stormwater management professional would account for the actual layout, sizing, and outlet control. Detailed survey information would need to be collected to accurately prescribe underdrain piping. Site preparation and fees were additional costs to be considered when implementing SuDS. Excavation and removal were estimated to cost $45 per cubic yard to prepare the park site. Fees such as planning, mobilization, bond, and construction contingency would need to be developed (EPA, 2016c).

Table 4. Sanford, Maine Bioretention Cell Implementation Costs

Traditional Bioretention	**Quantity**	**Unit**	**Price Per Unit**	**Total Price**
Fine Grading	5969	SF	$0.72	$4,298
Soil Media	169	CY	$40.00	$6,756
Filter Layer (sand and No. 8 stone)	38	CY	$45.00	$1,689
Vegetation	3040	SF	$4.00	$12,160
Mulch	19	CY	$55.00	$1,032
Curb and Gutter	478	LF	$22.00	$10,516

Other costs associated with maintenance would need to be taken into account for implementation. Maintenance considerations are similar to tasks for public gardens and landscaped areas found parks and other public areas. Trash removal and monitoring plant health are the primary activities for bioretention cells. These two tasks should be performed once a month. Other maintenance activities such as monitoring infiltration and drainage, pruning, mowing, mulching, watering, fertilization, and infrastructure inspection should be completed annually (Appendix D, Table D-3) (EPA, 2016c).

CHAPTER V

CONCLUSION

The combination of increased impervious surfaces and outdated and broken stormwater infrastructure created a unique problem for Stillwater during the extensive precipitation received in May 2019. Runoff reached streams quicker due to the increase in impervious surfaces within the city limits. Streams reached their maximum capacity and causing flooding throughout the FEMA hazard area. The outdated, broken, and now misplaced stormwater infrastructure demonstrated failures throughout the City of Stillwater as a result of the additional flood pressure on the system. This created flooding in the streets and properties. The problem areas found in this study with the use of GIS helped reiterate the importance of assessing the condition of Stillwater's stormwater infrastructure so updates can be made. The City of Stillwater can utilize the updated information to contact FEMA and reevaluate the designated zones before another flood event takes place.

Targeting the flood-prone streets and prioritizing suitable areas for implementing SuDS with GIS and PCSWMM simulation saves planners and engineers time and money for finding other flood mitigation strategies. SuDS has proven to help many cities across the United States solve water quality and create more livable communities. The City of Stillwater can mimic nature by conserving water in SuDS and minimizing erosion, flooding, and damage to habitat, properties, and infrastructure caused by higher flows from outdated MS4s (EPA, 2014).

PCSWMM effectively demonstrates how the City of Stillwater can benefit from SuDS implementation. A single bioretention cell in the PCSWMM simulation scenarios can reduce runoff by 79 percent from a storm that could cause irreversible damage to properties, infrastructure, streambanks, and water quality. Additional bioretention cells and SuDS projects could protect Stillwater from another traumatic flood event.

Stillwater can use this study as an opportunity to integrate SuDS across several infrastructure improvement projects over a long-term plan. These projects mitigate flooding and stream channels through the direct reduction of runoff as seen in the hydrographs from the PCSWMM storm scenarios. The community of Stillwater benefits from this flood resiliency through a decrease in property damages and erosion along stream channels. SuDS creates a contingency to reduce the cost of implementation and promote economic-and sustainable-friendly stormwater practices.

The technical assistance program for green infrastructure offered by the EPA serves as a key for cities and communities looking for the best solution for their stormwater management challenges. Report summaries from areas that have implemented SuDS work as a reference guide for urbanized cities that are considering new ways to manage water resources better. Stillwater can benefit environmentally, economically, and socially from the implementation of SuDS. Climate change and urbanization are predicted to increase problems in Stillwater's watershed and watersheds around the world. Real-world applications have proven that SuDS improves water quality and conserves water, strengthens the local economy, and builds community and infrastructure resiliency.

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APPENDICES

APPENDIX A

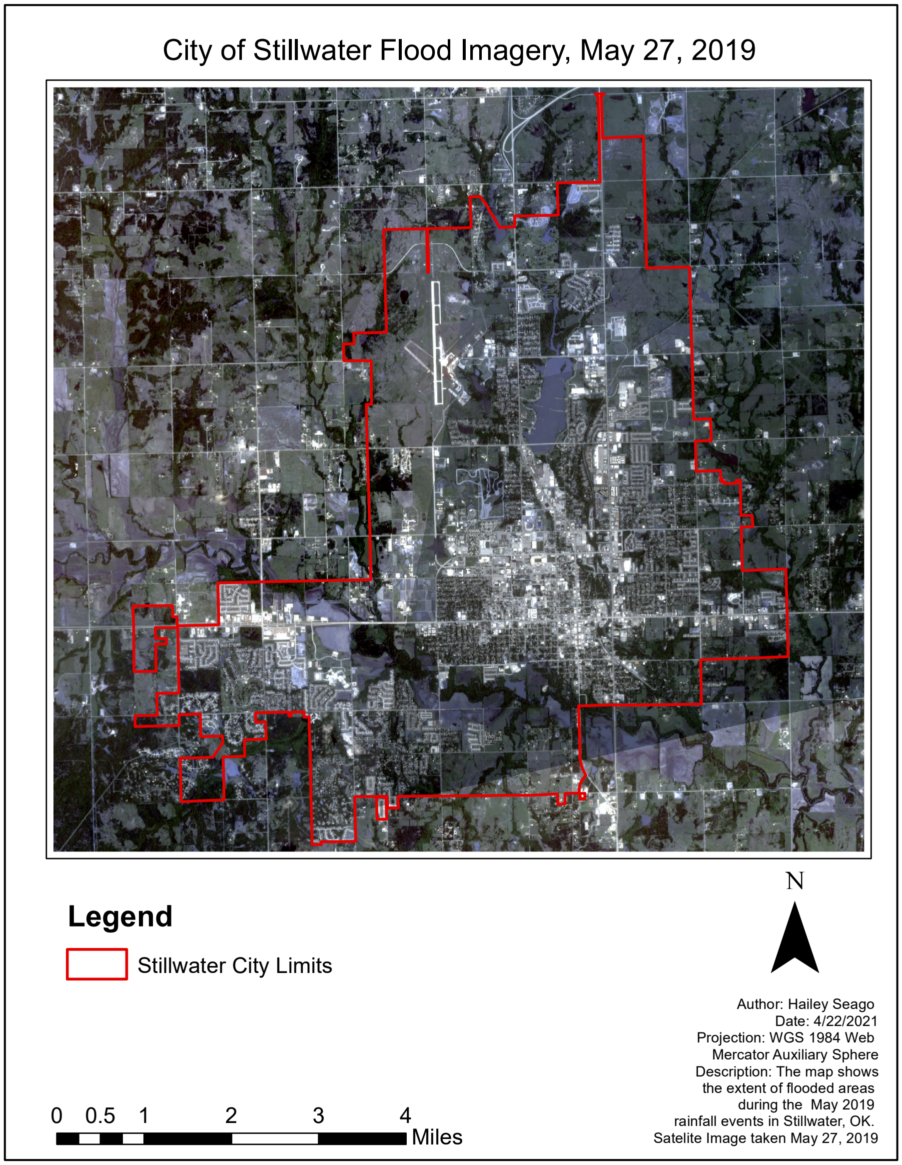


Figure A-1. A map of Stillwater, Oklahoma on May 27, 2019 via satellite imagery displaying the flooded regions throughout the city.

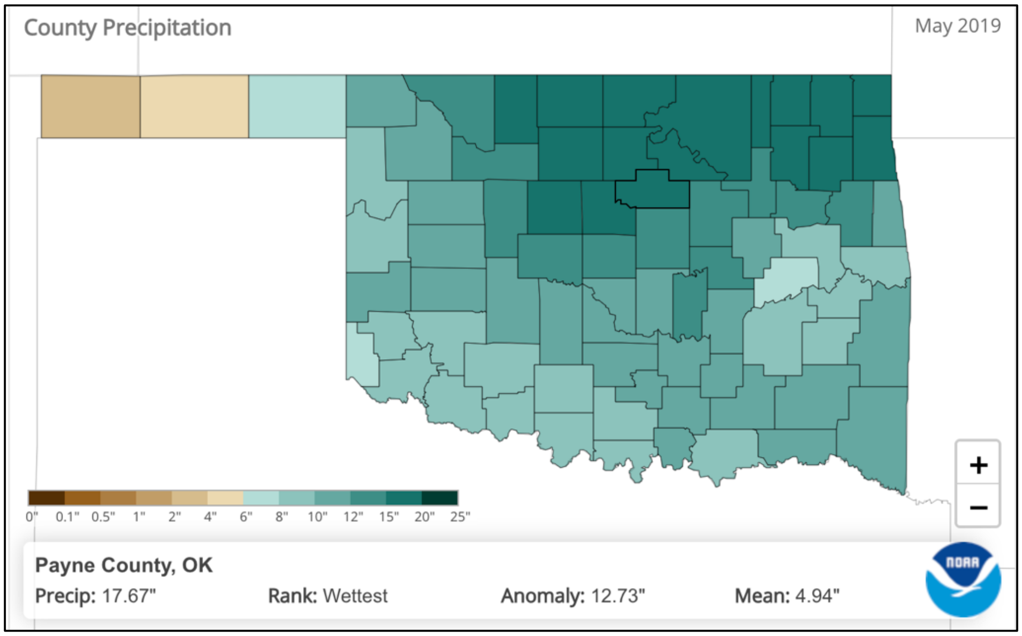
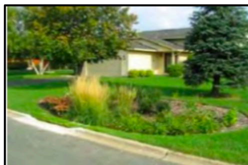
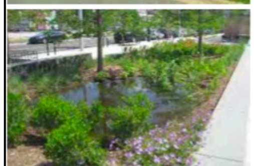


Figure A-2. A map of Oklahoma showing Payne County with the wettest recorded month (May 2019) with 17.67" of rain. *Source:* (NOAA, 2020)

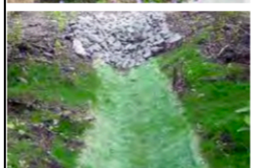
APPENDIX B



Rain Gardens. A depressed area in the landscape, planted with grasses, flowers, and other plants, that collects rain water from a roof, driveway, or street and allows it to infiltrate into the ground. Rain gardens can also help filter out pollutants in runoff and provide food and shelter for butterflies, song birds and other wildlife. More complex rain gardens with drainage systems and amended soils are often referred to as bioretention cells.



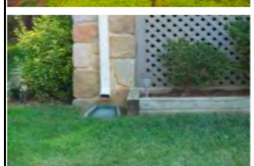
Bioretention Cells (or Bioswales). Depressions that contain vegetation grown in an engineered soil mixture placed above a gravel drainage bed which slow, infiltrate, and filter runoff. They provide storage, infiltration, and evaporation of both direct rainfall and runoff captured from surrounding areas. As linear features, bioretention cells are particularly well suited to being placed along streets and parking lots.



Vegetative Swales. Channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down the conveyance of collected runoff and allow it more time to infiltrate the native soil beneath it.

Infiltration Trenches. Narrow ditches filled with gravel that intercept runoff from upslope impervious areas. They provide storage volume and additional time for captured runoff to infiltrate the native soil below.

Green Roofs. A variation of a bioretention cell, green roofs have a soil layer laying atop a special drainage mat material that conveys excess percolated rainfall off of the roof. They contain vegetation that enable rainfall infiltration and evapotranspiration of stored water. Green roofs are particularly cost-effective in dense urban areas where land values are high and on large industrial or office buildings where stormwater management costs are likely to be high.



Rooftop (Downspout) Disconnection. This practice allows rooftop rainwater to discharge to pervious landscaped areas and lawns instead of directly into storm drains. You can use it to store stormwater and/or allow stormwater to infiltrate into the soil. Downspout disconnection could be especially beneficial to cities with combined sewer systems. SWMM can also model roofs with directly connected drains that overflow onto pervious areas.

Rain Barrels or Cisterns (Rainwater Harvesting). Containers that collect roof runoff during storm events and can either release or re-use the rainwater during dry periods. Cisterns may be located above or below ground and have a greater storage capacity than a rain barrel.

Continuous Permeable Pavement Systems. Excavated areas filled with gravel that are paved over with a porous concrete or asphalt mix. Normally, rainfall will immediately pass through the pavement into the gravel storage layer below where it can infiltrate at natural rates into the site's native soil. Block Paver systems consist of impervious paver blocks placed on a sand or pea gravel bed with a gravel storage layer below. Rainfall is captured in the open spaces between the blocks and conveyed to the storage zone and native soil below.

Figure B-1. SuDS options available for simulation in PCSWMM (EPA, 2016a).

Table B-1. Soil texture classes with corresponding criteria for SuDS implementation.

Soil texture class	Hydrologic soil group	Effective water capacity (C_w) (in/in)	Minimum infiltration rate (*f*) (in/hr)	Effective porosity, θe (in^3/in^3)
Sand	A	0.35	8.27	0.025 (0.022-0.029)
Loamy sand	A	0.31	2.41	0.024 (0.020-0.029)
Sandy loam	B	0.25	1.02	0.025 (0.017-0.033)
Loam	B	0.19	0.52**	0.026 (0.020-0.033)
Silt loam	C	0.17	0.27	0.300 (0.024-0.035)
Sandy clay loam	C	0.14	0.17	0.020 (0.014-0.026)
Clay loam	D	0.14	0.09	0.019 (0.017-0.031)
Silty clay loam	D	0.11	0.06	0.026 (0.021-0.032)
Sandy clay	D	0.09	0.05	0.200 (0.013-0.027)
Silty clay	D	0.09	0.04	0.026 (0.020-0.031)
Clay	D	0.08	0.02	0.023 (0.016-0.031)

**Minimum rate: soils with lower rates should not be considered for infiltration BMPs

APPENDIX C

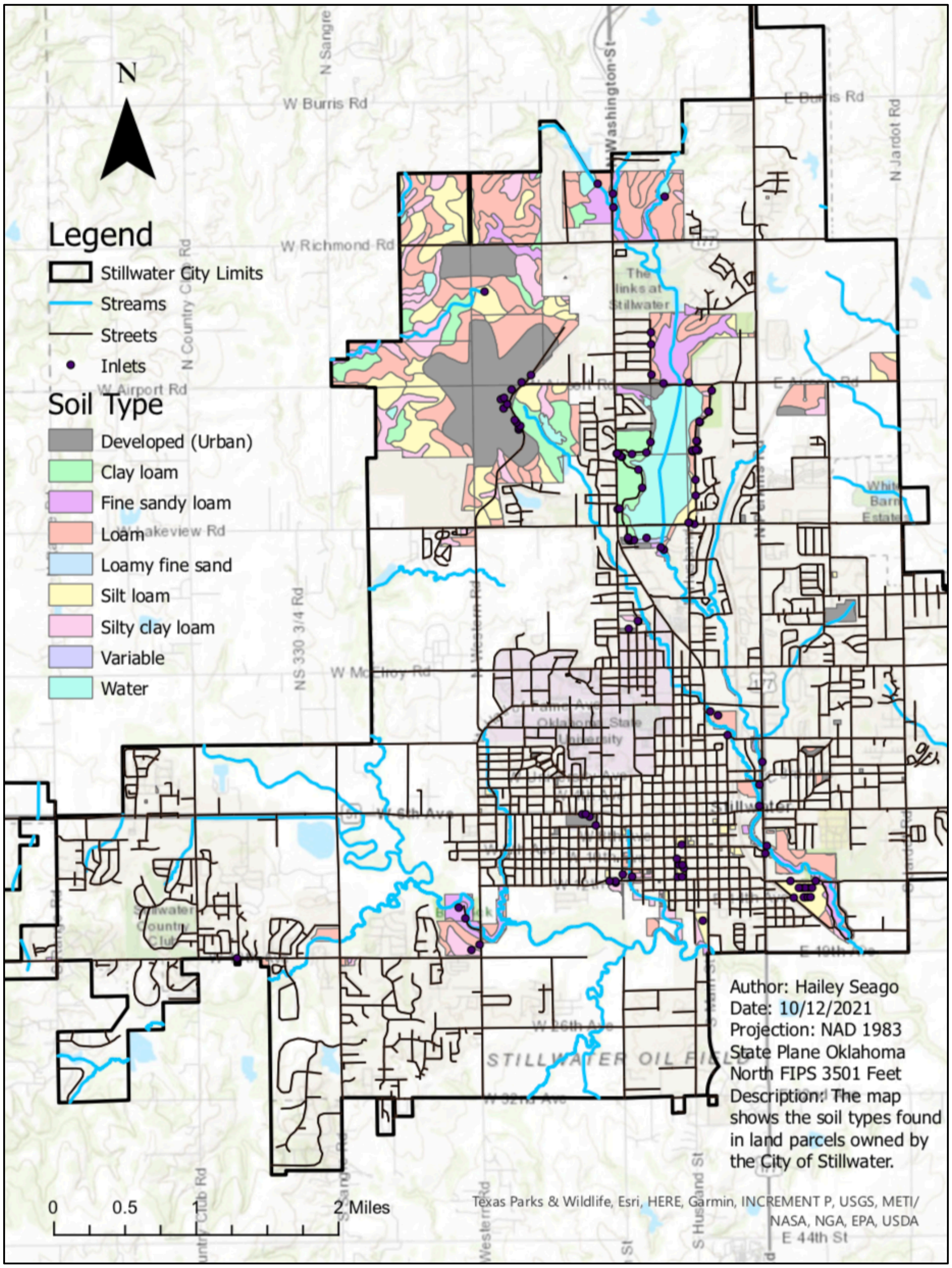


Figure C-1. Soil texture classes on City of Stillwater land parcels (USDA, 2021).

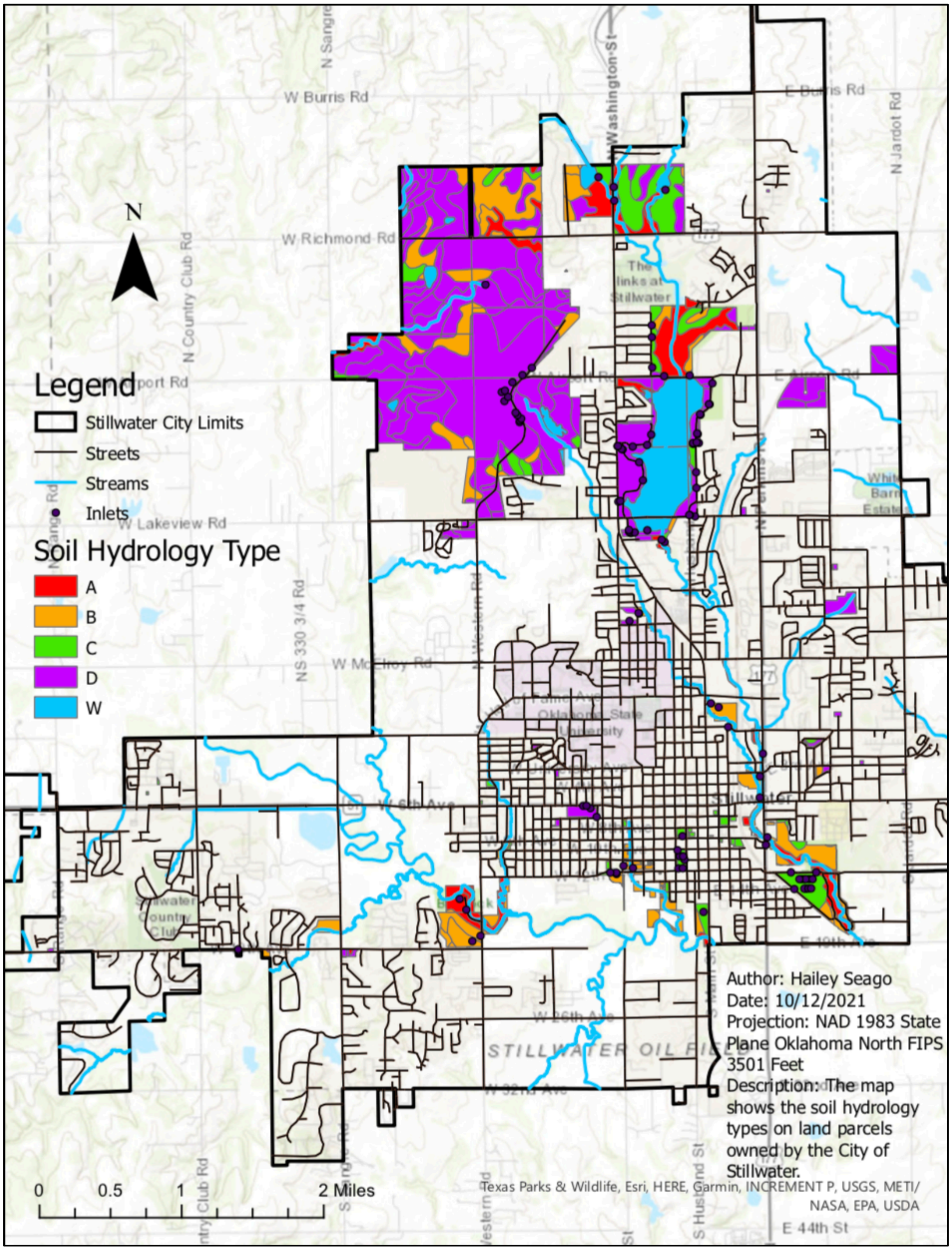


Figure C-2. Hydrologic soil groups located on City of Stillwater land parcels (USDA, 2021).

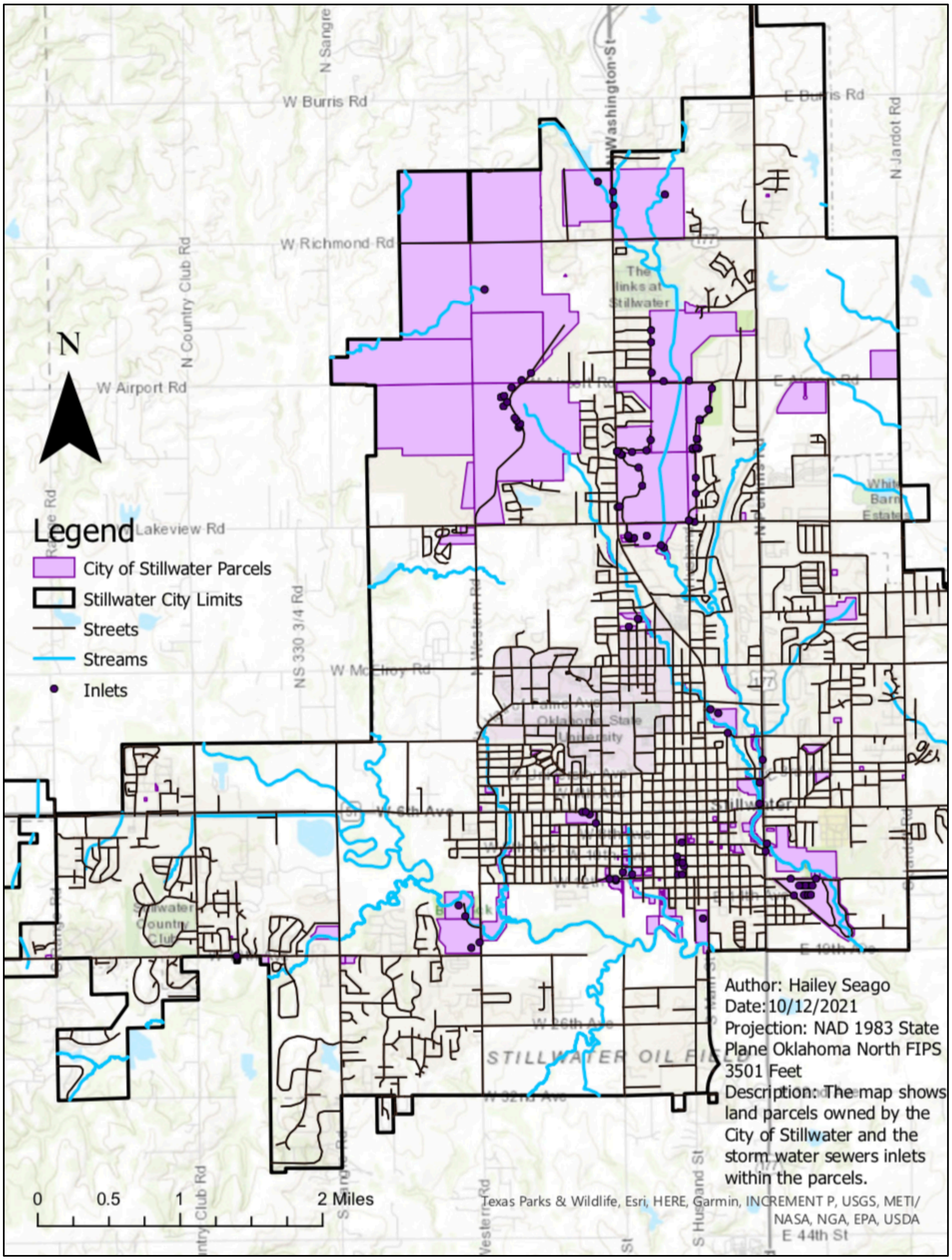


Figure C-3. City of Stillwater-owned land parcels highlighted, and stormwater sewer inlets identified on the property.

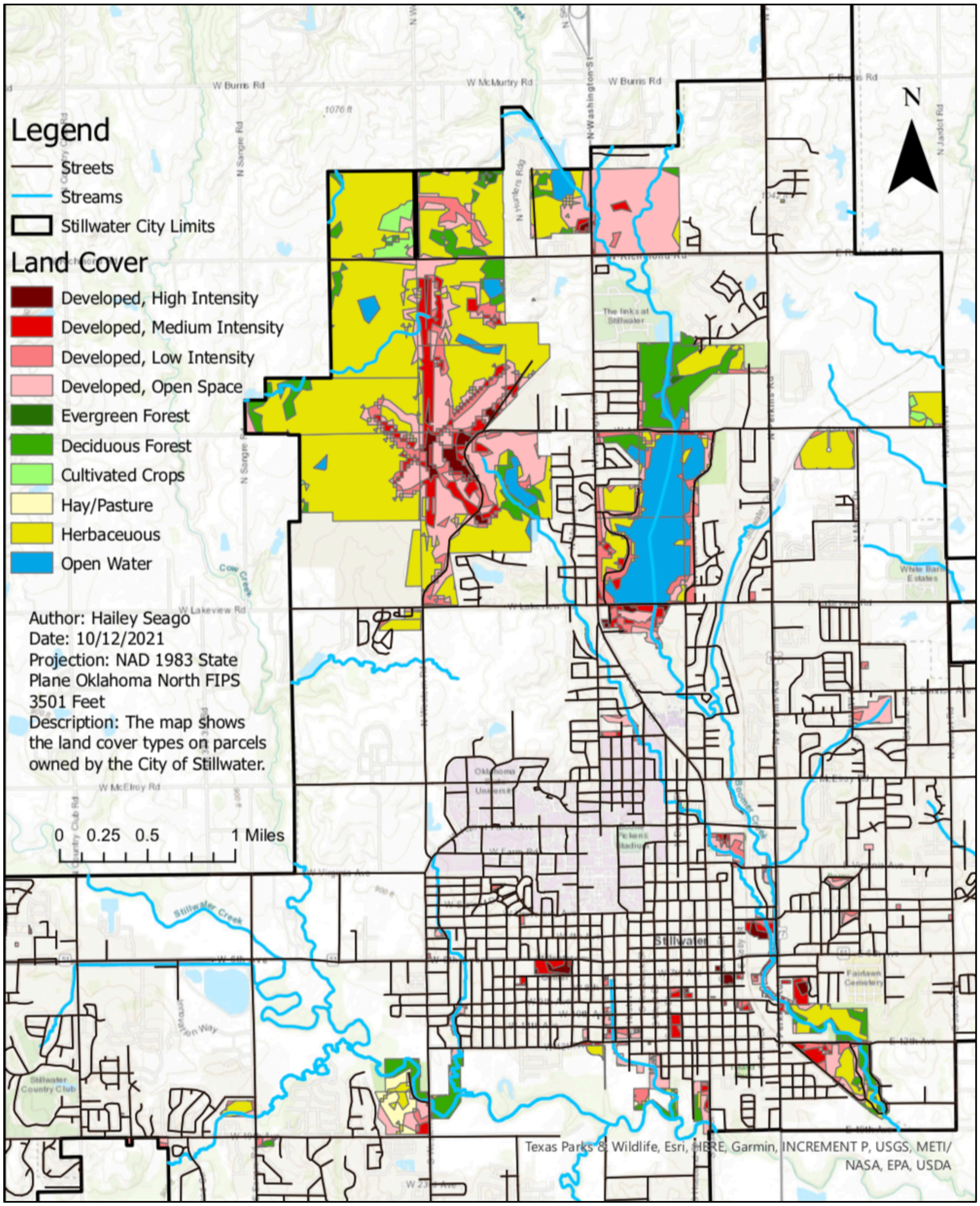


Figure C-4. Land use and land cover within City of Stillwater land parcels (NLCD, 2020).

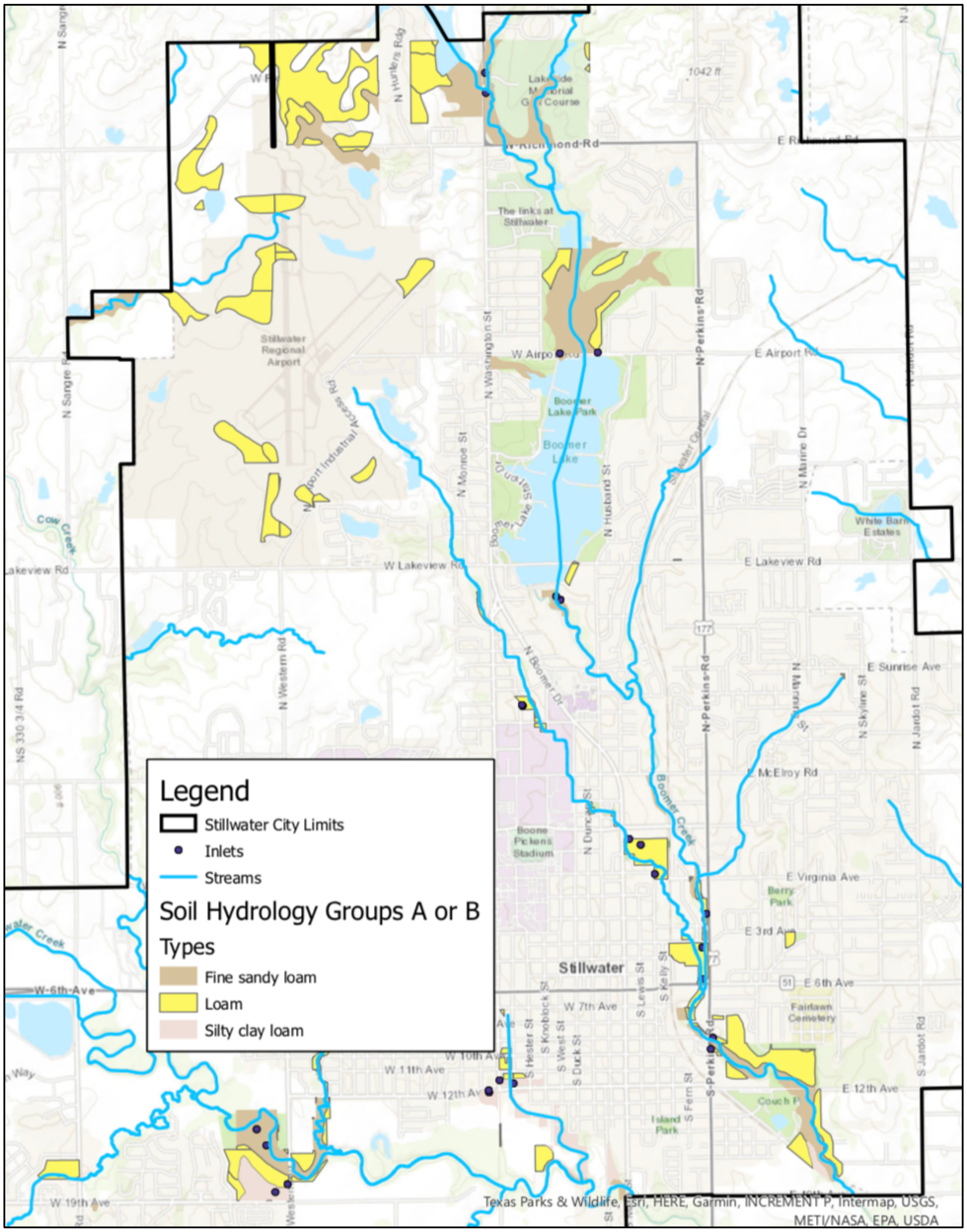


Figure C-5. The hydrologic soil groups A or B found in suitable areas for SuDS implementation (NRCS, 2021).

APPENDIX D

Table D-1. May 2019 Flooded Roadways Outside FEMA Hazard Area in Stillwater, Oklahoma (See Figure D-1 for reference).

Point (North to South on Figure D-1)	**Intersection**
1	E Airport Rd (East of N Husband St)
2	W Lakeview Rd (East of N Husband St)
3	W Miller Ave & N Duck St
4	W University (From S Willis St to S Orchard St)
5	W 12th Ave (From S Duck St to S Duncan St)
6	E 14th Ave (From S Main St to HWY 177)

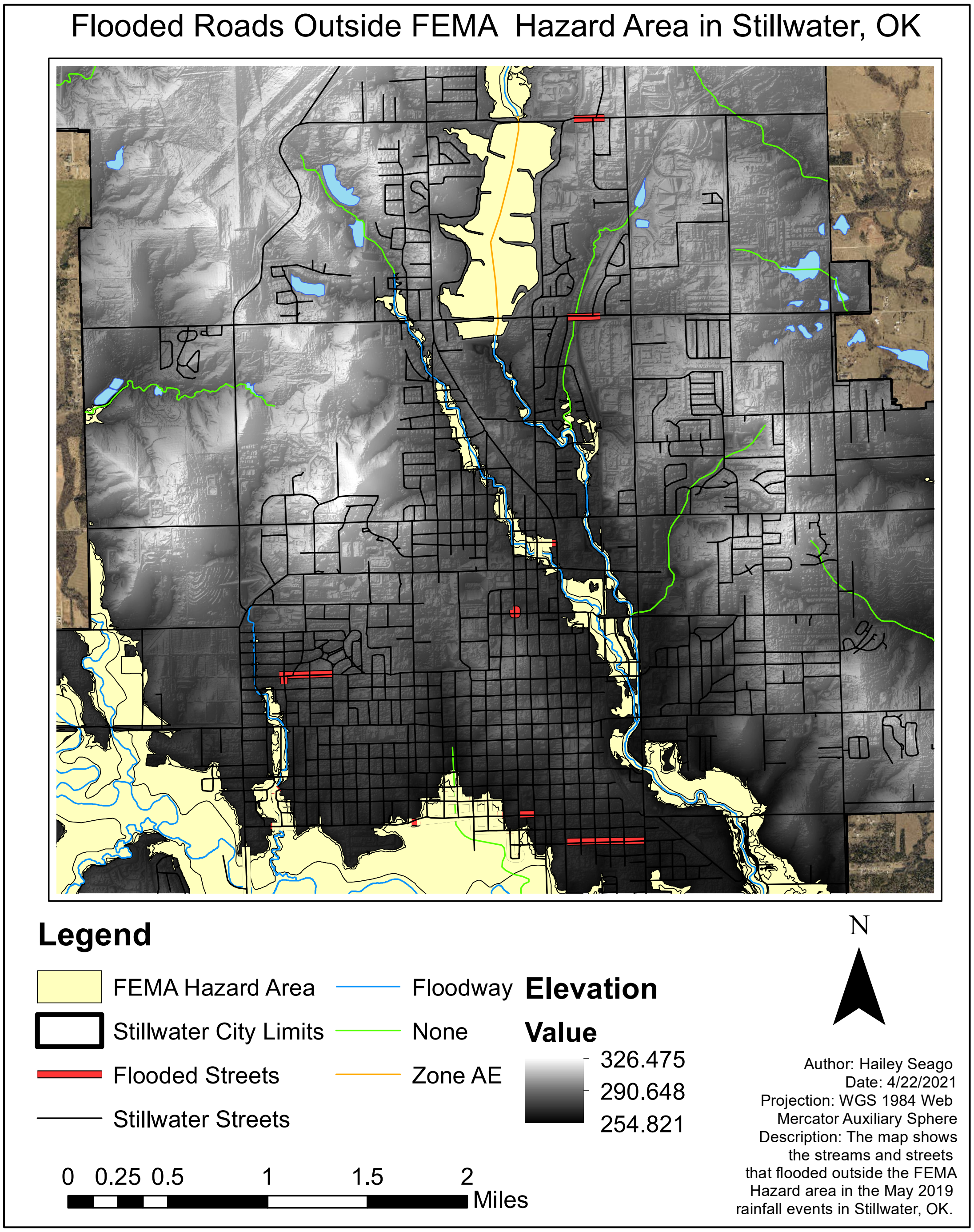


Figure D-1. Flooded streets that were located outside the FEMA Hazard Area (FEMA, 2020; USGS, 2021; NRCS, 2021).

Table D-2. Bioretention cell construction specifications (EPA, 2016c).

1. Siting Setbacks	
Pavement	No requirement
Building	No requirement with lined bottom; otherwise, Basement: ≥ 10 feet No Basement: ≥ 5 feet
Property lines/ROW	≥ 2 feet / ≥ 0 feet
2. Volume	
Bottom slope	Flat
Side slopes	Bioretention: 2H:1V or flatter Planter Box: Vertical retaining wall
Freeboard	6 to 12 inches
3. Vertical Component	
Surface Storage	6 to 12 inches
Growing Layer	≥ 12 inches soil media; 3 inches of mulch, max
Filter Layer	2 to 4 inches of clean medium sand (ASTM c-33) over 2 to 3 inches of #8 or #78 washed stone when drainage layer is used
Drainage Layer	Recommended 12 to 30 in. of clean coarse aggregate AASHTO #4, #5, or equivalent
Native Material	Test infiltration; ≥ 1/2 in/hr if designing with infiltration
4. Drainage	
Inlet	Curb inlet; sheet flow through grass filter strip; downspout w/ energy dissipation
Underdrain	4-inch perforated PVC placed to meet dewatering requirement if needed; cleanout at terminal ends and every 250-300 feet
Outlet	Required to meet release rates
Overflow	Downstream inlet or catch basin set 6 to 12 inches above soil surface and connected to storm drainage network
Infiltration	Meet water quality volume requirement
Dewatering	Surface: ≤ 24 hours Sub-surface: ≤ 72 hours
5. Composition	
Surface Treatment	Vegetation and mulch
Soil Media	With or without an underdrain, meets dewatering requirement; supports plant growth
Side Slopes	Grass or mulch
Mulch	Triple-shredded hardwood
6. Pollutant	
Pretreatment	Required. May include grass filter strip, stone trench, forebay, sump inlets
7. Maintenance	
Access	Able to be accessed by a vehicle
Requirements	Designed and maintained to improve water quality; Maintenance plan should be in place

Table D-3. Maintenance Considerations for Bioretention Cell (EPA, 2016c)

Task	Frequency	Maintenance notes
Monitor infiltration and drainage	1 time/year	Visually inspect drainage time (12 hours). Might have to determine infiltration rate (every 2–3 years). Turning over or replacing the media (top 2–3 inches) might be necessary to improve infiltration (at least 0.5 in/hr).
Pruning	1–2 times/year	Nutrients in runoff often cause bioretention vegetation to flourish.
Mowing	2–12 times/year	Frequency depends on the location, plant selection and desired aesthetic appeal.
Mulching	1–2 times/ year	Recommend maintaining 1″–3″ uniform mulch layer.
Mulch removal	1 time/2–3 years	Mulch accumulation reduces available water storage volume. Removal of mulch also increases surface infiltration rate of fill soil.
Watering	1 time/2–3 days for first 1–2 months; sporadically after establishment	If drought conditions exist, watering after the initial year might be required.
Fertilization	1 time initially	One-time spot fertilization for first year vegetation.
Remove and replace dead plants	1 time/year	Within the first year, 10% of plants can die. Survival rates increase with time.
Inlet inspection	Once after snow season, then monthly during the remainder of the year.	Check for sediment accumulation to ensure that flow into the bioretention area is as designed. Remove any accumulated sediment.
Outlet inspection	Once after the snow season then monthly during the remainder of the year	Check for erosion at the outlet and remove any accumulated mulch or sediment.
Underdrain inspection	Once per year	Check for accumulated mulch or sediment. Flush if water is ponded in the bioretention area for more than 12 hours.
Miscellaneous upkeep	12 times/year	Tasks include trash collection, plant health, spot weeding, and removing mulch from the overflow device.

VITA

Hailey Nicole Seago

Candidate for the Degree of

Master of Science

Thesis: USING GIS TO IDENTIFY SUITABLE AREAS FOR SUSTAINABLE DRAINAGE SYSTEMS FOR FLOODPLAIN AND STREAM CHANNEL MITIGATION IN STILLWATER, OKLAHOMA

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Ecosystem Management Intern, Grand River Dam Authority, Langley, Oklahoma, Summer 2018 and 2019. Responsibilities include collecting water quality samples at reservoirs, monitoring for harmful algal blooms, collecting and evaluating fish kill events, water quality sampling 303(d) list creeks upstream of reservoirs, creating artificial fish habitats, youth educational outreach programs, and monitoring endangered bat caves.