AN EXAMINATION OF DOWNSCALING A FLOOD RISK SCREENING TOOL AT THE WATERSHED, SUBWATERSHED, AND MUNICIPAL LEVELS

by

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This thesis was prepared under the direction of the candidate's thesis co-advisors, Dr. Frederick Bloetscher and Dr. Hongbo Su, Department of Civil, Environmental and Geomatics Engineering, and has been approved by all members of the supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

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This research aims to develop a large-scale locally relevant flood risk screening tool, that is, one capable of generating accurate probabilistic inundation maps quickly while still detecting localized nuisance-destructive flood potential. The CASCADE 2001 routing model is integrated with GIS to compare the predicted flood response to heavy rains at the watershed, subwatershed, and municipal levels. Therefore, the objective is to evaluate the impact of scale for determining flood risk in a community. The findings indicate that a watershed-level analysis captures most flooding. However, the flood prediction improves to match existing FEMA flood maps as drill-down occurs at the subwatershed and municipal scales. The drill-down modeling solution presented in this study provides the necessary degree of local relevance for excellent detection in developed areas because of the downscaling techniques and local infrastructure. This validated model framework supports the development and prioritization of protection plans that address flood resilience in the context of watershed master planning and the Community Rating System.

AN EXAMINATION OF DOWNSCALING A FLOOD RISK SCREENING TOOL AT THE WATERSHED, SUBWATERSHED, AND MUNICIPAL LEVELS

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1: INTRODUCTION

Flooding is a temporary inundation of water on normally dry land. FEMA (2017) identified flooding as a frequently occurring and costly disaster that can negatively impact community resources, including damage to property and infrastructure or disruption of transportation and essential services. Therefore, making sound, science-based, long-term decisions to improve resiliency is crucial for future growth and prosperity. Efforts in response to flooding that are consistent with the objectives of Florida Atlantic University (FAU)'s Watershed Master Planning Initiative Program and the National Flood Insurance Program (NFIP)'s Community Rating System (CRS) seek to inform flood management practices to assess risk and mitigate the effects of flooding. For example, through public information, mapping and regulations, flood damage reduction, and warning and response. The procedures for developing a screening tool suggest combining readily available data on topography, groundwater, surface water, tidal information for coastal communities, soils, open space, and rainfall data. Hence, there is a need for risk assessments and scenario modeling to identify critical flood-prone areas in a watershed, subwatershed, or municipality of interest to support the development of flood protection plans and prioritize improved management efforts.

Many studies on flood inundation modeling either develop a simplified conceptual framework using limited data in major river basins (Paiva et al., 2011; Jafarzadegan and

Merwade, 2017; Nastiti et al., 2018) or a highly detailed model requiring immense data input for small urban areas or individual river segments (Son and Jeong, 2019). However, Rajib et al. (2020) note the lack of local relevance in current large-scale modeling efforts typically achieved only in small-scale studies. FAU noted this issue in their modeling efforts but found little evidence in the literature to support decision-making regarding the limits on the infrastructure needed for modeling at different scaling.

As a result, this research aims to evaluate the impact of scale for determining flood risk in a community. The proposed framework seeks to address this need and appears to produce reasonable floodplain inundation maps while still detecting localized nuisance flooding (Rojas, 2020). CASCADE 2001, a data-driven hydrologic/hydraulic routing model with geographic information system (GIS) integration, was selected to compare the predicted flood response at three nested levels of drill-down starting with the 8-digit hydrologic unit code (HUC) level (Caloosahatchee Watershed), the 12-digit HUC level (Ninemile Canal Subwatershed), and the local municipal level (City of Clewiston, Florida) using a combination of conditions, including low land elevations, high groundwater levels, poor soil storage, heavy rains, and controlled drainage. Developing maps from its spatiotemporal output of floodwater levels and leveraging the overlap of study areas makes it possible to determine how the scale of data and modeling efforts affected those resulting flood risk maps and how downscaling changes the at-risk properties. An objective is to determine the level of detail (e.g., infrastructure at the watershed or local level) needed to generate accurate flood maps quickly. Once downscaling is better understood, flood risk mapping and scenario modeling can support comprehensive action plans that address flood resilience at the watershed and community levels.

1.1 Background

1.1.1 Community Rating System

The National Flood Insurance Program (NFIP) protects against flood losses through intentional and comprehensive floodplain management practices on the part of participating communities. Communities that take action to reduce flood risks to future development in known hazard areas and strengthen their overall flood resilience can receive federal insurance, which offers protection to property owners against flood-related damages. A voluntary incentive program of the NFIP is the Community Rating System (CRS). A CRS plan aims to evaluate the activities that, if implemented, can reduce food risk, improve a community's current CRS classification, and reduce flood insurance costs for property owners. The plan includes recommendations for implementing activities related to public information, mapping and regulations, flood damage reduction, warnings, and responses that will qualify to receive CRS credits. The focus is to reduce the risk of flooding both inside and outside of known flood hazard areas, thereby reducing the exposure of existing structures to flood damage, especially critical facilities and properties classified as repetitive losses. In addition, implementing standards higher than those set out in the minimum criteria of the National Flood Insurance Program (NFIP) protect new buildings from future flood hazards.

South Florida communities are particularly susceptible to flooding due to location-specific issues. For example, the City of Clewiston is subject to flooding due to low land elevations, high groundwater levels, poor soil storage, heavy rains, and controlled drainage. According to the 2015 Flood Insurance Rate Map (FIRM) for Clewiston, the Federal Emergency Management Agency (FEMA) has designated nearly 70% of the city as a Special Flood Hazard Area (SFHA), which indicates a 1% annual chance of flooding in these areas. These known hazard areas pose a threat as just one inch of floodwaters can cause up to $25,000 in damage (FEMA, 2017). Clewiston is interested in protecting the community by reducing the overall flood risk to residents by preventing flood damage to new and existing development and lowering flood insurance rates to property owners; however, the city may not have the financial resources to accomplish all these objectives in the near term but desires to implement as many measures as possible within their current budget.

The CRS is a voluntary incentive program that offers flood insurance premium discounts to communities that take action beyond the minimum NFIP requirements to reduce flood risk in their respective communities through successful floodplain management. The CRS consists of 19 creditable activities that vary in the number of credit points awarded, organized into the 300, 400, 500, and 600 series, as shown in Table 1.

Table 1. Summary listing of series in the Community Rating System

ID	Series	Description	Points
100	Introduction	Purpose and goals of the program	0
200	Procedures	Initial application for classification	0
300	Public Information	Flood hazards, insurance, & protection	981
400	Mapping & Regulations	Limit development in the floodplain	5,841
500	Flood Damage Reduction	Flood protection for infrastructure	5,042
600	Warning & Response	Emergency management response plans	790
700	Community Classification	Credit point calculation for classification	0

The 300 series informs and advises the public about flood hazards, encourages property owners to buy flood insurance, and provides information to reduce flood damage. The 400 series details actions to increase protection to new and existing development. For example, the activities include mapping areas not shown on the FIRM, encouraging the preservation of open space, protecting natural floodplain functions, enforcing higher regulatory standards, and managing stormwater infrastructure. The 500 series credits comprehensive floodplain management with protection measures such as flood control projects, relocation or renovation of flood-prone structures, and preventative maintenance of drainage systems and natural channels. The 600 series credits flood warning and response programs that protect the community and infrastructure before, during, and after a flood event.

The CRS Coordinator’s Manual 110-1 is the Federal Emergency Management Agency (FEMA) document that establishes the details for the credit system by providing a series of activities that local jurisdictions can undertake to reduce the risk of flooding. For a community to be eligible, it must be in full compliance with the NFIP and be in the regular phase of the program. A community receives a CRS classification based upon the total credits awarded for its activities. Class 1 requires the most credit points and gives the greatest premium discount. A community that does not apply for the CRS, or does not obtain the minimum number of credit points, is a Class 10 community and receives no discount on premiums. When communities implement these activities, they can request CRS credit to accumulate enough to earn one of the 10 CRS classes, provided they meet the pre-requisites. Table 2 shows the qualifying community total points, CRS classes, and flood insurance premium discounts. However, a community cannot escape Classes 5-9 without a watershed plan. The problem is the amount of modeling and other data needed for the watershed plan and the lack of ability to identify and prioritize areas for further investigation. A screening tool is designed to help with that, but the amount of local data, cost, and the confidence in a drill-down from an aerially extensive model to a local community are barriers to utilization.

Table 2. CRS Classification Credits to Achieve Flood Insurance Premium Discounts

CRS Class	**Credits**	**In SFHA**	**Outside SFHA**
1	4500 and above	45%	10%
2	4000 – 4499	40%	10%
3	3500 – 3999	35%	10%
4	3000 – 3499	30%	10%
5	2500 – 2999	25%	10%
6	2000 – 2499	20%	10%
7	1500 – 1999	15%	5%
8	1000 – 1499	10%	5%
9	500 – 999	5%	5%
10	0 – 499	0%	0%

1.1.2 Watershed Master Planning

The Florida Division of Emergency Management (FDEM) contracted with FAU, establishing the Watershed Master Planning Initiative Program, for supporting local communities seeking to reduce flood insurance costs through flood mitigation and resiliency efforts by developing Watershed Master Plans (WMPs), which are needed for Community Rating System planning. There are several steps to address planning efforts, including developing support documents to establish community-specific applications of the CRS, a program that incentivizes actions to reduce flood damage, promote flood insurance, and improve flood management.

Watershed master planning provides a decision-making framework to inform affected communities on how they can reduce flooding on a watershed-wide basis that addresses the major driving factors of flooding in the watershed. The approach must focus on an entire watershed, a geographic area defined by a drainage basin (i.e., a hydrologic boundary), rather than an administrative boundary such as a municipality. To be effective, WMPs need to manage flood risk across an entire watershed to consider all those impacted within its hydrologic boundary and possible driving factors of flooding, instead of separate municipalities which have some geographic relationship. For example, downstream drainage systems being overwhelmed by upstream discharges may be neglected if only local models are used; the entire drainage area contributes to surface water runoff, leading to increased flooding. Developing watershed models initially informs the decision-making process to assess risk and mitigate flooding by identifying critical areas of concern. For example, identifying vulnerable land and infrastructure that may be periodically affected through floodplain mapping (e.g., delineating hazard zones shown on FEMA FIRMs) is used to cover insurance claims, implement local policies and resilience standards, and prohibit development in the floodplain. The community can then take intentional steps toward reducing and avoiding flood damage, for example, by restricting development in known hazard zones. In the context of the present study, the watershed must be characterized by gathering technical data and pertinent information into a GIS database to effectively develop a watershed's flood response model for delineating the floodplain. This informs an action plan for implementing improved management and mitigation efforts to reduce flooding by prioritizing those critical areas identified as having the highest risk in communities. FAU's current efforts address watershed master planning in the context of the Community Rating System.

1.2 Literature Review

Prior studies by Rojas (2020) and Hoque (2021) outline the need for risk assessments and scenario modeling that incorporate major contributing factors of flooding to identify critical flood-prone areas in a watershed, subwatershed, or municipality of interest for supporting the development of flood protection plans and prioritizing improved management efforts. Adequate data are required to inform an effective model framework at the appropriate scale to identify vulnerable land and infrastructure (FAU, 2020). Accuracy and resolution requirements dictate the scale of a study and, therefore, the data and methods used for delineating flood-prone areas. Gaps and insufficient resolution challenge the increasing need for data quantity and quality to downscale a model. However, modeling in GIS provides a means to improve existing datasets, solving technical data issues with downscaling unrelated to missing pertinent information (Ge et al., 2019). Teng et al. (2017) note that a simplified conceptual model capable of capturing various levels of detail is appropriate for flood risk assessments and scenario modeling. Therefore, CASCADE 2001, a macro-scale, interconnected multi-basin, GIS-based hydrologic-hydraulic routing model, was selected for this study. This data-driven model predicts the flood response of an input basin to a combination of conditions, including low land elevations, high groundwater levels, poor soil storage, heavy rains, and controlled drainage (SFWMD, 2001). One question to study is its application at different scales.

1.2.1 Existing Flood Inundation Modeling Frameworks

Large-scale hydrologic model frameworks tend to be conceptual and use limited data. While some models incorporate more variables than others, commonalities include the use of digital elevation models (DEMs), land cover and soil type, and precipitation data to account for most of the flooding. Often, GIS methods are used to extract model parameters from readily available data such as LiDAR-derived DEMs or satellite-based imagery when there is a lack of observational data in data-scarce regions. The advantage is that reasonable floodplain inundation maps and the associated results of predicted rainfall-runoff discharge, water level, and flood extent can be developed for large areas despite relatively low input data requirements and computational burden. The resulting maps typically use a binary classification of either flooded or non-flooded and are validated against FEMA FIRMs based on the 100-year flood event. However, the disadvantage of this approach is that potential flood hazards are only identified near major water bodies from overflow, leaving most of the so-called “actual flooding” undetected (Paiva et al., 2011; Jafarzadegan and Merwade, 2017; Nastiti et al., 2018).

Other studies do not suffer from inadequate data quantity and quality. For example, Son and Jeong (2019) developed a highly detailed model for a specific and known flood event in a coastal urban area. However, their small-scale study of flooding due to direct runoff from intense rainfall and poor inner drainage required immense data input, including individual buildings, roads, and local infrastructure (e.g., a river culvert and drainage pump facility). Additionally, the predicted flood response was compared to a post-disaster survey of inundation extent and height. This level of detail is not feasible for large-scale applications.

However, as FAU (2020) and Rajib et al. (2020) note, there is a gap in the literature for large-scale locally relevant flood inundation modeling frameworks. This "lack of geospecificity" stems from the limitation of current large-scale studies that map only overflow inundation from large water bodies (i.e., hazard zones of the floodplain) and not localized nuisance flooding experienced at the community level. Rajib et al. (2020) defined the degree of local relevance based on the spatial density of the stream network so that flooding could be detected along lower order streams, given a high-resolution stream network. In part, this comes down to feature engineering supported by advanced GIS methods to develop a more comprehensive framework that incorporates all major contributing factors of flooding. For example, one component frequently neglected is the influence of high groundwater levels leading to insufficient soil storage capacity, which increases the risk of flooding (Romah, 2011; Wood, 2016). Additionally, drainage infrastructure and treating watersheds as interconnected sub-basins are ignored in large-scale frameworks.

1.2.2 Challenges of Downscaling

Singh and Kumar (2017) investigated the effects of varying data scale and model complexity in watershed hydrological simulations; that is, how changes to scale or resolution are reflected in the resulting flood maps. Specifically, the resolution of input DEMs, land cover, and precipitation data were examined. The findings indicate that higher resolution datasets yield more accurate watershed characterization at the expense of greater data collection and processing needs. Accurately describing the unique characteristics of a watershed with adequate technical data and pertinent information is a necessary starting point to increase the complexity of a model. In other words, the ability of models to simulate realistic flood scenarios is dependent on the accurate description of watershed characteristics extracted from input data. However, the resources required and the difficulty of collecting adequate data when it is not readily available are challenging. It is then vital to balance data scale and model complexity (Singh and Kumar, 2017). Yang et al.'s (2014) findings show that utilizing higher resolution data (e.g., meter or sub-meter scale elevation grids to represent subtle variations in topography) to determine response to runoff does not necessarily improve the large-scale watershed model results. Although, they may produce more realistic representations of characteristics rather than approximations. Additionally, they note that using 10-meter gridded data as input achieves a rational balance that facilitates data collection with lessened processing requirements, meanwhile not compromising model accuracy.

A recent study by Zhao et al. (2021) addressed local relevance for large-scale applications. They developed a GIS-based multi-scale simulation framework and compared the predicted flood extent and water depth from a 100-year rainfall event. They applied their model at three nested levels of drill-down, including the entire drainage basin, a sub-model domain, and a municipality contained by the previous areas. A good agreement of predicted inundation extents in most areas was found by overlaying the output flood maps developed at the three scales to visualize differences, emphasizing the importance of appropriate model complexity for each scale. Perhaps a better way to define the geographic boundary for modeling is by the United States Geological Survey (USGS) map of hydrologic units, a watershed mapping classification system that considers hydrologic boundaries based on various areas of land that contribute surface water runoff to designated outlets. The USGS designates drainage areas by hydrologic unit codes (HUCs). For example, in the present study, the flood response will be predicted and compared at three levels of nested drill down, including the 8-digit HUC level (Caloosahatchee Watershed), the 12-digit HUC level (Ninemile Canal Subwatershed), and the local municipal level (City of Clewiston, Florida).

1.3 Study Area

In South Florida, groundwater and surface water are interconnected due to the shallow water table, low land elevations, and controlled drainage system. Historically, the region's drainage system was not controlled as there were no canals or structures to direct the flow of water. Today, groundwater flows from the Kissimmee River to Lake Okeechobee, where it is then controlled to flow throughout South Florida. Drainage may travel south through the constructed canal system and the Everglades; however, drainage can also be directed west through the C-43 Canal into the Caloosahatchee Watershed. Along the Caloosahatchee River, several gated spillway drainage structures alter the flow of water. The destination of drainage through this flow path is the Gulf of Mexico at San Carlos Bay (SFWMD, 2010). The South Florida Water Management District's depiction of the historic and current groundwater flow in the region is shown in Figure 1.

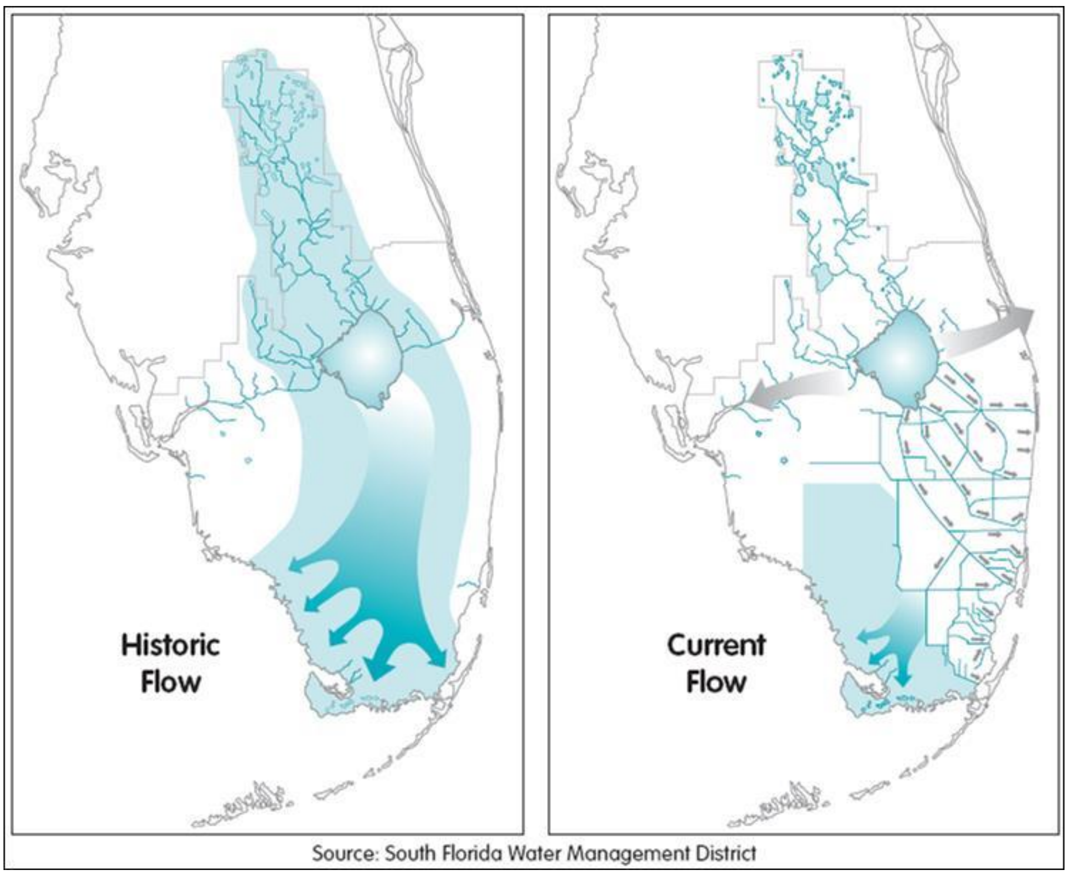


Figure 1. Change in natural flow paths in South Florida (from SFWMD)

Lake Okeechobee and the Caloosahatchee River are the major features within this watershed. Due to the drainage structures along the river, there are three subwatersheds: East Caloosahatchee, West Caloosahatchee, and Tidal Caloosahatchee. Water flows from Lake Okeechobee into East Caloosahatchee's C-43 Canal, where it is limited to a maximum stage elevation of 11.3 feet NGVD29 due to the Ortona Lock and Dam (S-78) structure. The flow continues into West Caloosahatchee, where the river is limited to a maximum stage elevation of 3.4 feet NGVD29 due to the Franklin Lock and Dam (S-79) structure. The river's water flow is restricted to these stage elevations primarily for flood control as flooding is expected to occur adjacent to the surface water features in the watershed. Special features such as open surface water bodies, drainage structures, and subwatersheds were incorporated into the flood simulation model to represent realistic flooding conditions under heavy rains (FDEP, 2005).

The study area shown in Figure 2 contains three nested levels of drill-down scale used for modeling, including the 8-digit HUC level (Caloosahatchee Watershed), the 12-digit HUC level (Ninemile Canal Subwatershed), and the local municipal level (City of Clewiston, Florida).

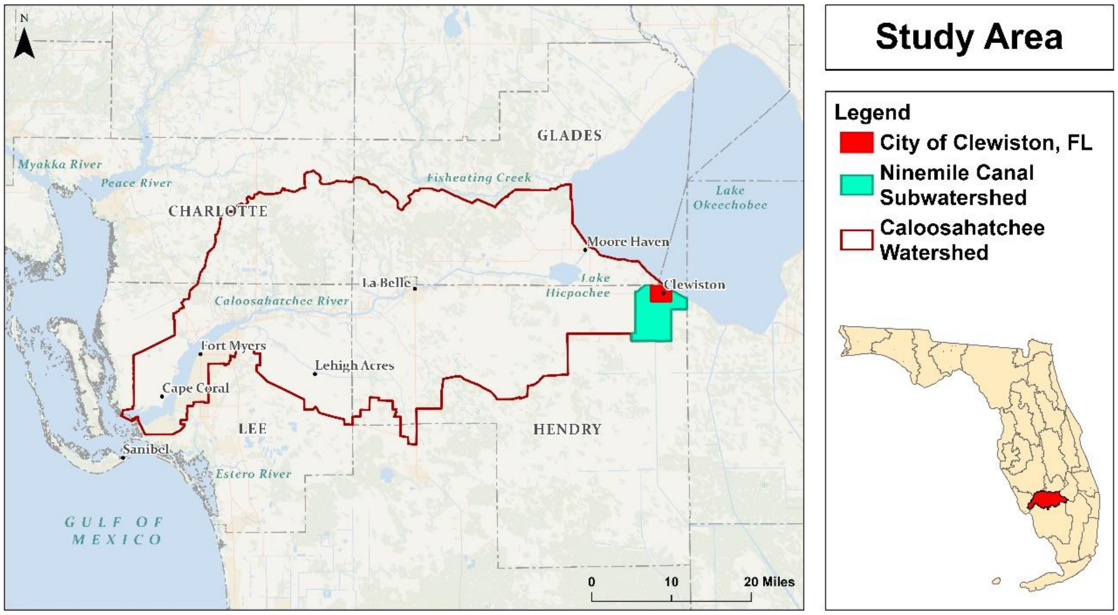


Figure 2. Study area showing the three scales used for modeling

1.3.1 Caloosahatchee Watershed

The first effort discussed focuses on the development procedures to assess flood risk in the Caloosahatchee Watershed. The 8-digit HUC Caloosahatchee Watershed defines the study area boundary and covers nearly 1,340 square miles in southwest Florida across four counties, including Charlotte, Glades, Hendry, and Lee. This region has a humid, subtropical climate with both a wet and dry season. The average temperatures range from approximately 60° F to 80° F in the winter and summer, respectively. South Florida typically experiences heavy rains in the summer and fall months, which can be further intensified during hurricane season (Webb, 1999). Additionally, wetlands, swamps, and marshes are scattered throughout the watershed, which must be considered when assessing the watershed's flood response to a rainfall event. These areas are incorporated into the study through the soils and hydrography data sets.

All data was gathered for a 10-mile extended boundary to ensure complete coverage of the study area, as shown in Figure 3. The primary surface water features of the watershed driving the flow of water from east to west are as follows: Lake Okeechobee, C-43 Canal/Caloosahatchee River, Caloosahatchee Estuary, and San Carlos Bay. The Caloosahatchee River flows approximately 75 miles from Lake Okeechobee in the east to the Gulf of Mexico in the west. Three gated spillway drainage structures control the river's flow. At its origin, the Moore Haven Lock (S-77) moves water from Lake Okeechobee into the C-43 Canal, which is an upstream segment of the river. Then, water travels downstream from the East Caloosahatchee Subwatershed into the West Caloosahatchee Subwatershed through the Ortona Lock (S-78). All upstream inland areas drain to the river, discharging into the Caloosahatchee Estuary through the Franklin Lock (S-79). It is expected that flooding will primarily occur adjacent to this river system and be localized to developed land areas in the Caloosahatchee Watershed's coastal regions and inland cities such as Clewiston, Moore Haven, and LaBelle. The extent of flooding will be determined by utilizing existing spatial and hydrologic data to follow a modeling protocol developed by FAU (2020) to simulate and analyze the watershed's flood response to a specified rainfall event. Then, the risk associated with the flooded area will be classified to identify critical target areas vulnerable to flooding.

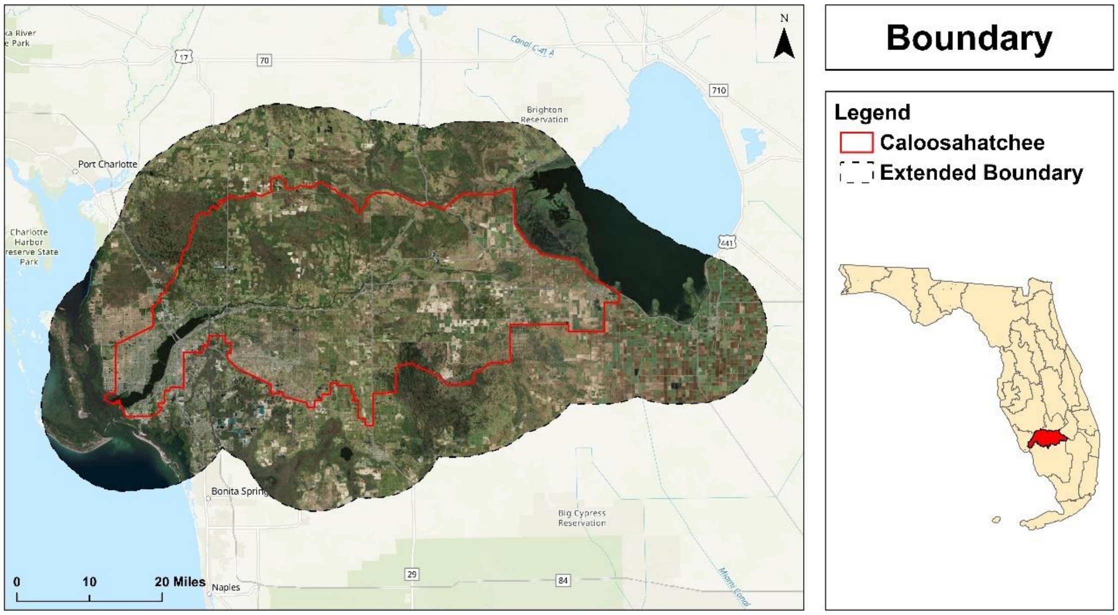


Figure 3. Location of the Caloosahatchee Watershed in Florida

The ground surface elevations in the watershed are lowest along the Caloosahatchee River, coastal region, and agricultural land between 5 feet and 15 feet NAVD88. The land elevations gradually increase north and south of the river into the inland areas of the watershed. The low elevations and subtle changes in topography may contribute to flooding as excess rainfall overflows from the river, imposing risk on nearby areas. In the coastal region of the watershed, there are a variety of sandy soils. This type of soil may improve drainage; however, impervious surfaces in the coastal cities may increase surface runoff by preventing soil infiltration. The eastern portion of the watershed has soil types found in the Florida Everglades. Sandy soils and muck compose most of the soil layer in these areas.

The demographics and housing characteristics have been compiled for each county in the Caloosahatchee Watershed from the U.S. Census Bureau’s 2018 American Community

Survey (ACS) 5-Year Estimates. A summary of the statistics is included in Table 3. In total, Charlotte, Glades, Hendry, and Lee Counties have a population of 949,123.

Property values are highest in the coastal region of the watershed around major cities such as Cape Coral and Fort Myers. Charlotte, Glades, and Hendry Counties consist of primarily agricultural land and upland forests with a few urban areas in cities such as LaBelle, Moore Haven, and Clewiston. The portion of the watershed in Lee County is primarily urban areas along the coast and Caloosahatchee River. According to the U.S. Census Bureau's 2018 American Community Survey, the median housing values in Charlotte, Glades, Hendry, and Lee Counties are $176,500, $76,400, $82,000, and $207,700, respectively.

Table 3. Demographics and Housing Characteristics

County Name Demographic	Charlotte County	Glades County	Hendry County	Lee County
Area	680.9 mi^2	806.5 mi^2	1,156 mi^2	783.9 mi^2
Population	176,954	13,363	40,127	718,679
No. of Households	76,150	4,433	12,027	271,861
Med. Household Income	$49,225	$39,879	$40,728	$54,691
Median Age	58.6	47.2	33.9	48.1
White	90.2%	79.5%	80.1%	84.8%
Black, African American	5.5%	13.9%	11.5%	8.6%
American Indian, Native	0.3%	4.0%	1.9%	0.2%
Asian	1.2%	0.4%	0.8%	1.6%
Other Race	0.7%	0.8%	2.8%	3.0%
Two or More Races	2.0%	1.4%	2.8%	1.8%
Hispanic or Latino (Regardless of Race)	7.0%	20.9%	52.9%	20.7%

The primary economic activity in Charlotte, Glades, and Hendry Counties is agriculture, while Lee County's primary business is tourism. Punta Gorda is the only incorporated municipality in Charlotte County, and Moore Haven is the only incorporated municipality in Glades County. In Hendry County, Clewiston and LaBelle are the only two incorporated municipalities. In Lee County, a metropolitan area comprises Cape Coral and Fort Myers, where tourism is centered around its sandy beaches.

Watershed restoration plans and projects in the region have been funded by the state, SFWMD, and federal government. Historical flood control projects altered the drainage pattern of South Florida to reduce flooding in nearby cities. These restoration plans seek to restore the natural state of Florida's watersheds; for example, the Comprehensive Everglades Restoration Plan (CERP) is a major effort to restore and preserve South Florida. Additionally, local counties have funded stormwater management plans and programs. Many efforts focus on protecting and restoring the natural functions of the watershed.

1.3.2 Ninemile Canal Subwatershed

On the eastern edge of the Caloosahatchee Watershed is the 12-digit HUC Caloosahatchee East/Clewiston subwatershed, also known as the Ninemile Canal subwatershed. These two terms are used interchangeably in this document. The area is primarily agricultural, except for the City of Clewiston, which is an urban area. Figure 4 shows aerial imagery of the subwatershed with the location of Clewiston labeled on the map.

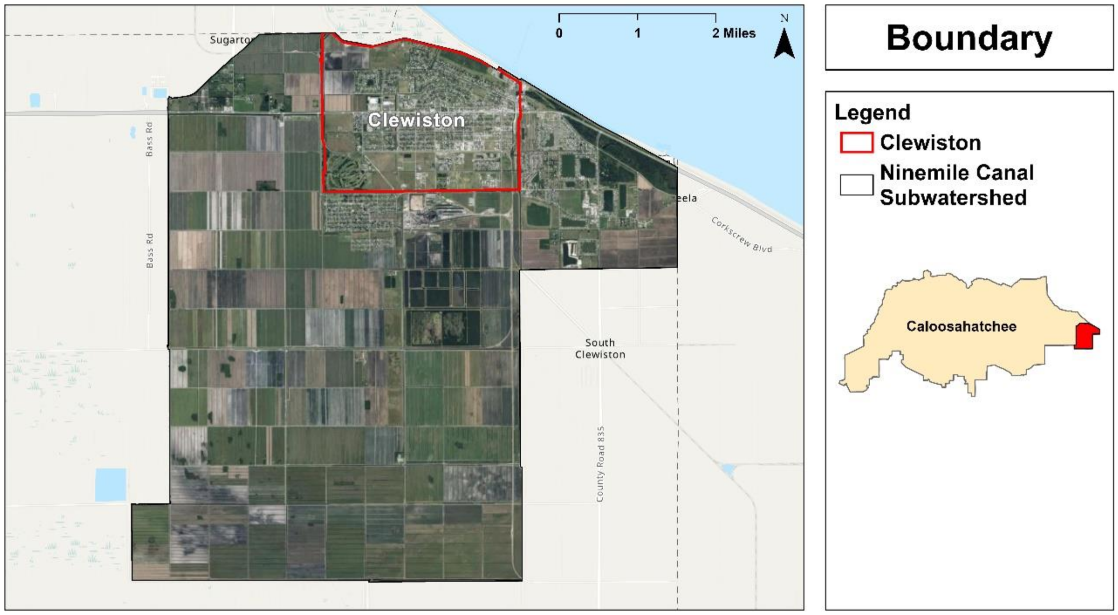


Figure 4. Location of the Ninemile Canal Subwatershed

Table 4 details the summary of land use/land cover in the Caloosahatchee East/Clewiston Subwatershed using the SFWMD-modified Level-1 FLUCCS dataset (left) and the NLCD 2016 land cover dataset adjusted to match the FLUCCS categories (right). Note that the future land use in unincorporated areas expects minimal differences from current land use, given that agricultural activity is expected to persist for the foreseeable future. Figure 5 and Figure 6 show the current land use in the subwatershed based on these classification systems.

Table 4. Comparison of FLUCCS (left) and NLCD (right) land use

Modified Level-1 FLUCCS	Area (sq mi)	Percent	Modified NLCD2016 Land Cover	Area (sq mi)	Percent	Future Area	Percent
Agriculture	24.81	72.10%	Cultivated Crops and Hay/Pasture	24.37	73.60%	19.87	57.70%
Barren Land	0.29	0.80%	Barren Land	0	0.00%	0	0.00%
Transportation, Communication and Utilities	0.54	1.60%	Transportation, Communication and Utilities	0.54	1.60%	0.54	1.60%
Upland Forests	0.06	0.20%	Upland Forests	0.02	0.10%	0.02	0.10%
Upland Non-forested	0.56	1.60%	Upland Non-forested	0.48	1.40%	0.48	1.40%
Urban and Built Up	6.81	19.80%	Developed (open space, low, medium, high density)	6.4	18.70%	10.9	31.70%
Water	0.68	2.00%	Open Water	1.1	3.10%	1.1	3.10%
Wetlands	0.67	1.90%	Wetlands	1.4	4.00%	1.4	4.00%
Total	**34.41**	**100.00%**	**Total**	**34.41**	**100.00%**	**34.41**	**100.00%**

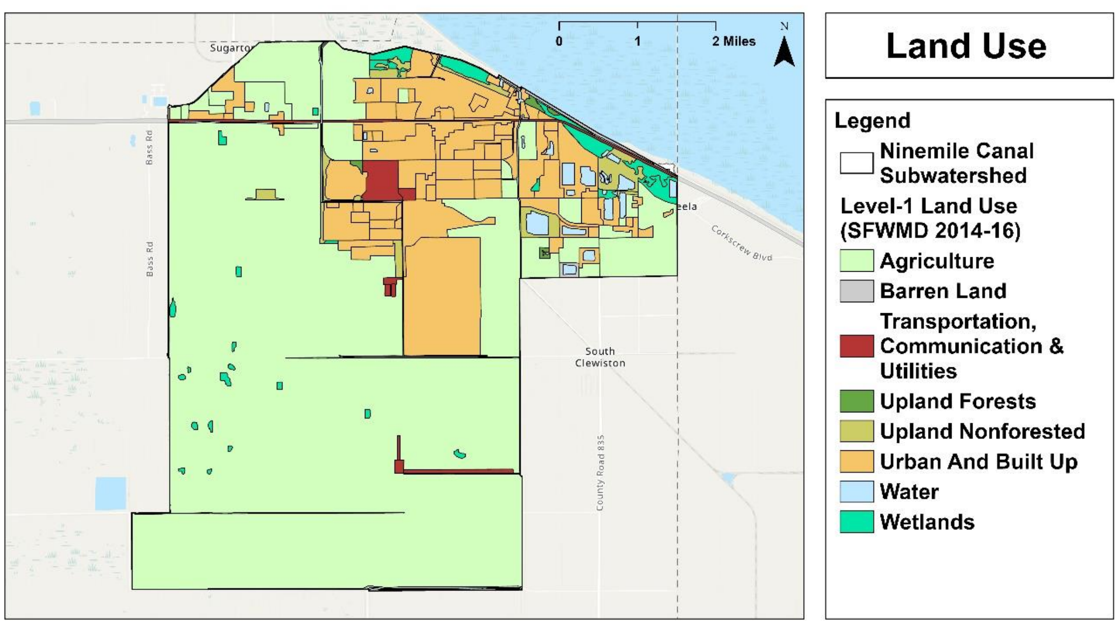


Figure 5. Modified FLUCCS (2014-16) Level-1 Land Use of the Subwatershed

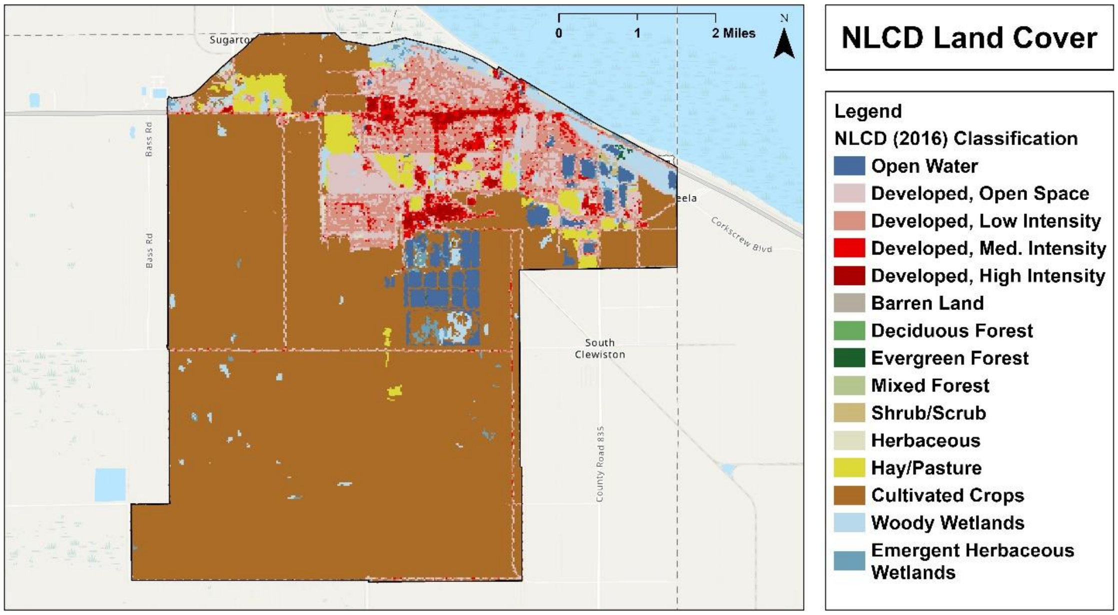


Figure 6. NLCD 2016 Land Cover of the Ninemile Canal Subwatershed

1.3.3 City of Clewiston, Florida

The only incorporated community in the Caloosahatchee East/Clewiston subwatershed is the City of Clewiston. The City of Clewiston is directly southwest of Lake Okeechobee in northeast Hendry County and has a total area of 4.51 mi^2. The City is located on the eastern edge of the 12-digit HUC Caloosahatchee East/Clewiston subwatershed. Clewiston was incorporated in 1925 and is centrally located in South Florida, about 60 miles east of Fort Myers on the Gulf of Mexico and 60 miles west of Palm Beach. The City of Clewiston is located on the eastern edge of Hendry County, south of Lake Okeechobee (see Figure 7). The community is primarily residential, with small concentrations of light industry and commercial property (e.g., shopping and offices) within the corporate limits. A small industrial sector was added in the most recent annexation, but none of the industries would be considered “intensive.” Figure 8 shows the future land use of the City. This classification is similar to the current land use (2014-2016) derived from aerial photo-interpretation depicted in Appendix B-15.

Figure 7. Location of Clewiston

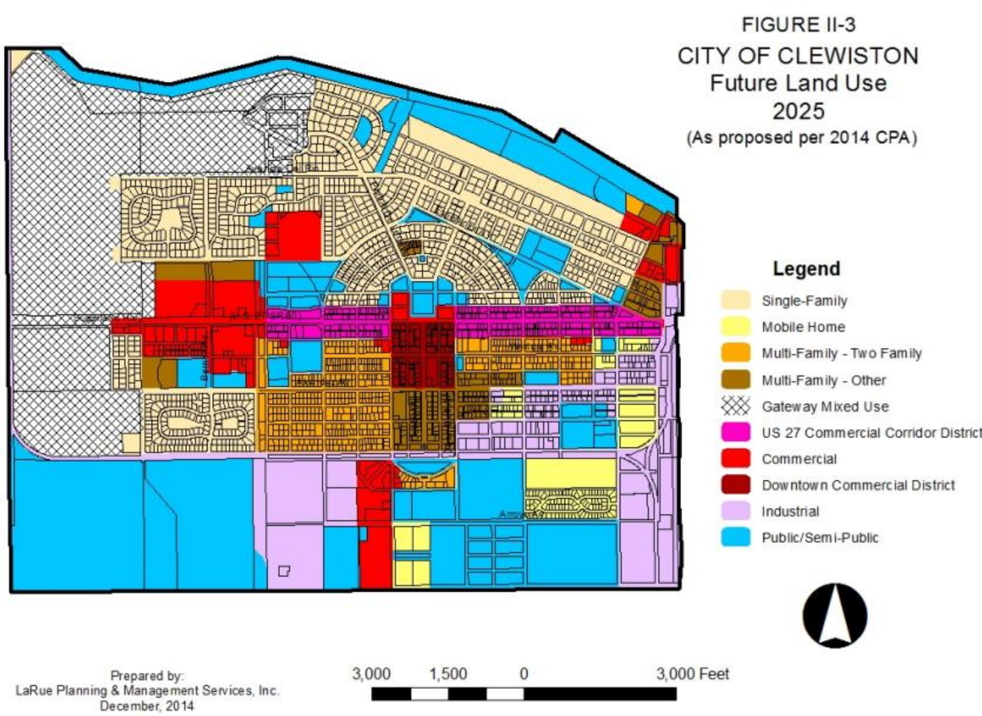


Figure 8. Future land use for the City of Clewiston

1.4 Objectives

This research adds to prior work by Romah (2011), Wood (2016), Rojas (2020), and Hoque (2021). FAU's flood inundation modeling efforts were examined to develop a large-scale locally relevant framework, that is, one capable of generating accurate floodplain inundation maps quickly while still detecting localized nuisance flooding. The CASCADE 2001 model is paired with GIS to compare the predicted flood response at three nested levels of drill-down, including the 8-digit HUC level (Caloosahatchee Watershed), the 12-digit HUC level (Ninemile Canal Subwatershed), and the local municipal level (City of Clewiston, Florida). Therefore, the objective is to evaluate the impact of scale for determining flood risk in a community.

The objective will be to evaluate the three levels of drill-down and similarity to the FEMA flood maps by comparing them to the analysis results at each scale. The goal is to determine:

- How the predicted flood extent changes with drill-down modeling
- Which infrastructure explains the differences observed at each scale
- How similar the FEMA flood maps are to the 1:100 storm event

Of interest is that as the drill-down occurs, more localized infrastructure will matter. Of interest is that data gaps at the community level, such as unavailable stormwater system models with a missing inventory of local drainage infrastructure, may disrupt accuracy. Furthermore, GIS methods are presented as possible solutions to overcome the increasing need for data quantity and quality to downscale a model.

2: METHODOLOGY

2.1 CASCADE 2001 Flood Risk Modeling

There is a need for screening analysis of flood risk in watersheds to identify areas of concern and inform mitigation and improvement strategies to reduce flood potential in affected communities. To address this need, FAU (2020) established the planning level framework conceptualized Figure 9 as a tool to develop probabilistic flood maps and assess community risk through watershed master planning, which involves defining flood risk due to compounding hydrographic influences. The concept of a watershed-wide screening tool utilizes a GIS-based approach to flood inundation modeling that combines readily available data on topography, groundwater levels, tidal and surface water levels, soil storage, land cover, stormwater infrastructure, and design storm rainfall amounts into the CASCADE 2001 flood response model. Based on these compounding geo-hydrological features, the screening tool predicts how low-lying areas may be affected by inundation in three ways: 1) from direct surface flooding, 2) from rising groundwater levels, and 3) from the inability of inland areas to drain (FAU, 2020). Therefore, this methodology aims to produce a spatiotemporally quantified understanding of nuisance-destructive flood potential in the study area given observed values. Early application of this framework in Florida's watersheds has demonstrated local relevance through drill-downs of flood maps to selected communities. Additionally, the maps are consistent with previous findings and flood experiences from prior work by FAU in South Florida (Romah, 2011).

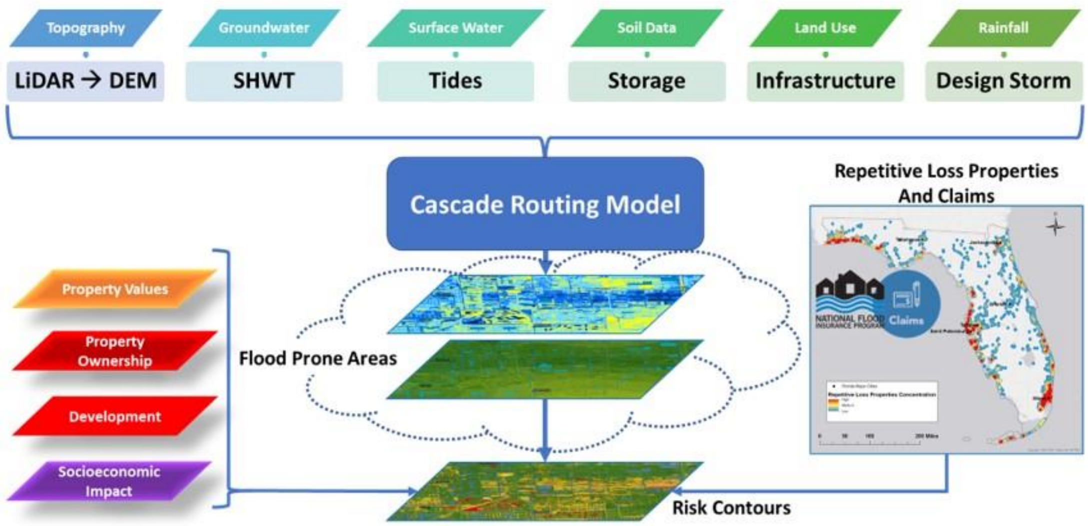


Figure 9. Screening tool framework (FAU, 2020)

CASCADE 2001 simulates the rise of floodwater levels over time, allowing for quick and deterministic identification of wet (flooded) and dry areas mapped as a GIS layer. Flood-prone areas are delineated based on Light Detection and Ranging (LiDAR)-derived elevation data as those low-lying areas below the maximum elevation of floodwaters, referred to as the predicted high headwater height. Probabilistic flood maps can increase the value of information available to decision-makers, so lands are further classified according to their inundation probability (Alfonso et al., 2016).

To determine the probability of flooding, one must consider the vertical accuracy of elevation data (i.e., the LiDAR-derived DEM) used to generate flood maps and the underlying uncertainties or errors associated with derived datasets used as CASCADE 2001 input parameters. The Root Mean Square Error (RMSE) computation incorporates these uncertainties and errors.

Then, an inundation probability surface is created by calculating Z-scores to describe the maximum headwater height's relationship to the ground elevations from the LiDAR DEM throughout the study area. The Z-score surface defines the probability of inundation under the assumption of a normal distribution for the measurement and modeling errors (Schmid et al., 2014). Thus, the value representing the combined effect of errors is equal to the SQRT ($RMSE\_LiDARDEM^2 + RMSE\_CASCADE2001Model^2$). NOAA (2010) suggests a value of 0.46 for compact coastal county vulnerability assessments. Finally, Equation 1 is executed on a cell-by-cell basis using GIS to determine the Z-score for developing flood inundation probability maps.

Equation 1. Z-score = [(High Headwater Height) − (Ground Elevation from DEM)] / SQRT ($RMSE\_LiDARDEM^2 + RMSE\_CASCADE2001Model^2$)

= (High Headwater Height – LiDAR DEM Elevation) / 0.46

Based on the calculated Z-score, probabilities of inundation are derived as equal to CDF_{normal}(Z-score). The Z-scores corresponding to the 50%, 75%, and 90% probabilities are mapped directly in GIS to generate flood risk maps. Figure 10 depicts this methodology. For example, the Z-score value for the 75th percentile is 0.675. Thus, one must be 0.675

standard deviations above the mean to be in the 75th percentile. For flood risk map development, the GIS layer legend is classified with cutoff Z-scores according to Table 5.

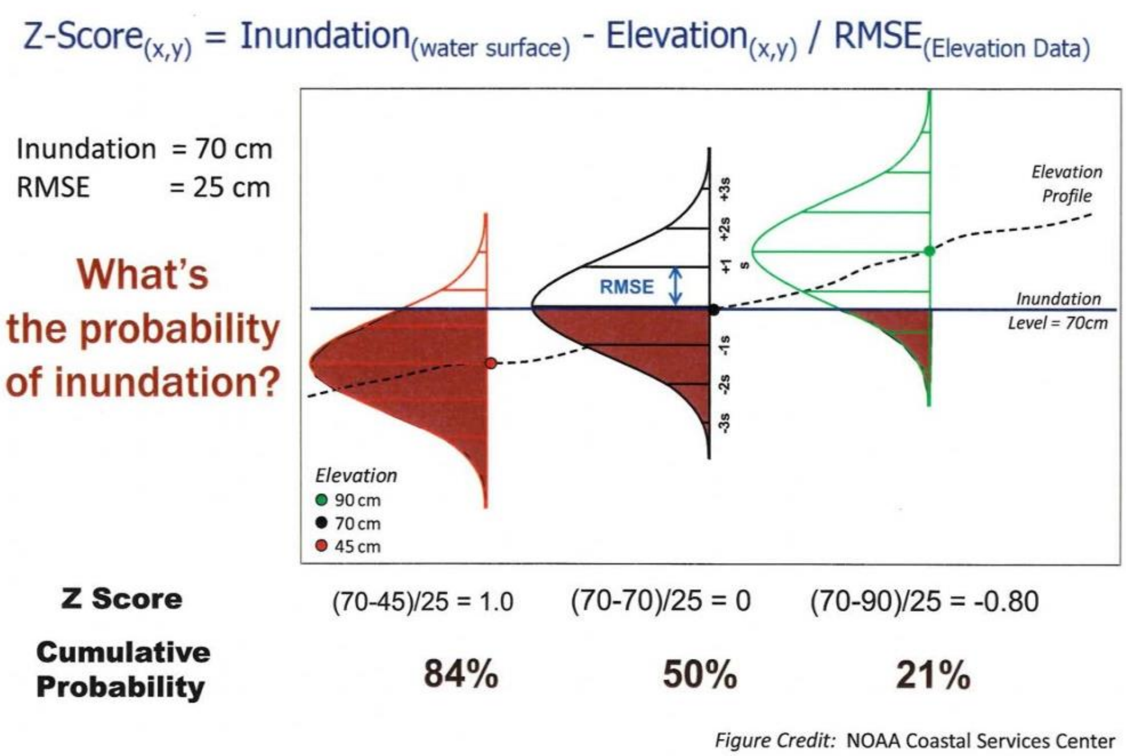


Figure 10. Calculation of flood risk Z-scores (NOAA, 2010)

Table 5. Flood risk map development from Z-scores

Risk of Flooding	Range of Z-scores	Map Color
Below 50%	< 0	
50% to 75%	0 to 0.675	
75% to 90%	0.675 to 1.282	
Above 90%	> 1.282	

The data sources used in this study are shown in Appendix A, and all are publicly available. The datasets from Appendix A, when applied through the FAU (2020) modeling protocol shown in Figure 9 and associated with the Z-scores in Table 5, provide the results used for flood risk map development. Several advanced GIS methods were utilized to address the challenges of downscaling.

2.2 GIS Methods to Support Downscaling

Romah (2011) and Wood (2016) note the importance of a groundwater-influenced model for assessing flood risk in South Florida. For example, the high groundwater levels lead to poor soil storage capacity where large portions of the soil layer are already saturated at the start of rainfall events and cannot store any additional water, resulting in an increased risk of flooding. Station-based observation data (i.e., groundwater monitoring wells, surface water stage gauges, and tidal stations) are commonly used in water table mapping studies based on geostatistical interpolation methods. The South Florida Water Management District (SFWMD)'s DBHYDRO database provides such data. The issue arises in data-scarce regions with limited and poorly distributed observations since spatial interpolators such as ordinary Kriging cannot predict beyond the extent of its known measurements or generate reliable surfaces from sparse and uneven data points. Hence, Zhang et al. (2020) evaluated multiple linear regression (MLR) as an alternative method to mapping the groundwater table from limited observations and LiDAR-derived DEM data in a region where there is a direct interaction between groundwater and surface water. The output surface, generated according to the methodology in Figure 11, was compared to the results of ordinary Kriging, as shown in Figure 12. The objective of the multiple linear regression technique is to model the relationship between closely related variables, including one dependent variable (i.e., the groundwater table elevation, WTE), and two independent variables or explanatory predictors (i.e., the surface water elevation, MWTE, and the distance between the bare land and surface water, Depth to MWTE). This is done by fitting a linear equation, Equation 2, to the dataset and then applying it on a cell-by-cell basis using GIS.

Equation 2. $\quad WTE = \alpha + \beta_1(MWTE) + \beta_2(\text{Depth to } MWTE) + \varepsilon$

where α = intercept, β_1 and β_2 = coefficients of predictors, and ε = statistical error

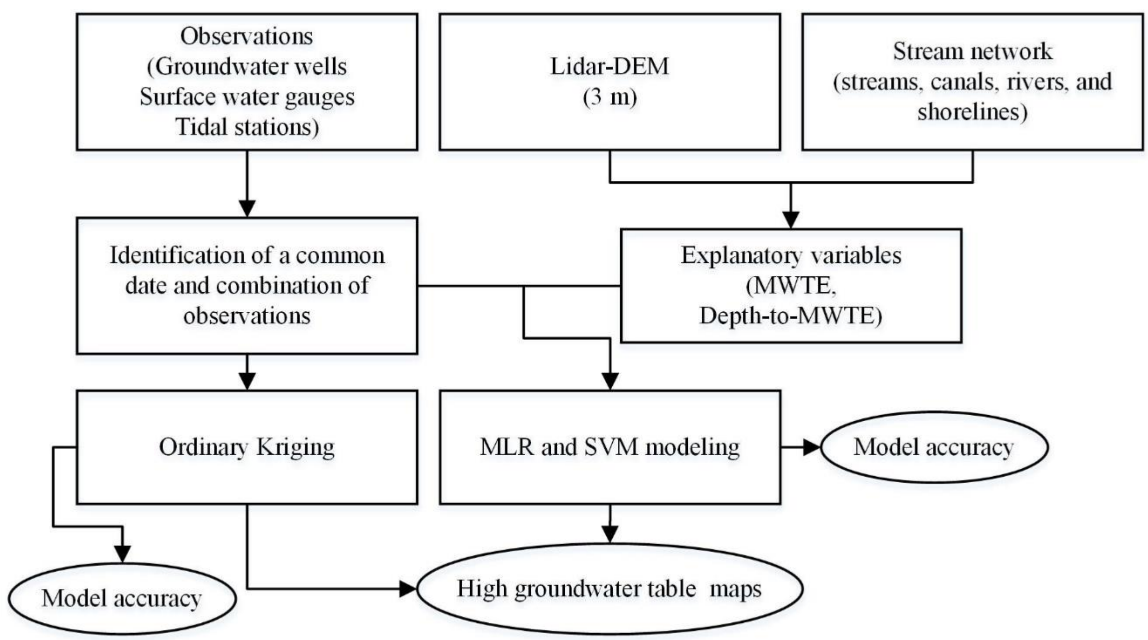


Figure 11. Ordinary Kriging and MLR flowchart (Zhang et al., 2020)

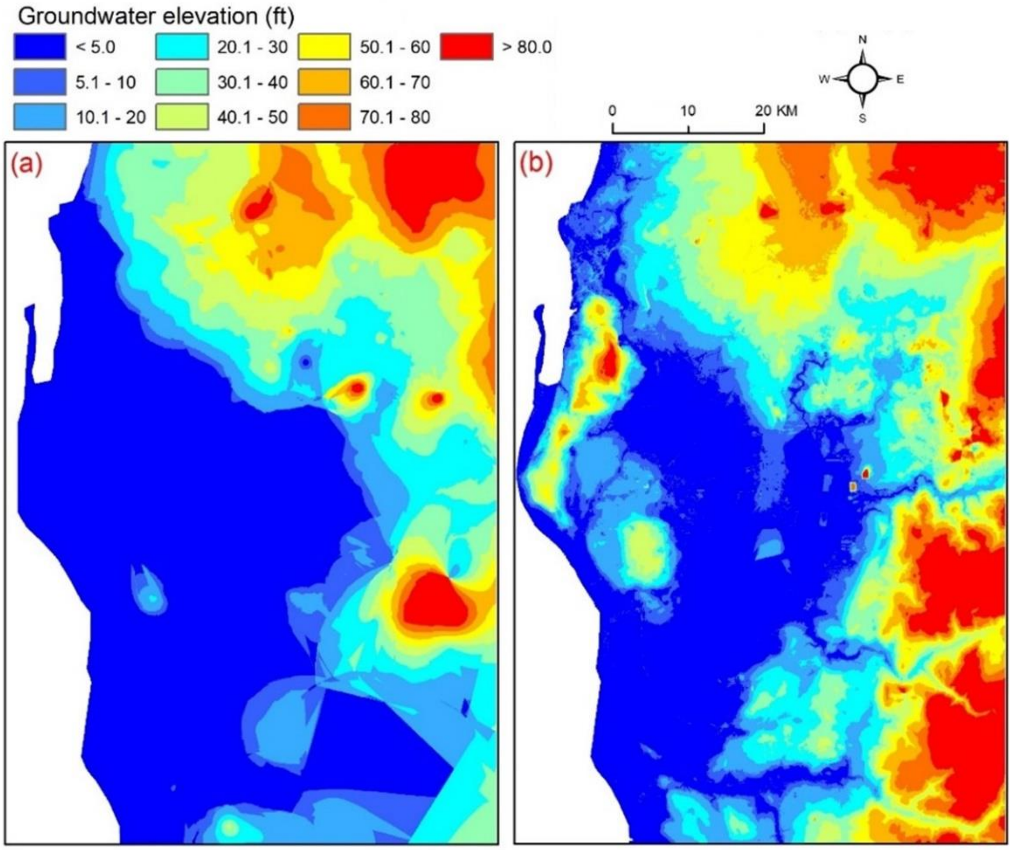


Figure 12. Comparison of (a) Kriging and (b) MLR (Zhang et al., 2020)

Incorporating land cover types into modeling frameworks is common due to their strong influence on flooding. For example, while the soil may have the capacity to store water, the land cover type will either allow or prevent soil infiltration. If impervious surfaces cover an area, the rainfall will not infiltrate the soil, causing surface runoff and increased flooding. Many large-scale studies use the readily available impervious surface layer of roads and urban areas in the National Land Cover Database (NLCD). This 30-meter resolution data product offers minimal processing and widespread coverage of the United States. However, for small-scale studies, the resolution may be too coarse and unable to represent local features (e.g., individual buildings) at the necessary level of detail.

Viswambharan (2020) presents an alternative using supervised object-based image classification of land cover type to map impervious surfaces from high-resolution spectral imagery at the neighborhood level. Figure 13 shows a flowchart of this procedure as follows: (a) 6-inch resolution color-infrared aerial photograph, (b) segmented image with training samples displayed, (c) classified image into specific land cover types, and (d) reclassified image into a binary impervious surfaces layer of 6-inch resolution.

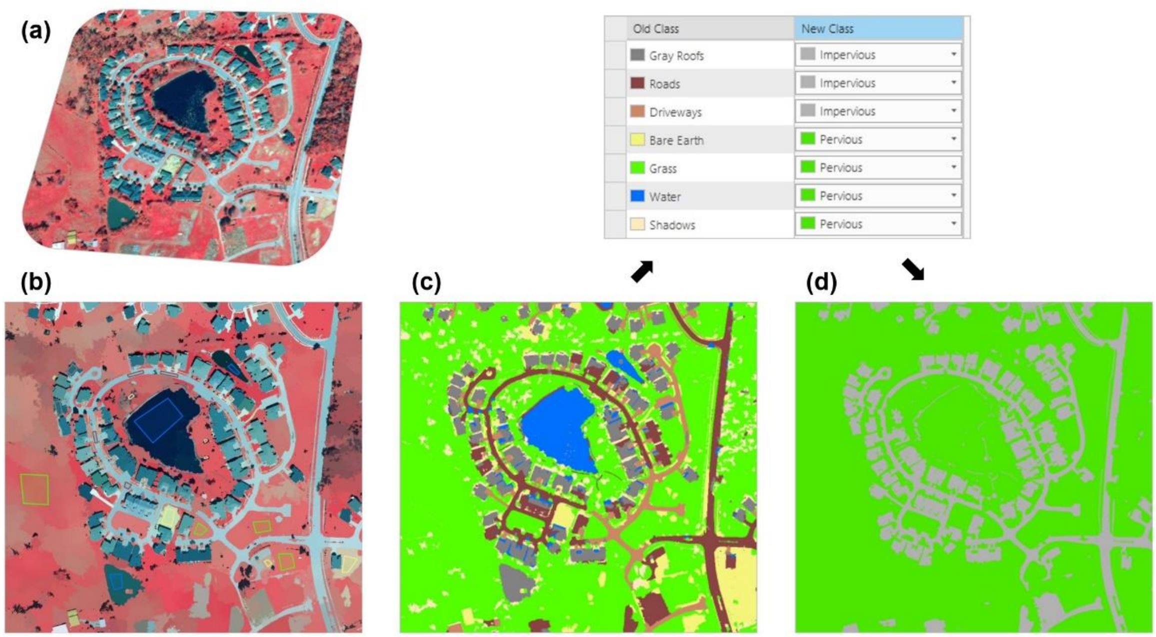


Figure 13. Flowchart of a GIS-based procedure for mapping impervious surfaces from spectral imagery at the neighborhood level (from Viswambharan, 2020)

The CASCADE 2001 flood response model supports simulations of multiple basins interconnected by drainage structures (SFWMD, 2001). This allows for a high degree of local detail relevant to where stormwater runoff is collecting and flowing toward drainage outlets. Ideally, communities would have readily available stormwater system models and an inventory of drainage infrastructure to determine the necessary input parameters. However, that is not always the case; for example, the City of Clewiston currently has no pertinent mapping information available. On the other hand, all major infrastructure of the containing watershed is easily obtained from the United States Army Corps of Engineers (USACE). For example, there are three gated spillways along the Caloosahatchee River, a clear flow path originating from Lake Okeechobee, and a designated outlet into the Gulf of Mexico, leaving no unknowns for developing a watershed model. So then, how can a representative model be constructed at the local level? The GIS-based Arc Hydro tools can delineate catchments and drainage flow paths/outlets from elevation data (i.e., a DEM) when local stormwater system models are unavailable. The physical characteristics of drainage areas based solely on surface topography are extracted through a geoprocessing workflow (ESRI, 2011).

2.3 Comparative Analysis

Three parallel analyses were conducted. The flood risk modeling efforts and comparative analysis discussed herein were evaluated visually and statistically at three nested levels of drill-down starting with the 8-digit HUC level (Caloosahatchee Watershed), the 12-digit HUC level (Ninemile Canal Subwatershed), and the local municipal level (City of Clewiston, Florida). The design storms for calculation purposes were the 3-day 25-year storm, which is the standard used by the South Florida Water Management District (SFWMD), and the 1-day 100-year storm used by FEMA and other water management districts. This statistical comparison is an objective method to measure the following quantitatively:

- How the predicted flood extent changes with drill-down modeling
- Which infrastructure explains the differences observed at each scale
- How similar the FEMA flood maps are to the 1:100 storm event

CASCADE 2001's spatiotemporal output of floodwater levels provides a prediction for the high headwater height during the applicable design storm, mapped as a GIS layer to identify the extent of flooding. Modeling was conducted separately at each scale corresponding to the three nested levels of drill-down; therefore, the spatial overlap of study areas makes it possible to determine how the predicted flood extent changes with drill-down modeling. Clewiston is the overlapping study area that is common to all three model scales. Hence, the output from CASCADE 2001 and the flooded area calculations in Clewiston are compared using GIS to evaluate these changes. Additionally, the input parameters at each level of modeling are tabulated to determine how the scale of data and drill-down modeling efforts affected the resulting flood risk maps. For example, the regional or local infrastructure used to construct a model may explain the differences observed at each scale.

FEMA's 100-year floodplain delineations are often used as reference maps in studies to validate predicted flood extents from a model (Afshari et al., 2018). However, it is important to note that the FEMA maps are not observed inundation extents, and it is unclear which data and methods are used in FEMA's map development (Jafarzadegan and

Merwade, 2017). Therefore, an objective is to determine how similar the FEMA flood maps are to a storm event that can be readily modeled, allowing for validation of the model and justification for simulating other storm events or flood scenarios. Rojas (2020) and Hoque (2021) conducted a visual comparison of flood maps derived from a CASCADE 2001 simulation of the 1:100 storm event to the FEMA reference maps and compared the percentage of flooded areas. However, this does not consider measures of spatial agreement. For example, it is possible that these maps predict inundation in different areas of the watershed while still having approximately equal values for the percentage of flooded areas. To address this need, the comparative analysis in this study utilizes the Jaccard index (also referred to as the Jaccard similarity coefficient) as a spatial similarity measure between the predicted flood extent from CASCADE 2001 modeling and the existing FEMA maps based on the 1-percent annual chance flood (100-year event).

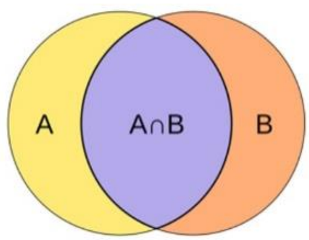
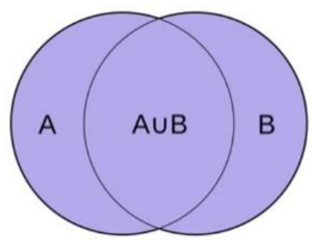
The Jaccard index is a well-established metric and has been used to evaluate the similarity between two flood maps, typically using a model prediction and validation dataset based on the binary classification of wet (flooded) and dry land (Giustarini et al., 2015; Muhadi et al., 2020). Given the two flood maps in a GIS raster data format, the Jaccard index quantifies how strong the spatial overlap, or similarity, is between their flooded areas based on a value in the range from zero (0 = no overlap) to one (1 = identical). It is calculated according to Equation 3 as the intersection divided by the union of the two flood maps.

Equation 3. Jaccard Similarity Index = $|A \cap B| / |A \cup B|$

where A = predicted flooding from the CASCADE 2001 model, and B = floodplain delineations from the FEMA flood maps

Based on this equation, GIS is used to calculate the number of cells common to both flood maps and the total number of cells in either flood map to determine the Jaccard similarity coefficient (Muhadi et al., 2020). This GIS calculation between two raster datasets is performed by first evaluating the Map Algebra (MA) expressions for a “Boolean And” operation (intersection) and a “Boolean Or” operation (union), shown in Table 6.

Table 6. Intersection and Union Operations

Operation	INTERSECTION	UNION
MA Expression	"RASTER A" & "RASTER B"	"RASTER A" | "RASTER B"
Diagram		

Then, the count of cells with a value equal to 1 (True) in the output raster datasets is used to calculate the Jaccard similarity coefficient as INTERSECTION divided by UNION. The result will indicate how close, or similar, the FEMA flood maps are to the 1:100 storm event that can be readily modeled in CASCADE 2001. This procedure is executed for each of the three levels of drill-down.

3: RESULTS AND DISCUSSION

The full Caloosahatchee results will be discussed in the following pages. The parallel processed data for the Caloosahatchee East/Clewiston subwatershed and the City of Clewiston are presented in Appendix B.

3.1 Topography

In a flood risk assessment, the ground surface elevation is an important consideration as low-lying land areas are often highly vulnerable to flooding. FAU gathered elevation datasets with a high spatial and vertical resolution to ensure the integrity of all final flood risk maps, which will inform decision-making efforts for successful watershed management planning. The elevation datasets used in this study were obtained from the U.S. Geological Survey (USGS) 3D Elevation Program (3DEP) available through The National Map Viewer. Specifically, the LiDAR-derived DEM products used have a horizontal resolution of three meters and a vertical accuracy between 22 centimeters and 30 centimeters. This dataset covers all coastal regions and areas near Lake Okeechobee. However, a data gap existing in the inland portion of the watershed was filled using LiDAR DEM products with a horizontal resolution of 10 meters and a vertical accuracy of approximately 1.16 meters. Further processing of the data involved mosaicking into a seamless ground elevation surface, projecting into the NAD 1983 UTM Zone 17N coordinate system, and converting vertical units from meters to feet in the North American Vertical Datum of 1988 (NAVD 88). The resulting bare-earth surface elevation of the Caloosahatchee Watershed is shown on the map in Figure 14.

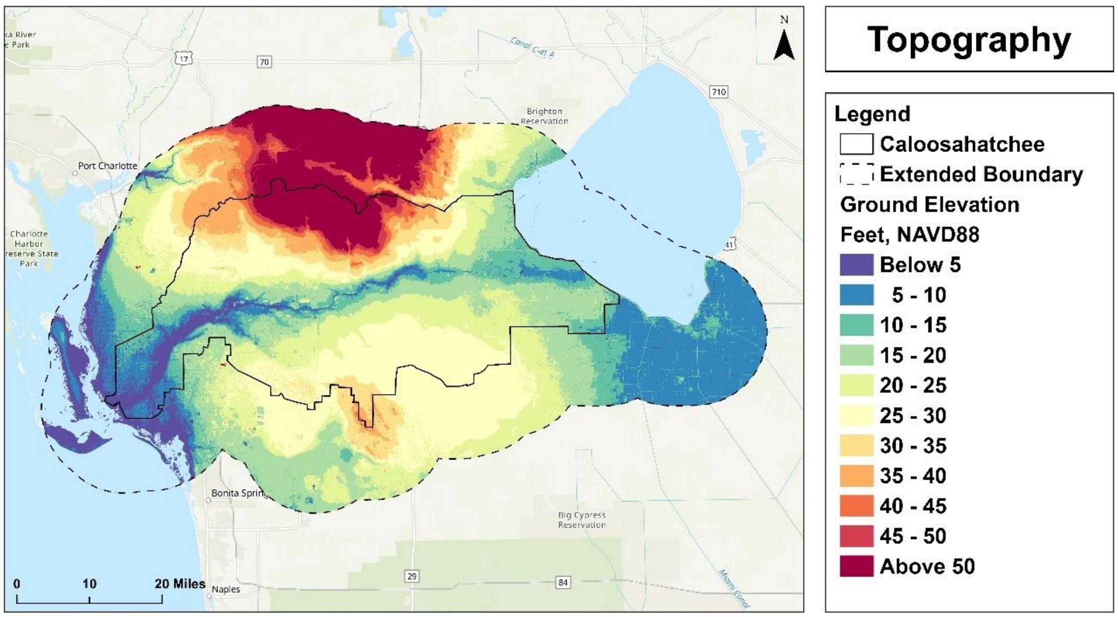


Figure 14. Ground Elevation in the Caloosahatchee Watershed

3.2 Groundwater

The high groundwater table commonly associated with this region of Florida contributes to flooding as large portions of the soil layer are typically saturated at the start of rainfall events and cannot store any additional water, which would relieve flooding in many areas. Accurately mapping the groundwater table is possible through spatial interpolation and extrapolation techniques that utilize observed groundwater levels at monitoring stations to generate an elevation surface. Mapping the groundwater table is a critical effort that requires station-based observation data for groundwater, surface water, and tides observed in the 99th percentile on a common date without any influence from major storm events. The South Florida Water Management District's DBHYDRO environmental database was used to gather daily maximum groundwater levels on September 27th, 2013, in the Caloosahatchee Watershed. These data include the identification, coordinates, and observed elevation of each station in a comma-separated values (CSV) file, which is then imported into a GIS application. Any elevations recorded in reference to the National Geodetic Vertical Datum of 1929 or Mean Higher High Water (MHHW) should be converted to reference the North American Vertical Datum of 1988 before importing the dataset. The vertical datum transformation can be competed using NOAA's VDatum software tool. The available monitoring stations were further processed to keep only those groundwater wells in the surficial aquifer system, which are interconnected with the surface water and will influence flooding in the region. The remaining 16 groundwater monitoring stations, shown on the map in Figure 15, were used to extrapolate groundwater levels across the entire watershed spatially.

3.3 Surface Water

In this region of Florida, there is a direct interaction between groundwater and surface water. In addition to low land elevations and topographic relief, the groundwater and surface water are controlled by canals, rivers, and tides. Since there are limited groundwater monitoring stations, the strong relationship between groundwater and surface water was leveraged to map groundwater table elevation accurately. All daily mean surface water level observations on September 27th, 2013, were gathered from monitoring stations in the DBHYDRO database and processed according to the previous discussion for groundwater monitoring stations. Many stations are located along canals and rivers, which assists in determining the water levels across open and connected surface water bodies. As shown on the map in Figure 15, there are 79 station observations available on this date. Additionally, water levels recorded by NOAA's nearest tidal station, 8725520 Fort Myers, FL, located in the Caloosahatchee Estuary, were used to determine the elevation of high tides.

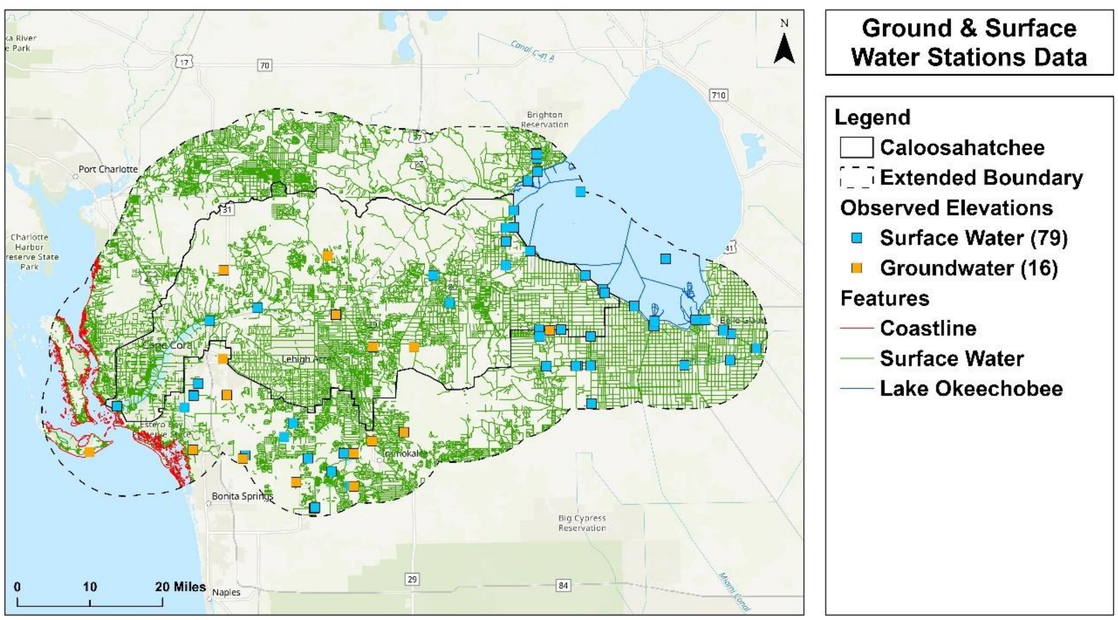


Figure 15. Groundwater and Surface Water Monitoring Stations

While low land elevations and high groundwater table elevations influence flooding, the soil storage capacity will also greatly influence the watershed's vulnerability to flooding. Open surface water bodies and frequently inundated lands will not store additional water during a rainfall event. Hence, when mapping the soil storage capacity across the watershed, these areas were set to zero storage capacity as these areas cannot store additional water. As shown in Figure 16, these areas are available from statewide land use/land cover datasets and the USGS National Hydrography Dataset (NHD). Flooding is likely to occur near open surface water bodies and areas such as wetlands, swamps, and marshes that are frequently inundated. These areas are converted to a raster data format using a 10-meter cell size to facilitate GIS calculations. Additionally, overlaying these water features onto the flood risk maps helps identify isolated and disconnected water bodies, wetlands, and frequently inundated lands that are missed and do not get captured by the model.

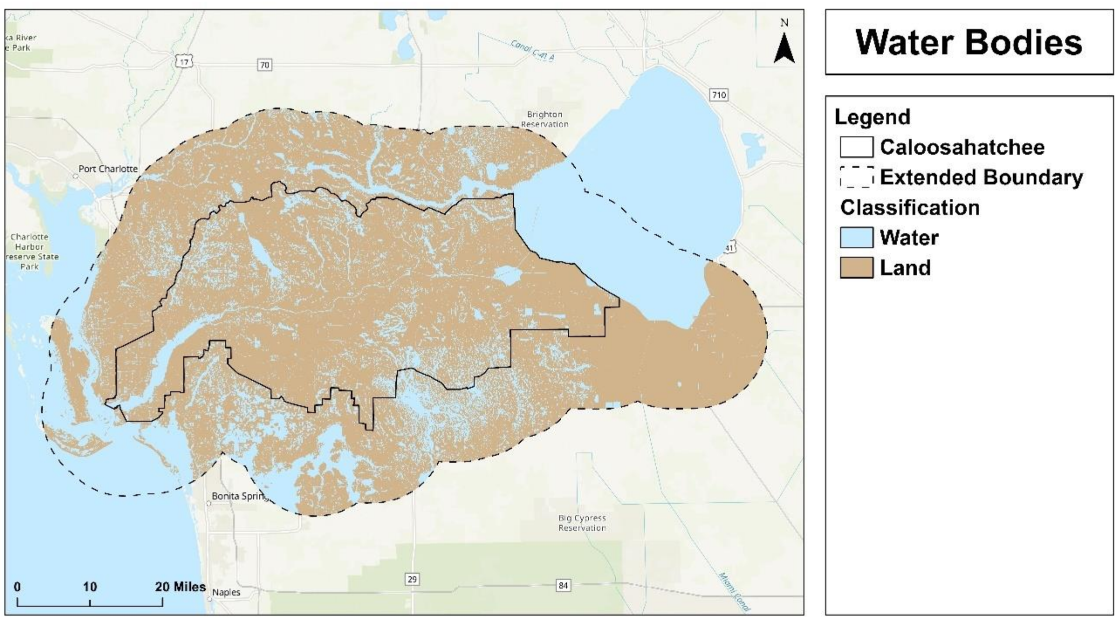


Figure 16. Existing Surface Water Bodies in the Caloosahatchee Watershed

3.4 Land Cover

Another consideration in calculating the soil storage capacity is the land areas covered by impervious surfaces. While the soil may have the capacity to store water, the land cover type will either allow or prevent soil infiltration. An assumption is made that if impervious surfaces cover an area, the rainfall will not infiltrate the soil, causing surface runoff and increased flooding. Only those areas classified as pervious land will minimize surface runoff, promoting soil infiltration and storage in the unsaturated zone. Therefore, incorporating impervious surfaces into the calculation of soil storage capacity is important. The National Land Cover Database (NLCD) 2016 includes a 30-meter impervious layer available in a GIS raster data format that classifies land as either pervious or impervious based on land cover type, as shown on the map in Figure 17. Then, impervious surfaces were assigned a value of zero to designate all impervious areas as having no soil storage capacity since rainfall will simply runoff along the surface without any soil infiltration, preventing storage in the unsaturated zone.

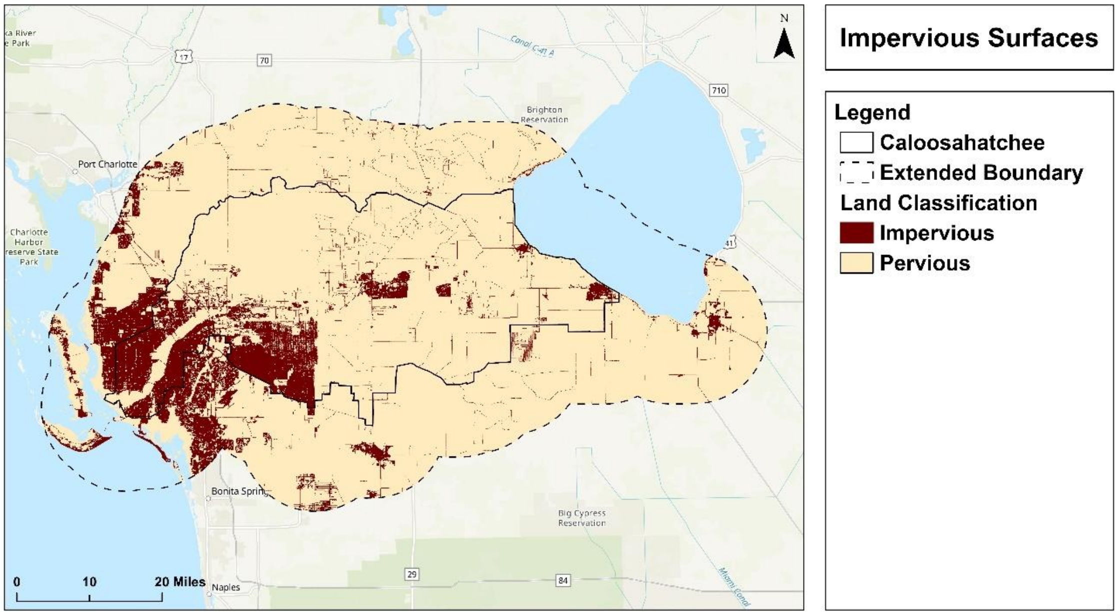


Figure 17. Impervious Land Classification in the Caloosahatchee Watershed

3.5 Soil Capacity

After determining which land will have the capacity to store excess rainfall in the soil layer, it is necessary to quantify the unsaturated zone's aptitude for storing water based on the type of soils present within the watershed. Since certain soils can store water, given an adequate distance between the land surface and groundwater, it is necessary to determine the relationship between the soils' characteristics and their capacity to store water. Soil data are available from the United States Department of Agriculture (USDA) in the gridded SSURGO (gSSURGO) dataset, which provides statewide coverage of soil data in a GIS raster data format at a 10-meter spatial resolution. Through further processing of the gSSURGO dataset, described in the following steps, a statewide soil water holding capacity (ratio) surface can be created.

The GIS dataset stores an attribute representing the available water storage (AWS), or the portion of the water holding capacity that is available for plants to absorb, derived based on the soil layer between 0-150 centimeters in depth. According to the Plant and Soil Sciences eLibrary of the University of Nebraska-Lincoln, the AWS is the water content after the soil has been saturated and then drained freely and the plants have extracted the maximum amount of water possible (i.e., the quantity of water held between field capacity and wilting point). Water holding capacity refers to the ability of a soil to hold water and is quantified as the amount of water held in the soil at field capacity. Generally, the available water storage is 50 percent of the water holding capacity (UNL, 1999). Therefore, the water holding capacity (ratio) is calculated by Equation 4.

Equation 4. $$\text{Water holding capacity} = 2 \times (\text{AWS for a soil layer of 0-150 cm}) / 150 \text{ cm}$$

By applying this equation on a cell-by-cell basis in GIS, a water holding capacity (ratio) surface was generated for the Caloosahatchee Watershed, as shown in Figure 18. It is used to calculate the total amount of water that can be stored in the soil layer during a rainfall event to account for poor ground storage conditions, which greatly contribute to flooding in the watershed.

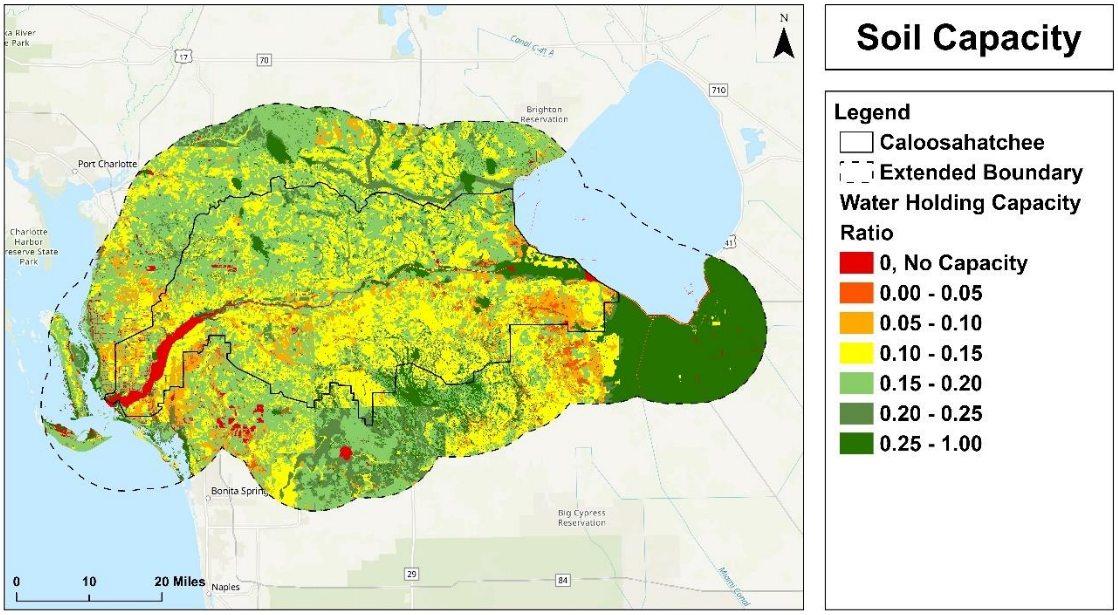


Figure 18. Soil Water Holding Capacity in the Caloosahatchee Watershed

3.6 Rainfall

Several datasets are needed to represent the unique characteristics of the watershed. By incorporating these characteristics into a flood simulation model, it is possible to determine the extent of flooding. For example, the Caloosahatchee Watershed has low land elevations, a high groundwater table, and poor soil storage, which all contribute to flooding. The goal of using a simulation model is to study the watershed's response to flooding under a specified rainfall event. The selected design storm event for this flood simulation is based on the 3-day 25-year storm event. This standard design storm characterizes a frequently occurring rainfall event that will yield results representing a realistic flooding scenario (SFWMD, 2010). The 3-day 25-year rainfall map based on the NOAA Atlas 14 dataset (approximately 883-meter resolution) is shown in Figure 19. The 1:10 and 1:100 year storms were also modeled for the watershed, subwatershed, and City of Clewiston.

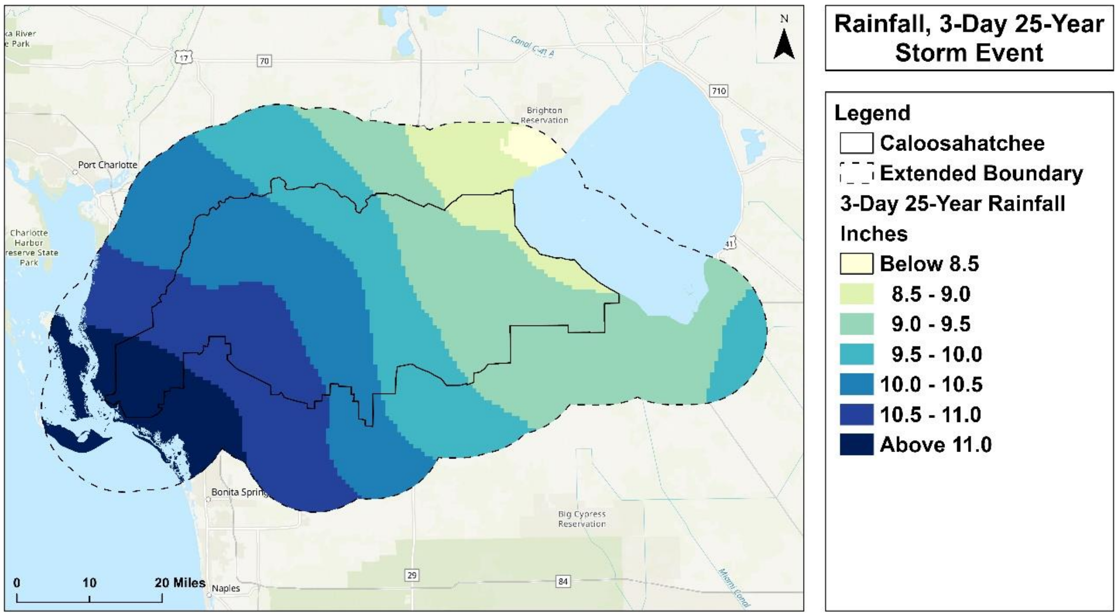


Figure 19. Rainfall During a 3-Day 25-Year Storm Event

3.7 Data Processing

There are many contributing factors to flooding in the Caloosahatchee Watershed, including the low land elevations, high groundwater table, and low soil storage capacity. To accurately identify land areas within the watershed that are vulnerable to flooding, all these factors were included in the flood risk model. The previously discussed datasets were used to calculate input parameters needed to run a flood simulation in the CASCADE 2001 model, which the South Florida Water Management District developed. The advantage of this model is that it incorporates several characteristics unique to each watershed, including the topography, groundwater, surface water, tides, soil type, land cover, and rainfall. Following FAU's modeling protocol for the Caloosahatchee Watershed, all the necessary input parameters to run CASCADE 2001 were either directly calculated or derived from existing datasets. Several surfaces were derived from the data and used to determine the watershed characteristics, which represent the primary contributing factors to flooding. While a contributing factor such as the land elevation in the watershed can be directly observed using data collection methods such as LiDAR, other factors require further data processing and modeling.

3.7.1 Groundwater Table

For example, determining water table elevations throughout the watershed requires spatial interpolation and extrapolation methods, and modeling. Since the high groundwater table greatly contributes to flooding in the region, it is necessary to expend the additional effort to incorporate this factor into the model. Furthermore, a model that utilizes the average of the observable extremes of groundwater/surface water elevations increases the value of information for long-term flood resilience planning. Through a previous survey with local officials, the number of days of continuous nuisance flooding that the public will tolerate before that flooding is considered destructive is about four days. Given 365 days in a year, this means that roughly 1% of the highest values among the fluctuating water inputs represent the days/times of year that a given area is at most considerable risk of experiencing a destructive-nuisance flooding event. An acceptable Level of Service (LOS) for the community must be defined to identify priority areas. A LOS would indicate how often it is acceptable for flooding to occur in a neighborhood on an annual basis. A discussion with Miami Beach officials indicated that 3 or 4 days of complaints per year from residents was tolerable, but no more (E Sciences, 2014). This corresponds to the top 1%, or 99th percentile, of observed groundwater elevation values.

Mapping the groundwater table is a critical effort that requires station-based observation data for groundwater, surface water, and tides observed in the 99th percentile on a common date without any influence from major storm events. Observed water levels are only available at single locations, groundwater wells and surface water stations. The South Florida Water Management District's DBHYDRO database was used to access their station observation data. The groundwater wells are sparsely distributed, while surface water stations are distributed throughout the watershed along canals and in Lake Okeechobee. Additionally, NOAA's Fort Myers tidal station was used to determine the elevation of tides along the coastline. All ground and surface water stations actively observing water levels are shown on the map in Figure 15. The Caloosahatchee Watershed is characterized by a direct interaction between groundwater and surface water with a tidal connection to the Gulf of Mexico. There are 16 groundwater wells in the surficial aquifer recording daily maximum elevations and 79 surface water stations recording daily mean stage elevations. Additionally, the nearest NOAA tidal station (8725520 Fort Myers, FL) located in the Caloosahatchee Estuary was used to determine the high tide elevation. The common date selected at the 99th percentile was September 27th, 2013.

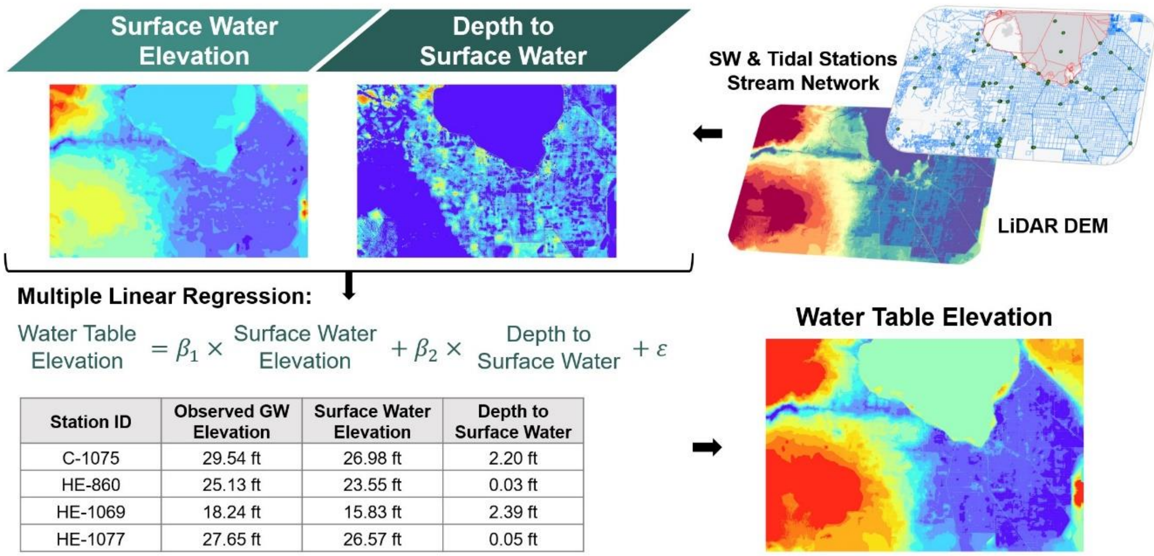
Geostatistical interpolation methods such as ordinary Kriging cannot predict beyond the extent of its known measurements or generate reliable surfaces from sparse and uneven data points. Given the limited and poorly distributed observations of groundwater levels in the Caloosahatchee Watershed, particularly for inland areas, a multiple linear regression (MLR) model was developed to calculate the water table elevations in the watershed. This requires several steps to complete.

First, in an intermediate step, a spatial interpolation method called Empirical Bayesian Kriging was used to estimate the water levels between surface water stations, which have a greater number and spatial distribution of observations than groundwater wells. The resulting elevation prediction surface is referred to as the local minimum water table (MINWTE) in literature. Only surface water elevations were used in this interpolation; consequently, the result underestimates the actual water table elevation in areas with no surface water features and must be adjusted to compensate for higher groundwater elevations. Second, the depths from the land elevations to the local minimum water table elevations were calculated. In the multiple linear regression model, the two surfaces, MINWTE and depth-to-MINWTE, represent independent variables, or predictors. The dependent variable, which is predicted, is the actual water table elevation representing both groundwater and surface water. At each of the groundwater wells, the observed water table elevation, predicted MINWTE elevation, and depth-to-MINWTE were determined and used in the multiple linear regression model as input, as shown in Table 7.

Table 7. Multiple Linear Regression Model Input

Station ID	Groundwater Well Observed Elevation (ft)	MINWTE (ft)	Depth-to-MINWTE (ft)
C-1075	29.4	27.1	2.1
C-462	33.3	32.8	0.0
C-492	16.8	16.3	1.0
C-687	23.9	20.4	1.3
C-981	19.5	18.7	1.3
CH323	29.1	26.1	0.0
GL-328	38.1	37.8	0.4
HE-1069	16.3	16.2	2.0
HE-1077	28.0	26.6	0.0
HE-558	15.2	15.2	3.5
HE-851	28.3	28.3	0.3
L-1403	2.4	0.8	1.9
L-1995	23.5	20.9	3.3
L-5667	17.2	15.4	0.4
L-5844	4.5	1.7	4.3
L-728R	20.3	19.4	2.7

Minitab Statistical Software was used to calculate the final regression equation for the water table as WTE = (0.9748 × MINWTE) + (0.0363 × Depth to MINWTE) + 1.8391. Then, this resulting equation was applied to the entire study area to predict the actual water table elevation at every location within its boundaries. In this region of Florida, groundwater, surface water, and tides are closely related and influence one another. Their direct interaction is attributed to the high groundwater table and low land elevations. For this reason, both ground and surface water were incorporated into the calculation of the water table elevation by using the multiple linear regression model illustrated in Figure 20. The predicted water table elevation, shown on the map in Figure 21, shares a similar spatial pattern with the land elevation in the DEM; however, the water table sits a few feet below the land surface. This is attributed to the fact that groundwater typically follows topography, and the water table is shallow in this region of Florida.



Station ID	Observed GW Elevation	Surface Water Elevation	Depth to Surface Water
C-1075	29.54 ft	26.98 ft	2.20 ft
HE-860	25.13 ft	23.55 ft	0.03 ft
HE-1069	18.24 ft	15.83 ft	2.39 ft
HE-1077	27.65 ft	26.57 ft	0.05 ft

Figure 20. Flowchart of Using the Multiple Linear Regression Technique to Map the Groundwater Table

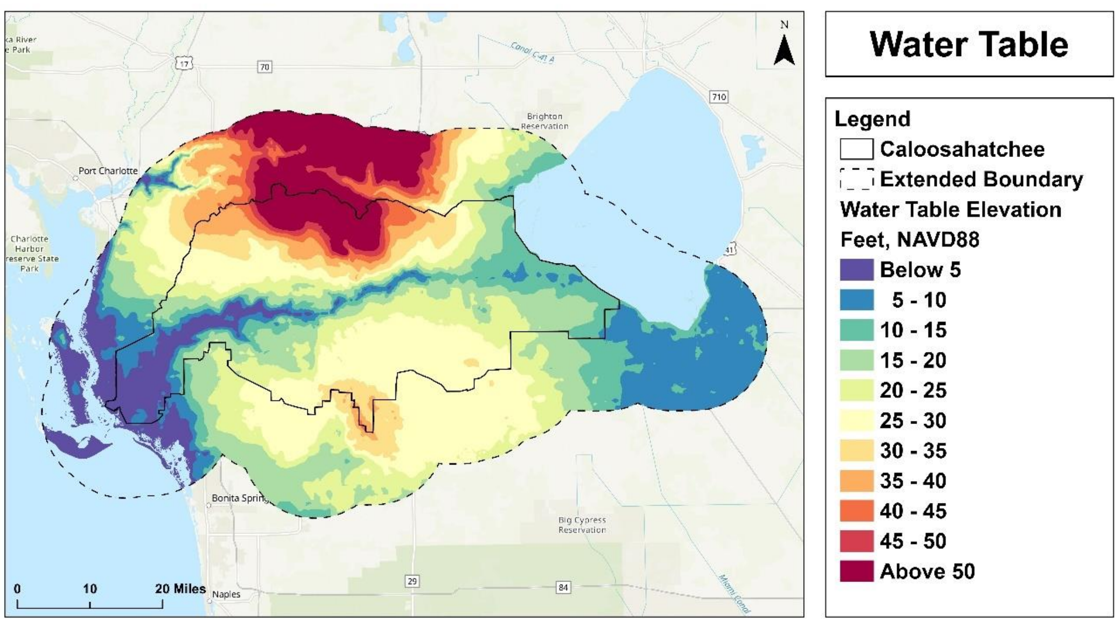


Figure 21. Groundwater Table Elevation Generated Using MLR

3.7.2 Unsaturated Zone

After modeling the groundwater table elevation surface, it is possible to determine the amount of water that can be stored in the soil, or soil storage capacity, which impacts flooding. Given that there is an adequate distance between the bare surface of the earth and the groundwater table, certain types of soil can store quantities of water in the soil layer. The objective is to calculate that distance and, therefore, the soil layer's depth known as the unsaturated zone. The unsaturated zone depth shown in Figure 22 is calculated by subtracting the MLR-generated groundwater table elevation surface from the LiDAR-derived DEM land elevation on a cell-by-cell basis using GIS according to Equation 5.

Equation 5. Unsaturated zone depth = Land Surface Elevation – Groundwater Table

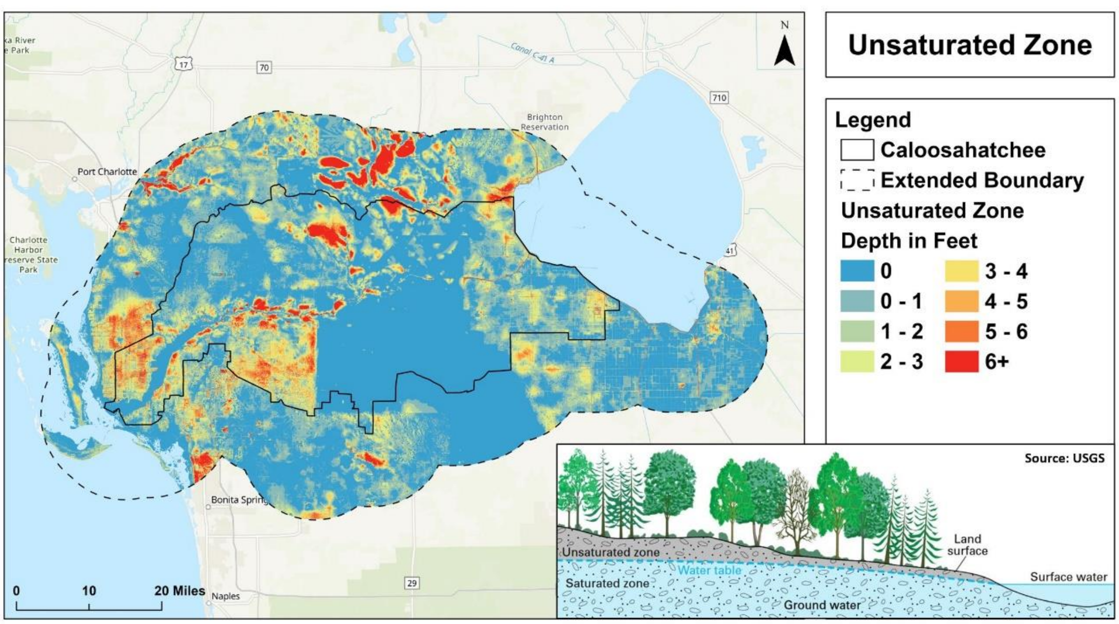


Figure 22. Unsaturated Zone Depth in the Caloosahatchee Watershed

3.7.3 Impervious Surfaces

Impervious areas do not permit the infiltration of rainfall to groundwater, and because the water cannot infiltrate, it runs off faster. Faster runoff means that flows to waterbodies and storm sewers occur faster and with higher peaks. The result is a disruption of the natural and potentially the planned hydrology. Impervious areas include pavement, buildings, and other areas that reduce runoff capacity. In other words, developed areas have much higher imperviousness than open spaces that are natural or agricultural.

For example, consider the land areas covered by impervious surfaces. While the soil may have the capacity to store water, the land cover type will either allow or prevent soil infiltration. If impervious surfaces cover an area, the rainfall will not infiltrate the soil, causing surface runoff and increased flooding. Many large-scale studies use the readily available impervious surface layer of roads and urban areas in the National Land Cover Database (NLCD). This 30-meter resolution data product offers minimal processing and widespread coverage of the United States. For this reason, the NLCD impervious layer was used at the 8-digit HUC watershed-level scale. However, it begins to reach its limitations at the 12-digit HUC subwatershed-level scale from being too generalized of a representation. For example, Clewiston, the only urban area in the Ninemile Canal Subwatershed and shown in Figure 23, is mostly classified as impervious at this scale. The implication is that the derived input value for soil storage is at or near zero because the model assumes almost no soil infiltration due to the high percentage of impervious land cover.

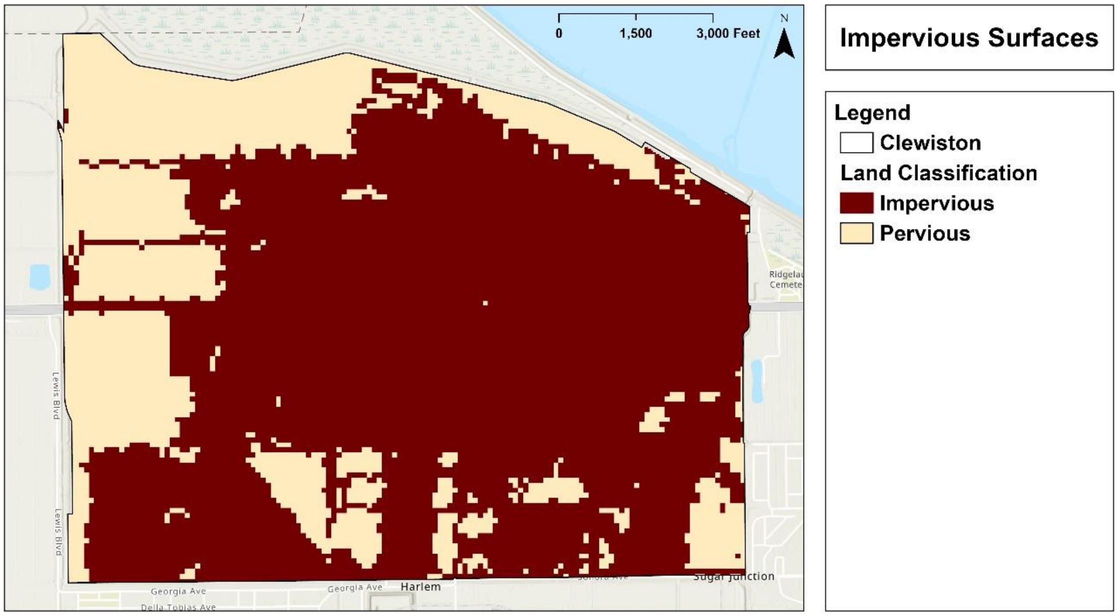


Figure 23. NLCD 30-meter impervious surfaces in the City of Clewiston

Therefore, for small-scale studies, the 30-meter resolution of the NLCD dataset may be too coarse and unable to represent local features (e.g., individual buildings) at the necessary level of detail. For example, urban areas would be designated as almost entirely impervious at this scale and resolution. This is an excellent opportunity to utilize GIS to improve an existing dataset and solve a technical data issue related to downscaling: insufficient resolution to capture local features. Hence, Viswambharan (2020) presents an alternative using supervised object-based image classification of land cover type to map impervious surfaces from high-resolution spectral imagery (i.e., a 6-inch resolution, 4-band aerial photograph) at the neighborhood level. This methodology was applied at the local scale in Clewiston using 1-meter resolution 4-band aerial imagery acquired in 2017 by the National Agriculture Imagery Program (NAIP). The trade-off is the data processing requirements which are computationally expensive and may not be practical nor offer any improvement for watershed-scale modeling.

The process begins by loading the imagery into a GIS application with the natural color band combination displayed. The band combination can be changed to better differentiate between urban features such as concrete from natural features such as vegetation and water by leveraging the near-infrared band of the imagery. This emphasizes man-made objects, vegetation, and water bodies so that they are easily distinguishable. The object-based classification type uses segmentation to group adjacent pixels based on their similarity and spectral characteristics. This generalizes the image and makes it easier to classify. The supervised classification method allows for manually selecting training samples that indicate what types of pixels should get classified in a certain way. The training samples are then used to classify the segments according to specific land cover types. Trying to classify the segmented image into only pervious and impervious surfaces is too generalized, so classifying the image based on specific land cover types is more effective. After creating the training samples, the classifier is trained. In this case, the support vector machine classifier was used. Lastly, the specific land cover types are reclassified as either pervious or impervious. A flowchart of this GIS-based procedure, applied to the City of Clewiston, is provided in Figure 24. The result is the binary classification of impervious surfaces mapped at a 1-meter cell size, as shown in Figure 25.

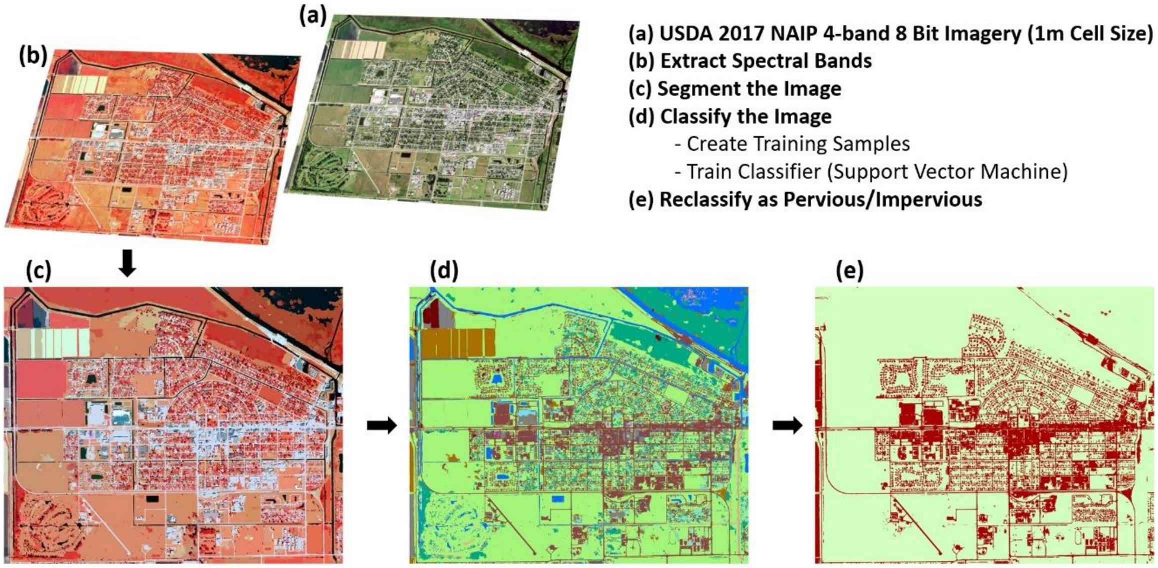


Figure 24. Flowchart of mapping impervious surfaces by image classification

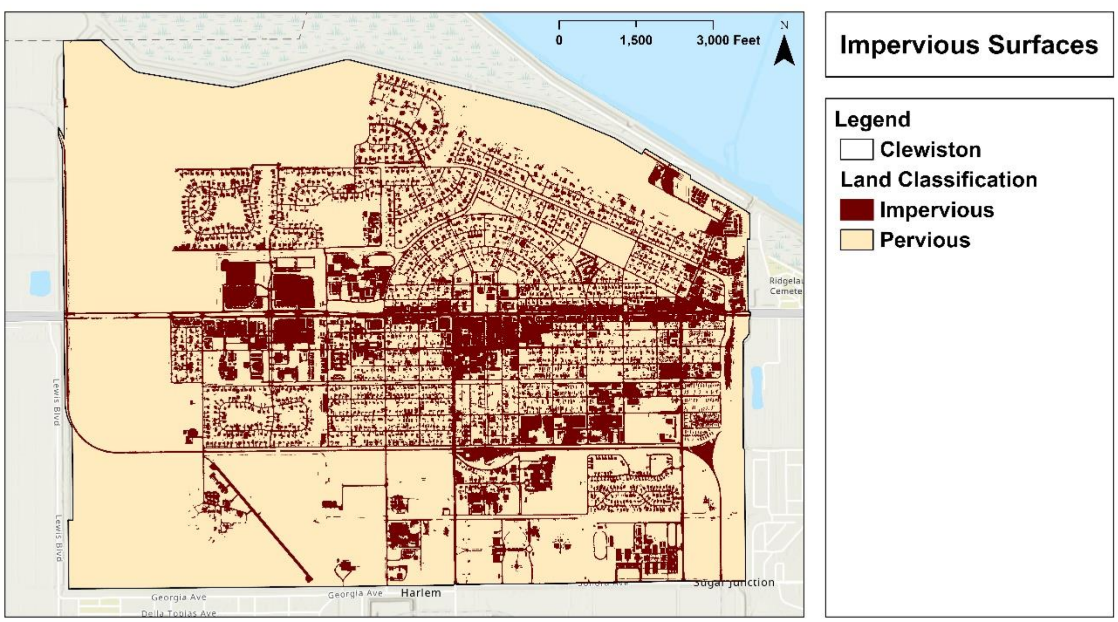


Figure 25. Impervious surfaces mapped from high-resolution spectral imagery

3.7.4 Soil Storage Capacity

The quantity of water that can be stored in the unsaturated zone during a rainfall event is an important consideration in any flood study. While there may be several feet in distance between the land surface and groundwater table, the actual ground storage depends on the water holding capacity of the soil and land classification type. The characteristics of the soil will affect the soil's capacity to store water. The soil storage capacity was calculated by multiplying the unsaturated zone depth surface by the water holding capacity ratio surface on a cell-by-cell basis. This calculation accounts for both the soil layer's total depth and unique characteristics that influence its capacity to store water. However, to better represent actual ground storage conditions, the output surface was adjusted based on its land classification type. Land areas representing existing water bodies and impervious surfaces were set to zero storage capacity. Existing water bodies covering land in the watershed cannot store additional water, and impervious surfaces prevent soil infiltration, increasing surface runoff (SFWMD, 2010). Figure 26 shows the general procedure for calculating soil storage capacity. Equation 6 is applied on a cell-by-cell basis using GIS to calculate soil storage capacity in inches. The output ground storage, adjusted to represent the soil's characteristics and land classification type, is shown on the map in Figure 27.

Equation 6. Soil Storage Capacity = (Unsaturated Zone Depth × Water Holding Capacity × Binary Impervious Surfaces Layer × Binary Waterbodies Layer) × 12 inches

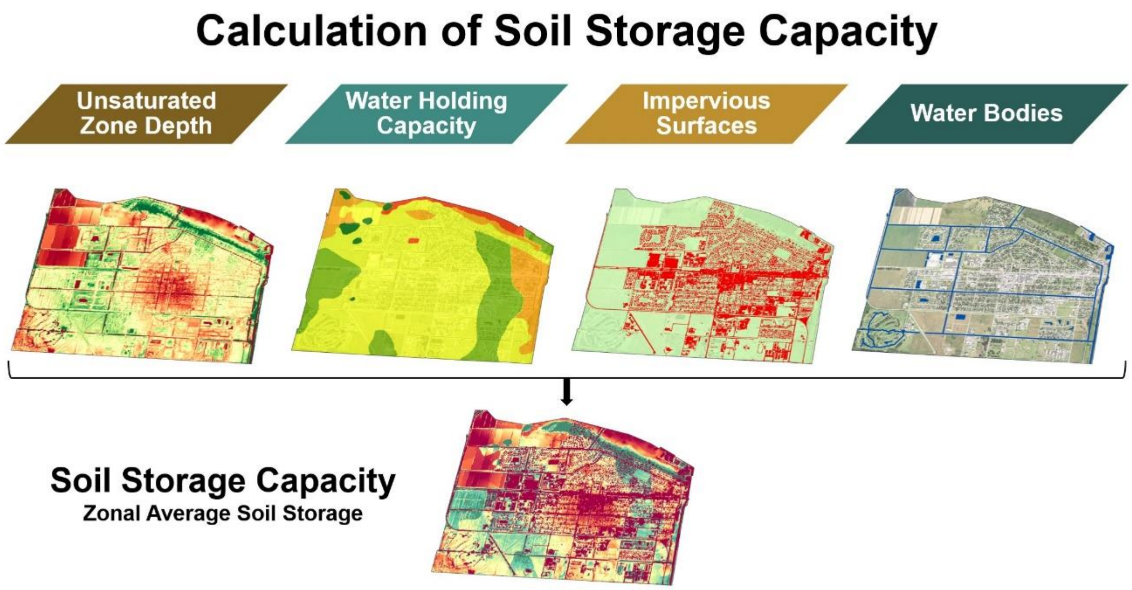


Figure 26. Flowchart of soil storage capacity calculation

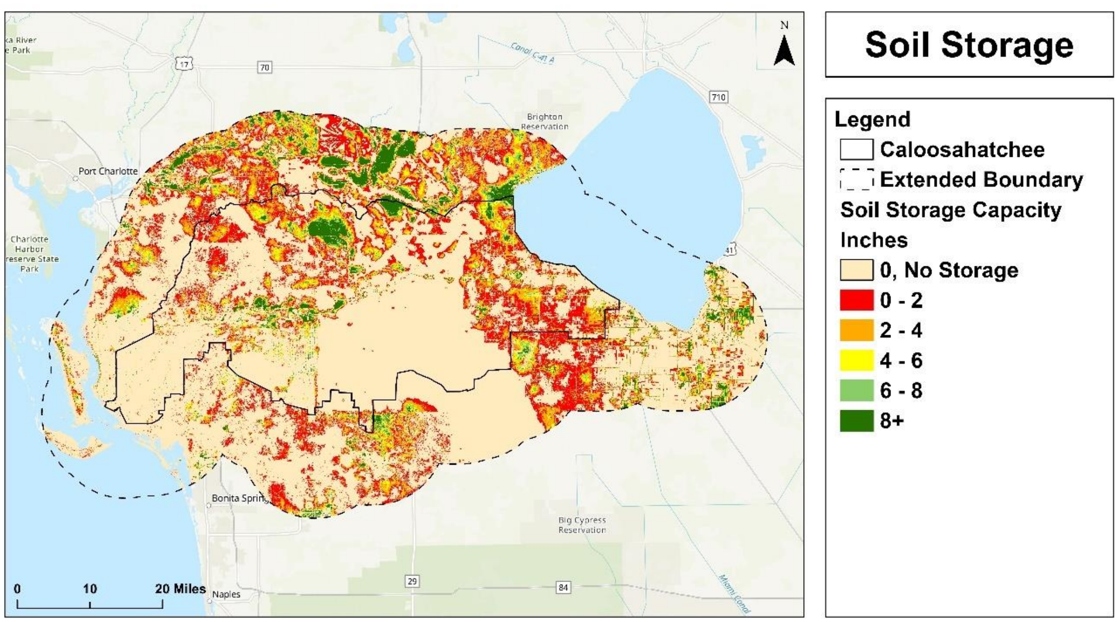


Figure 27. Soil Storage Capacity in the Caloosahatchee Watershed

3.7.5 Watershed Pathways

The GIS-based Arc Hydro tools can delineate catchments and drainage flow paths/outlets from elevation data (e.g., a LiDAR-derived DEM) to determine where drainage collects and travels as it follows a path along the surface toward an outlet. Surface water stations adjacent to the outlet point define the water level of the initial stage in the basin, which is the starting elevation of floodwaters as they rise and fall during the model simulation. The physical characteristics of drainage areas based solely on surface topography are extracted through the following geoprocessing workflow: fill sinks in the DEM, compute the flow direction and accumulation, define a stream grid, and then delineate catchments and drainage flow paths/outlets (ESRI, 2011). For example, Figure 28 shows the application of Arc Hydro along a segment of the Caloosahatchee River to delineate catchments and drainage flow paths/outlets from an input LiDAR-derived DEM.

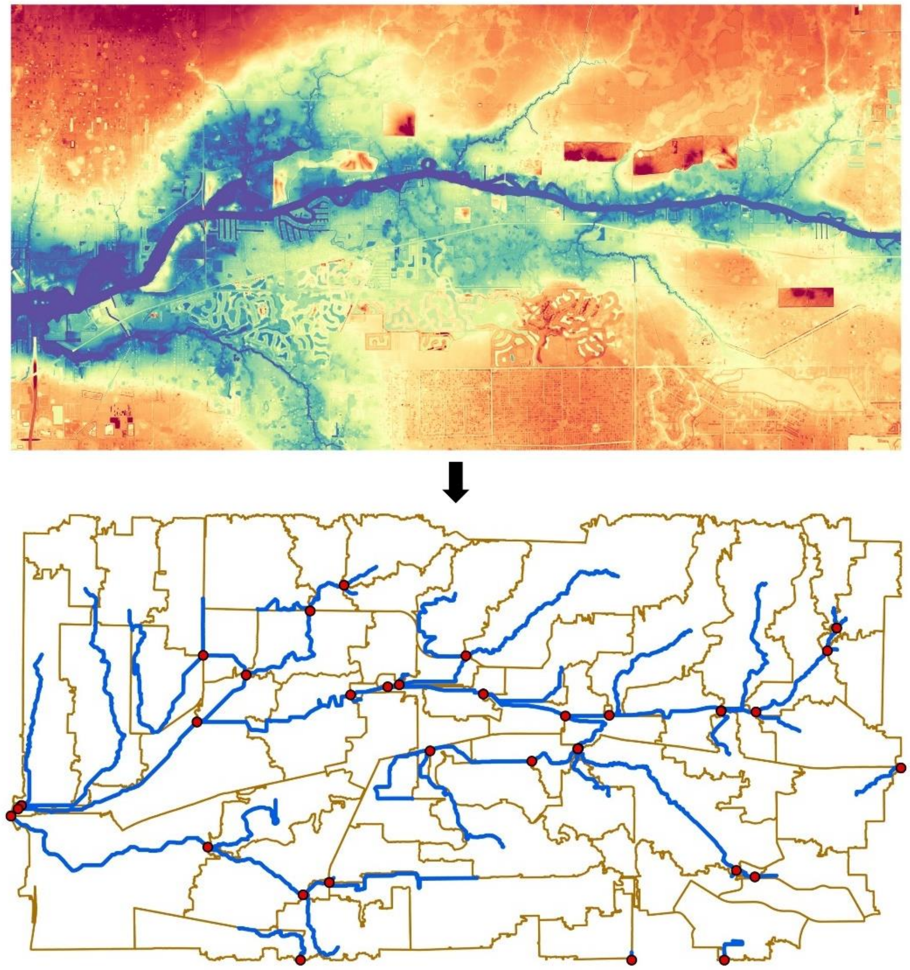


Figure 28. Using Arc Hydro to delineate the catchments and drainage network from a LiDAR-derived DEM along a segment of the Caloosahatchee River

The Caloosahatchee River carries drainage west from Lake Okeechobee into the Gulf of Mexico across the watershed’s large land area. Additionally, there are several drainage structures along the river that control its flow. It can be difficult to delineate where drainage is collecting and flowing within the watershed. The delineation of the catchments and drainage network was completed using the GIS-based Arc Hydro Tools. The resulting flow paths provided insight into the water movement throughout the watershed and were used to calculate the time required for runoff to reach the point of discharge from the most distant point in the watershed, a required input for CASCADE 2001. First, the length of the longest drainage flow path was calculated. Then, by using an assumed drainage velocity of two feet per second, the total time that the Caloosahatchee Watershed will be concentrated during a rainfall event was calculated using a simple conversion – i.e., from length (feet) to time (hours) using the conversion factor of two feet per second. The derived drainage network was overlaid onto subwatershed boundaries, as shown on the map in Figure 29. The watershed was subdivided since the CASCADE 2001 model supports multiple watershed inputs and drainage structures to represent the characteristics and connections of upstream and downstream areas.

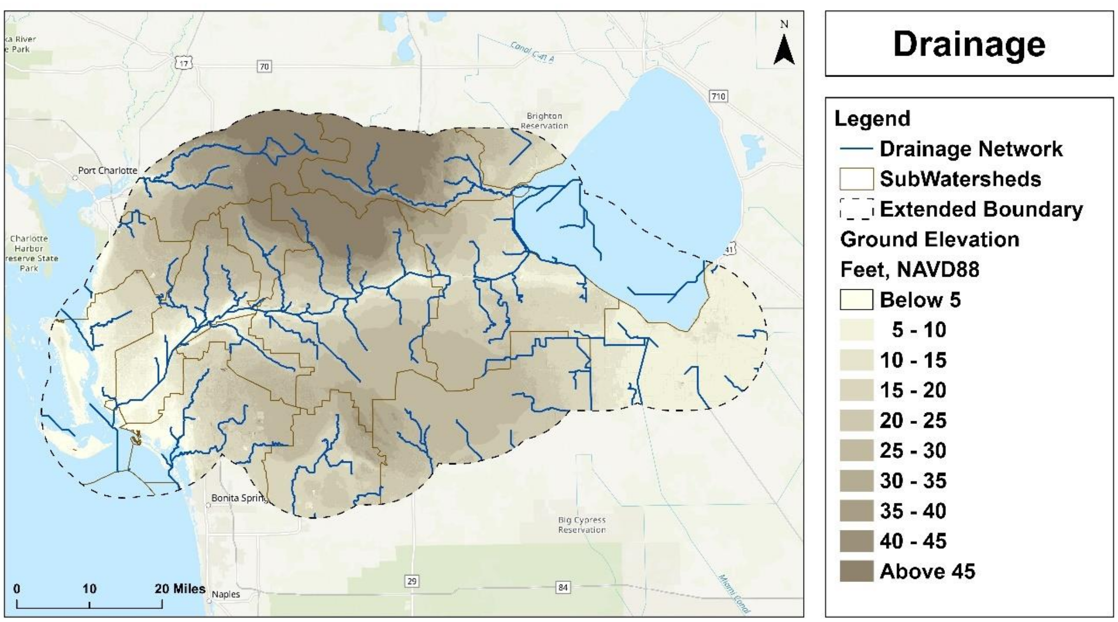


Figure 29. Catchment and Drainage Network Delineation in the Caloosahatchee

3.8 Infrastructure

CASCADE 2001 supports the simulation of multiple basins interconnected by drainage structures. There are three types of structures available for input, including gravity, pump, and gated spillway. If used, the gravity structure can consider the type of weir, bleeder, and pipe. For a pump structure, the discharge rate and the head water elevation to trigger a turn-on or a turn-off of the pump must be specified. The gated spillway structure type requires several technical specifications as input, including its crest elevation, design head, spillway width, and gate operations. Hence, a critical effort is accounting for all major infrastructure and utilizing the functionality of CASCADE 2001 to incorporate the controlled drainage system of the watershed, subwatershed, or local area being simulated, which will provide a better representation of flooding. CASCADE 2001's spatiotemporal output of floodwater levels mapped as a GIS layer can be used to identify where infrastructure improvements are needed and simulate the impact of future stormwater improvements yet to be implemented.

The major infrastructure with influence in the Caloosahatchee Watershed, Ninemile Canal Subwatershed, and the City of Clewiston are shown on the map in Figure 30. The infrastructure with the largest impact at the watershed level is maintained by the USACE and controls the flow of water along the Caloosahatchee River via gated spillways; these include the Moore Haven Lock and Dam (S77) at Lake Okeechobee, Ortona Lock and Dam (S78), and Franklin Lock and Dam (S79). Near the Ninemile Canal Subwatershed, key assets control inflow from Lake Okeechobee into the Caloosahatchee River, including the following structures: S235, S47B, S47D, C1, C1A, C2, S310, S169, and C3. Additionally, the SFWMD structures G134, G96, G150, and Montura stations are located just south of the subwatershed. Only one structure, G136, impacts the City of Clewiston while others simply provide irrigation for agricultural purposes. The City has no stormwater pumping stations and limited piping.

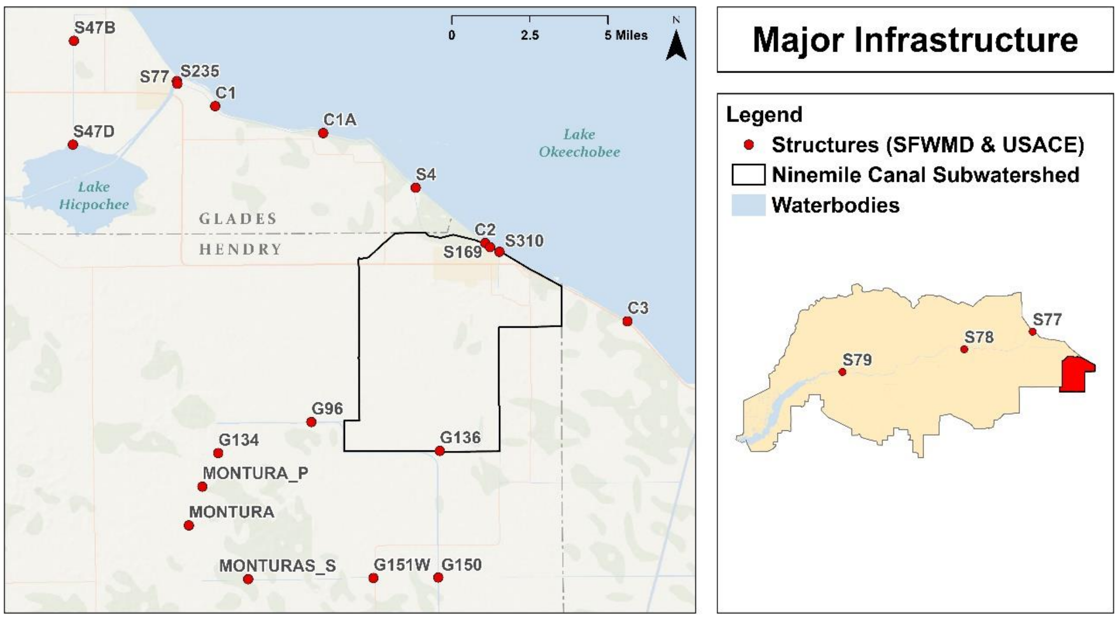


Figure 30. Major Infrastructure in the Study Area

3.8.1 Watershed Infrastructure

The Caloosahatchee Watershed was modeled according to the following description. Water is directed from Lake Okeechobee into the Caloosahatchee River, where it is carried through a linear system across control structures. Starting with the Moore Haven (S-77) gated spillway structure at the watershed's eastern boundary, Lake Okeechobee, water travels from east to west through the Ortona (S-78) gated spillway structure. The drainage area upstream of this structure is called East Caloosahatchee. The Ortona Lock and Dam structure is located 15.5 miles west of the Moore Haven structure at Lake Okeechobee. Its discharge capacity is 8,660 cubic feet per second (cfs), and the water level drop is 7.5 to 8.5 feet. The river stage in East Caloosahatchee is limited to a maximum stage elevation of 11.3 feet NGVD29 due to the Ortona Lock and Dam (S-78) structure. Note that the restriction of stage elevations is primarily for flood control as inundation from overflow is the main concern at the watershed level. The downstream drainage area is called West Caloosahatchee, and here, the river is limited to a maximum stage elevation of 3.4 feet NGVD29 due to the W.P. Franklin Lock and Dam (S-79) structure which is located 27.9 miles west of the Ortona (S-78) structure. The S-79 gated spillway has a discharge capacity of 28,900 cfs, and the water level drop is only a few feet to sea level (approximately 2 to 3 feet). The next downstream drainage area, Tidal Caloosahatchee, outflows to the Gulf of Mexico at San Carlos Bay. Its prominent water feature is the Caloosahatchee Estuary. The W.P. Franklin Lock and Dam (S-79) structure represents the confluence with the estuarine waters; it is located 33.2 miles upstream of the Gulf Intracoastal Waterway. Therefore, there are three drainage areas to simulate: East Caloosahatchee, West Caloosahatchee, and Tidal Caloosahatchee, which are interconnected by the S-78 and S-79 control structures along the river. Water inflows into the watershed from Lake Okeechobee, has its primary flow path along the Caloosahatchee River, and has an outlet with a tidal connection.

Highly localized infrastructure is unlikely to have any relevance in a watershed-level screening analysis of flood risk. For example, culverts along roadways will have minimal influence compared to USACE or SFWMD operations of rivers and large canals. Therefore, analysis at the watershed level should focus on the dams, canals, pump stations, gated spillways, and similar structures in terms of scale to construct the model. However, this large-scale analysis will provide insight into where local infrastructure may be required to reduce flooding. Then, a scaled-down modeling approach can be applied for drill-down analysis of the vulnerable areas, which increases the need and relevance of local infrastructure databases. This presents a challenge when local stormwater system models are unavailable or records of infrastructure are incomplete. The GIS-based Arc Hydro tools can delineate catchments and drainage flow paths/outlets from elevation data (i.e., a DEM) when there is limited or no stormwater data available. The physical characteristics of drainage areas based solely on surface topography are extracted through a geoprocessing workflow. The model developed for the Ninemile Canal Subwatershed and City of Clewiston relied on the Arc Hydro approach.

3.8.2 Subwatershed Infrastructure

The Ninemile Canal Subwatershed, which is nested within the Caloosahatchee Watershed, was delineated using Arc Hydro. Its hydrologic boundary is established from the major canals immediately surrounding Clewiston, including the Ninemile/C-21 Canal (north), Industrial Canal (east), L-1/L-1E Canal (south), and Sugarland Drainage District Canal 4 (west). The infrastructure considered at this subwatershed scale is the structures controlling inflow from Lake Okeechobee in the north and the SFWMD structures G136, G96, G134, G150, and Montura stations in the south, which influence the initial stage of canals at outlet points. The land use/land cover composition was considered to determine the time of concentration as the subwatershed is mostly agriculture (72.1%) and urban and built-up (19.8%). A network of secondary and tertiary canals throughout the subwatershed supports agriculture and urban development. Stormwater collected locally in the only urban area, Clewiston, interacts with minimal drainage infrastructure and the small Clewiston Drainage District Canals 1 through 7 and Lopez Canal, which connect to the major canals along the subwatershed boundary, the C-21 Canal and Industrial Canal. The Ninemile Canal Subwatershed is a self-contained hydrologic unit that contributes surface water runoff to designated outlets at the bounding canals via the catchments and drainage flow paths delineated using Arc Hydro, shown in Figure 31.

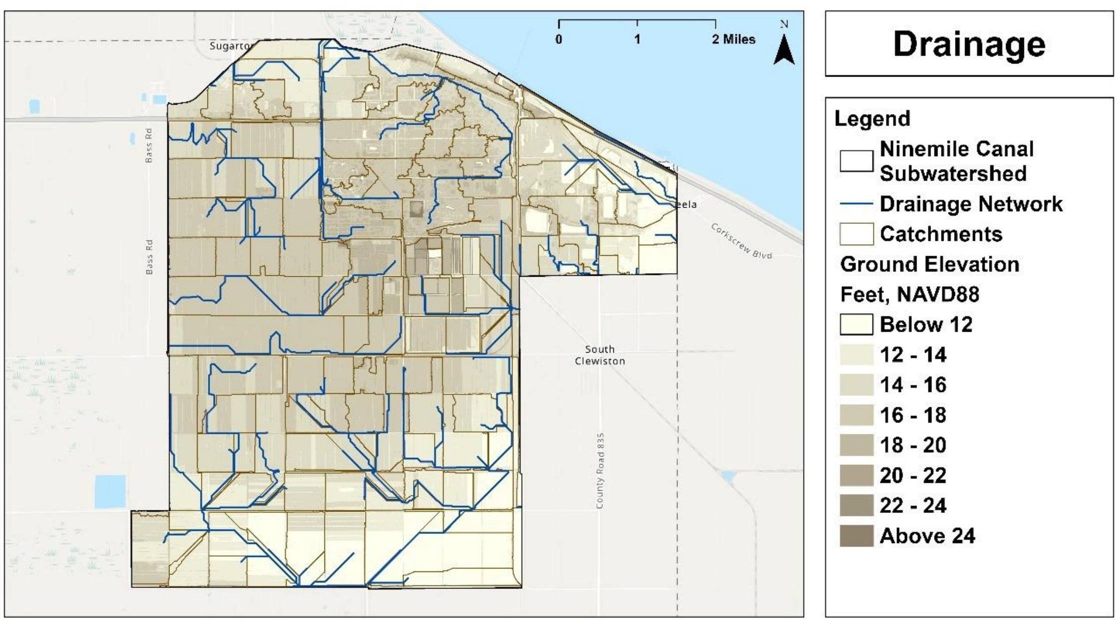


Figure 31. Catchment and Drainage Delineation in the Subwatershed

3.8.3 Local Infrastructure

In general, local community stormwater systems consist of drainage ditches, storm sewers, retention ponds, and other facilities constructed to store runoff or carry it to a receiving canal, lake, or other waterbody. Other man-made features include swales that collect runoff and direct it to the sewers and ditches to protect roadways. However, at a drill-down into the City of Clewiston, there is minimal drainage infrastructure. In fact, shallow swales are really the only structures (see Figure 32). There are very few street inlets, mostly along U.S.-27/Sugarland Highway, and no culverts under roadways in most of the City. Hence, there is not a master stormwater system in Clewiston. There are small canals that traverse the City, as shown in Figure 33, which were used to model the city's stormwater. These include the Clewiston Drainage District (CDD) Canals 1 through 7 and Lopez Canal, which connect to the major C-21 Canal (north) and Industrial Canal (east). A recent program to seal the sewer system eliminated the inflow of rainwater to the sanitary system, introducing "new" flooding to areas in the City.

Figure 32. Shallow Swales throughout the City of Clewiston (from Google Earth)

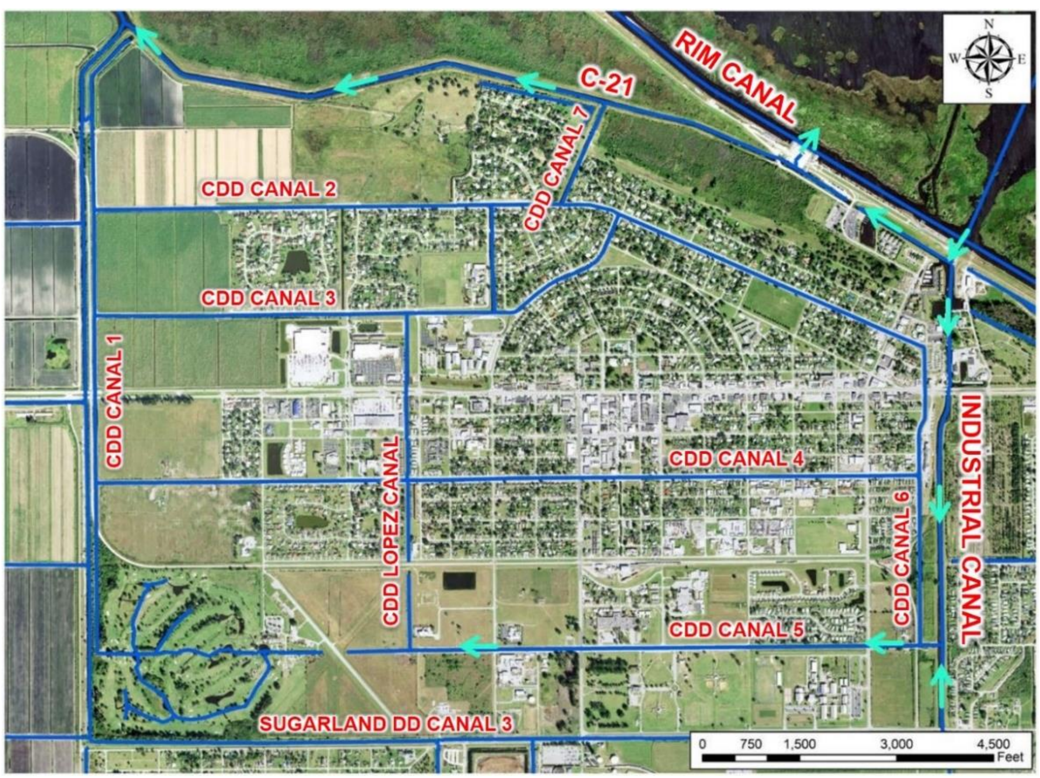


Figure 33. Local Drainage Canal System in the City of Clewiston

At present, drainage relies on sheet flow to low-lying areas and percolation into the soils; thus, topography plays a key role. Arc Hydro was used to understand where water collects and drains along flow paths to outlets. These physical characteristics were extracted solely from surface topography, which happens to be the only readily available data source (i.e., a high-resolution DEM of the City). Although Clewiston is a municipality and not a hydrologic unit, its boundary is formed by the C-21 Canal (north), Industrial Canal (east), and Sugarland Drainage District Canal 3 (west and south). The Arc Hydro delineation of catchments and drainage flow paths, shown in Figure 34, indicates that the City's drainage outlet is the Industrial Canal (east), and the catchment boundaries are formed by local canals, U.S.-27/Sugarland Highway, and U.S. Sugar's South Central Florida Express railroad.

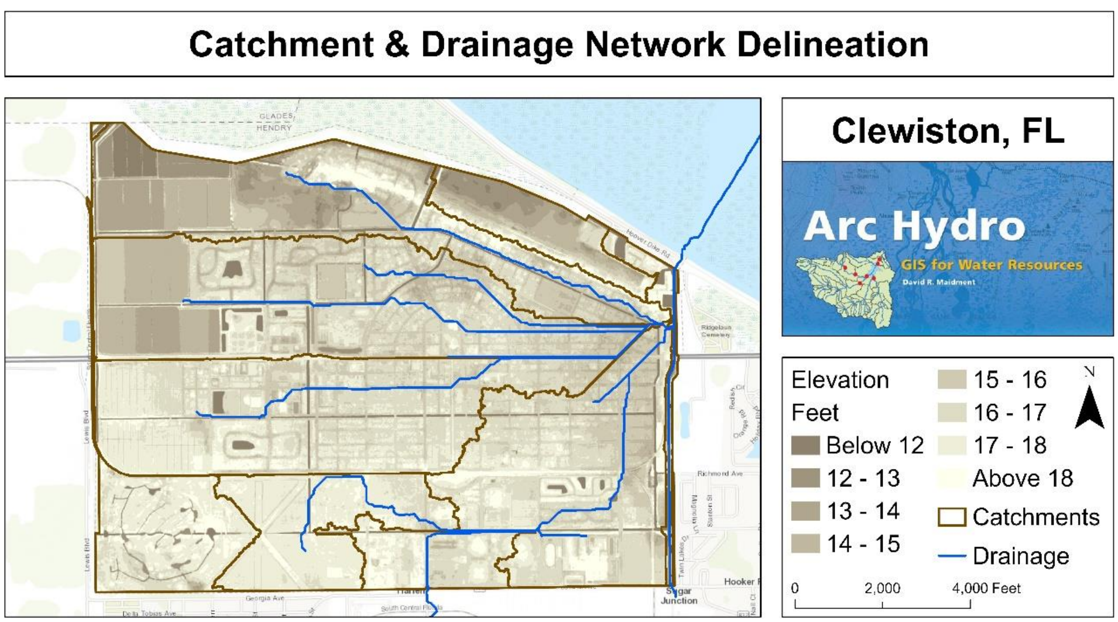


Figure 34. Catchment and Drainage Delineation in the City of Clewiston

3.9 Model

After following FAU's modeling protocol, all required input parameters for CASCADE 2001 were calculated. The Caloosahatchee Watershed was simulated using three subwatersheds separated by the Ortona Lock (S-78) and Franklin Lock (S-79) drainage structures. The input parameters represent factors that influence flooding, for example, the topography, groundwater table elevation, and soil storage capacity. The original datasets and derived surfaces are GIS-compatible, so direct measurements and zonal average statistics were used to calculate the input parameters for each subwatershed. The drainage structures' information was obtained from the U.S. Army Corps of Engineers, the organization operating and maintaining these structures. A summary of the subwatershed and drainage structure input parameters for CASCADE 2001 is provided in Table 8 and Table 9, respectively.

Table 8. CASCADE 2001 Subwatershed Input Parameters

Subwatershed Name Input Parameter	Tidal Caloosahatchee	West Caloosahatchee	East Caloosahatchee
Area (ac)	263,865	349,730	267,244
Low Elev. (ft)	0.67	1.60	9.98
High Elev. (ft)	56.00	64.00	41.00
Soil Storage (in)	0.65	1.37	1.08
Concentration (hr)	27.76	19.08	11.84
Initial Stage (ft)	0.67	1.60	9.98
Design Storm	3-day 25-year	3-day 25-year	3-day 25-year
Rainfall (in)	10.64	10.01	9.16

Table 9. CASCADE 2001 Structure Input Parameters

Structure Name Input Parameter	Ortona Lock (S-78)	Franklin Lock (S-79)
Connection	East to West	West to Tidal
Structure Type	Gated Spillway	Gated Spillway
Crest Elev. (ft)	0.44	-16.24
Design Head (ft)	9.94	1.76
Spillway Width (ft)	86.50	304.00
No. of Piers	3	7

Under these constraints, the CASCADE 2001 model simulates the rise of floodwaters during a 3-day 25-year storm. It is important to note that a flood risk model attempts to “approximate reality” while being transparent regarding its uncertainties and limitations over a potentially open-ended time frame. The output, in this case, is the maximum headwater height in each subwatershed so that any land areas below this elevation can be designated as flooded. As illustrated in the framework in Figure 35, identifying flood-prone areas is crucial to assess community risk and inform the decision-making process of prioritizing and allocating funding.

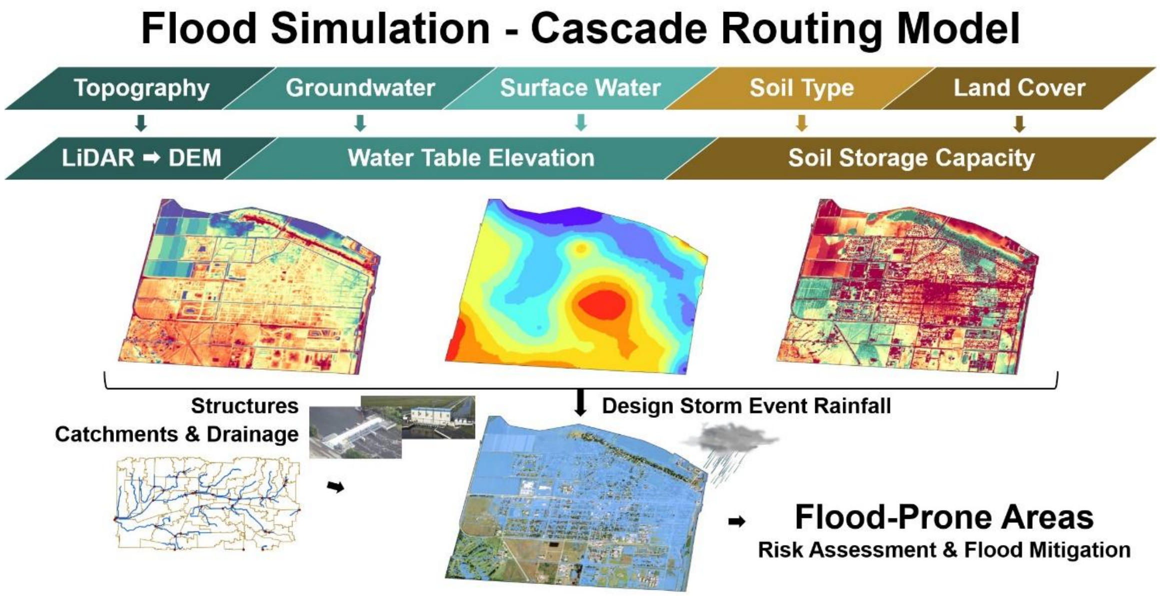


Figure 35. CASCADE 2001 model framework to identify flooded areas

In the East Caloosahatchee Subwatershed, it was determined that floodwaters would rise to a maximum headwater height of 15.82 feet NAVD88. The impacted incorporated cities are Clewiston and Moore Haven, which are expected to experience inundation in approximately 35% and 95% of their total areas, respectively. In the West Caloosahatchee Subwatershed, downstream of the Ortona Lock and Dam (S-78) and upstream of the W.P. Franklin Lock and Dam (S-79), it was determined that floodwaters would rise to a maximum headwater height of 10.53 feet NAVD88. The only impacted incorporated city is LaBelle, which is expected to experience inundation in nearly 7% of its total area. In the Tidal Caloosahatchee Subwatershed, it was determined that floodwaters would rise to a maximum headwater height of 6.94 feet NAVD88 which is below the level of the Ortona dam. The impacted incorporated cities are Fort Myers and Cape Coral, which are expected to experience inundation in approximately 20% and 48% of their total areas, respectively.

The flooded areas during a 3-day 25-year storm in the Caloosahatchee Watershed are shown in Figure 36.

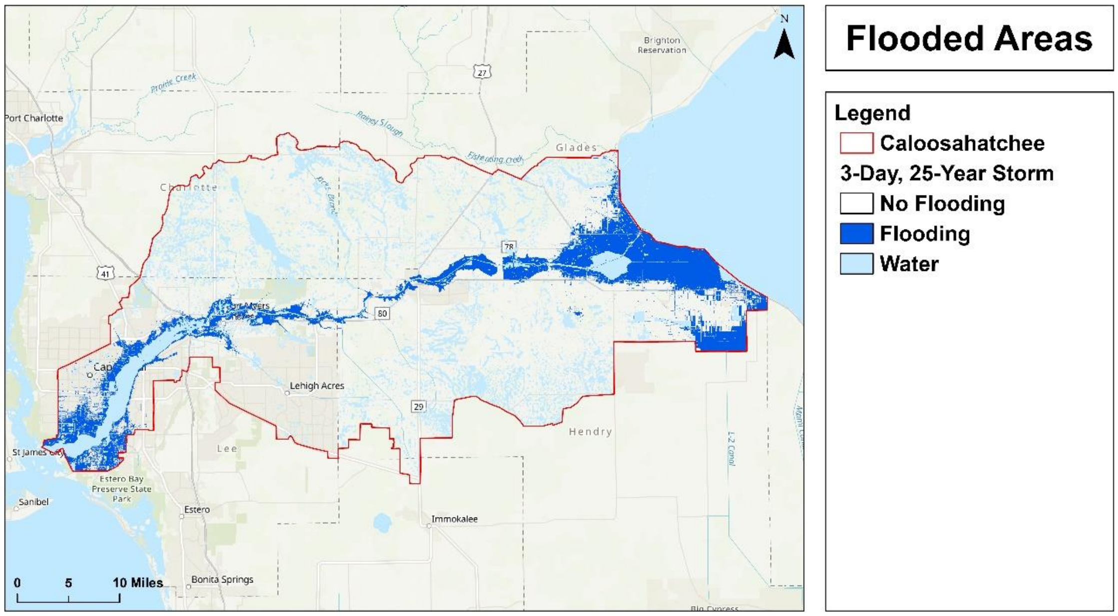


Figure 36. Flooded Areas During a 3-Day 25-Year Storm

The output of the CASCADE 2001 simulation (i.e., the maximum elevation of floodwaters) provides insight into the Caloosahatchee Watershed's flood response to a 3-day 25-year storm, used for producing flood inundation maps. After mapping wet (flooded) and dry areas within the watershed, it is important to classify the risk associated with those flooded areas. Developing binary flood maps that classify land as either flooded or non-flooded is deterministic, and, in the context of decision-making, this becomes an issue as there may be a false sense of precision amidst uncertainty in modeling. For example, there are uncertainties and assumptions in the source datasets used for input parameters such as the LiDAR DEM vertical accuracy or soil storage calculation and the CASCADE 2001 modeling approach itself. Alternatively, a probabilistic representation of flood extent can reflect the degree of certainty in predictions, which is consistent with the goals of a flood risk screening analysis to approximate reality (Alfonso et al., 2016). By further classifying flood risk as the probability of inundation, it is possible to increase the value of information shown on flood maps and improve the identification of critical target areas within the watershed that are particularly vulnerable to flooding and subject to further study. The flood inundation probability for the Caloosahatchee Watershed during the 3-day 25-year storm event is shown on the map in Figure 37.

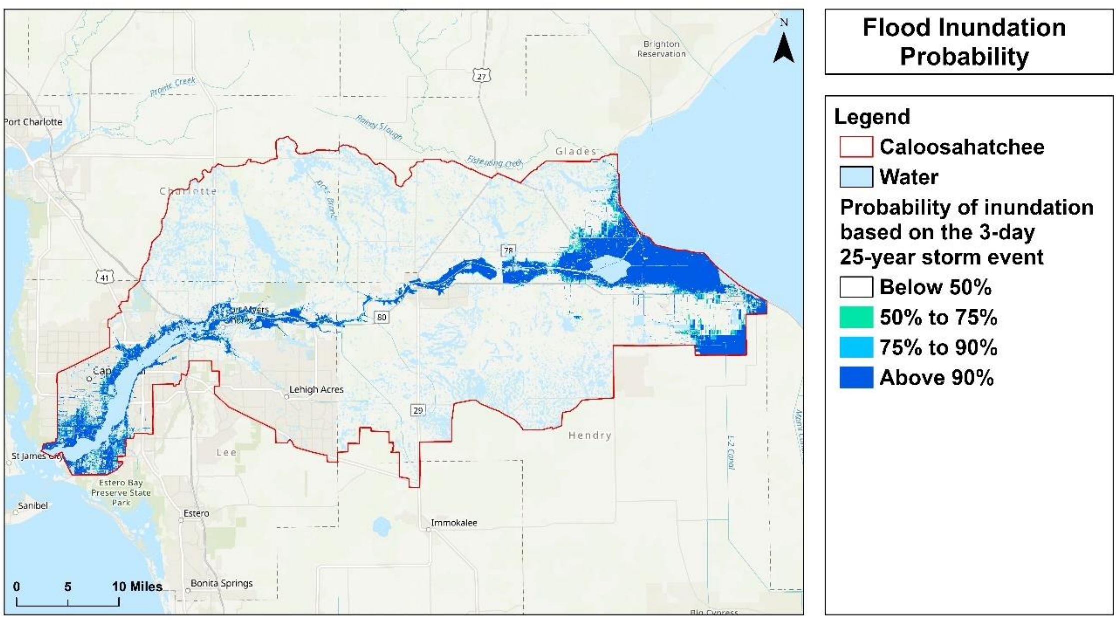


Figure 37. Probability of Inundation Based on the 3-day 25-year Storm Event in the Caloosahatchee Watershed

The design storm for calculation purposes was selected to be the storm event of 3-day duration and 25-year return frequency, which is the standard used by the SFWMD for flood management. CASCADE 2001 can also model other storm events of various durations and frequencies, such as the 24-hour, 100-year storm. While preserving the watershed's input parameters, the model is adjusted for the desired design storm event and associated rainfall. Therefore, it is a straightforward task to construct several model scenarios simulating the watershed's flood response under different design storm events. The flood risk in the Caloosahatchee Watershed during a 24-hour, 100-year storm is shown in Figure 38.

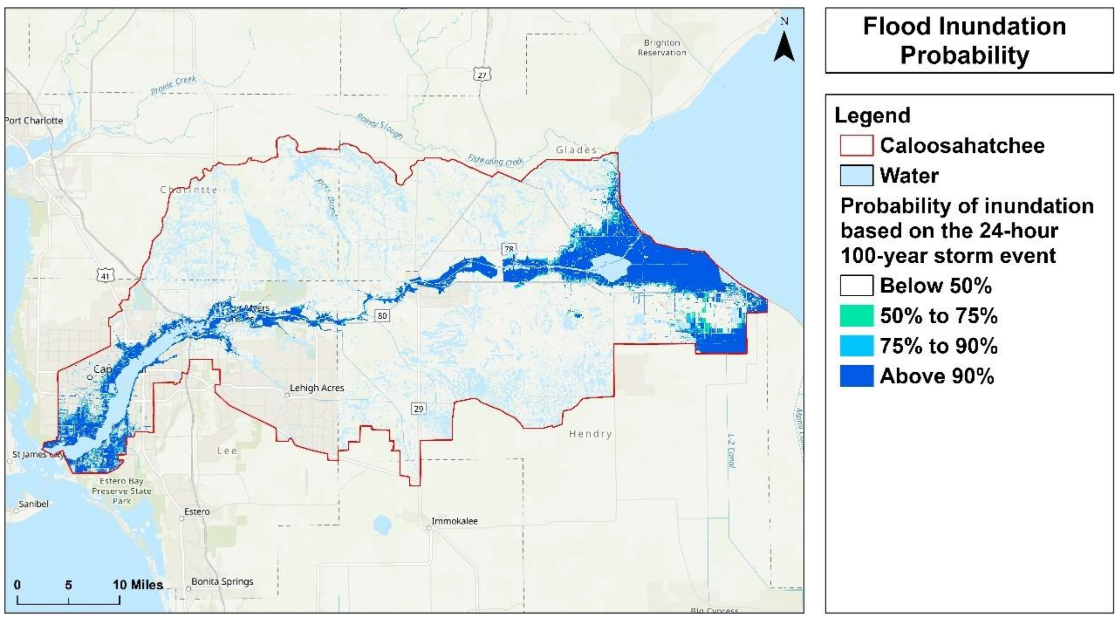


Figure 38. Flood Risk during a 1-day 100-year storm in the Caloosahatchee

3.10 Critical Target Areas

By modeling the Caloosahatchee Watershed's flood response to the 3-day 25-year, and the 1-day 100-year storm events and further classifying flood risk as the probability of inundation, it is possible to identify critical target areas within the watershed. These areas are particularly vulnerable to flooding and are subject to further study through a scaled-down modeling approach. The screening tool should first be applied at the watershed level to provide an initial risk assessment focused on the hydrologic response to a rainfall event, given the unique characteristics and features of the watershed. For example, characteristics of the Caloosahatchee Watershed are incorporated to represent possible driving factors of flooding in the region, such as low ground surface elevations, a high groundwater table, low soil storage capacity, and heavy rains. At this scale, flooding generally occurs around large water bodies, namely the Gulf of Mexico, Caloosahatchee River, and Lake Okeechobee. However, to prioritize funding for future mitigation and planning efforts at the local level, it is necessary to identify areas of concern within the watershed that are highly susceptible to flooding. Understanding localized flooding conditions is crucial for developing strategies to protect vulnerable communities and infrastructure. A closer look at the flood risk map created for the Caloosahatchee Watershed (i.e., the largest model domain at the 8-digit HUC watershed-level scale) provides additional drill-down perspectives of the watershed, increasing the displayed level of detail. The results zoomed to the Ninemile Canal Subwatershed and the City of Clewiston are examined.

The CASCADE 2001 model simulation determined that floodwaters will rise to a maximum headwater height of 15.82 feet NAVD88, given a 3-day 25-year storm event, in East Caloosahatchee where the Ninemile Canal Subwatershed and City of Clewiston are located. It is important to note that these scenarios assume that the drainage system is full, and therefore the ability to discharge water is limited. The flood risk map drill-down to the

Ninemile Canal Subwatershed is shown in Figure 39 (based on the 3-day 25-year storm) and Figure 40 (based on the 1-day 100-year storm).

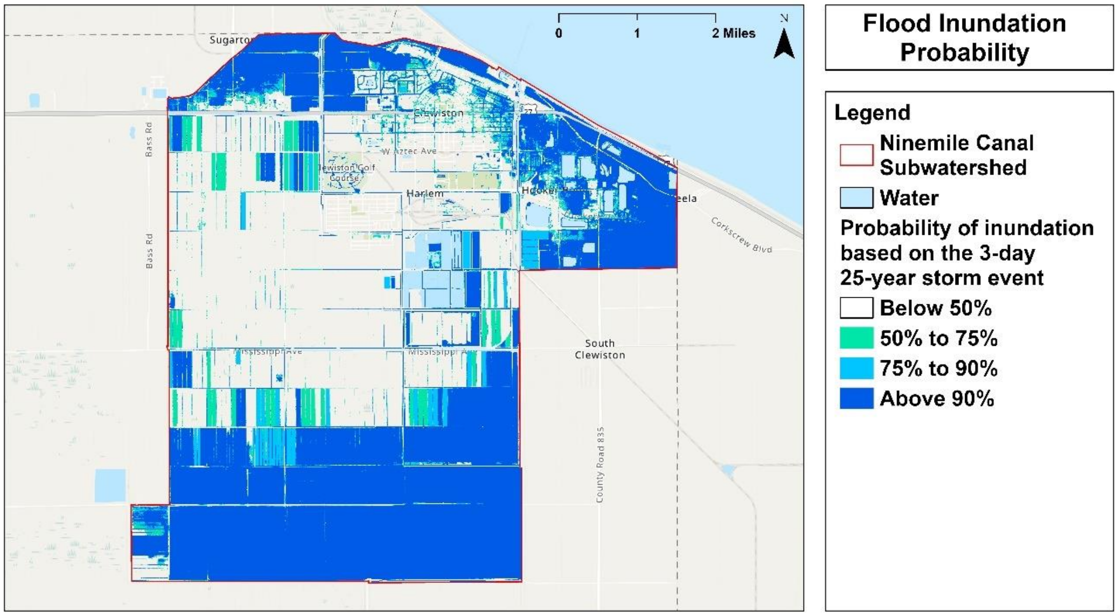


Figure 39. Flood risk (3-day 25-year storm) in the Ninemile Canal Subwatershed

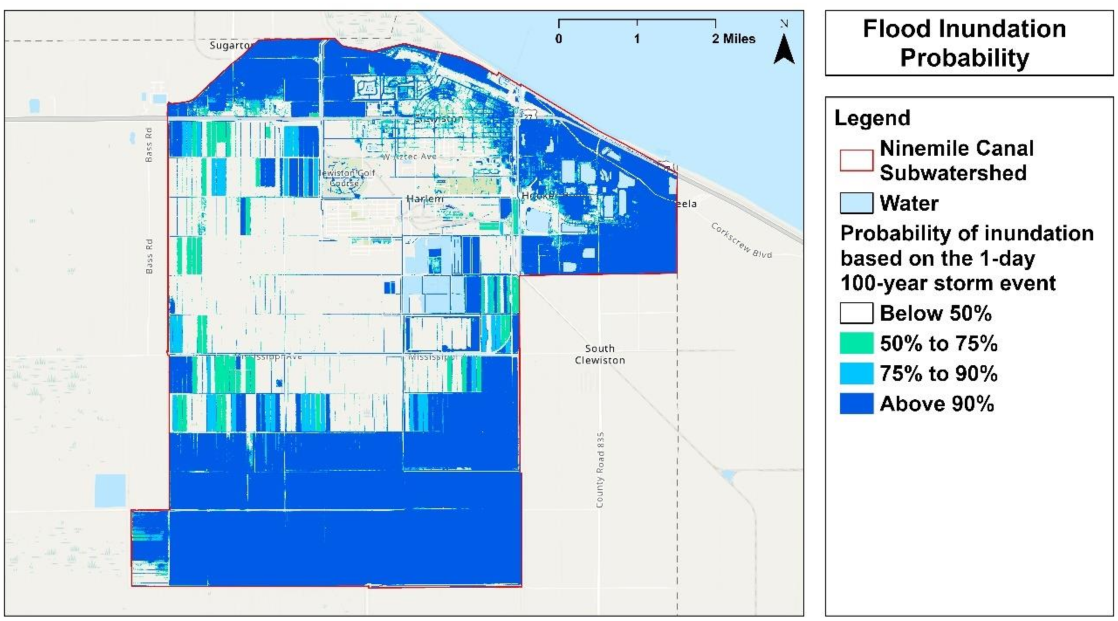


Figure 40. Flood risk (1-day 100-year storm) in the Ninemile Canal Subwatershed

Approximately 35% of Clewiston's total area, or 1.58 mi^2, has ground surface elevations below the maximum headwater height of 15.82 feet NAVD88 and would therefore be expected to be inundated during a 3-day 25-year storm. The flooded areas include agricultural lands in the northwest and wetlands in the north; however, flooding in the east is of more concern as it poses a threat to residential housing, commercial businesses, and existing infrastructure. The flood risk map drill-down to the City of Clewiston based on the 3-day 25-year storm is shown in Figure 41. For comparison, during a 1-day 100-year design storm, 41.5% of Clewiston's total area, or 1.87 mi^2, has ground surface elevations below the predicted maximum headwater height of 16.11 feet and would therefore be expected to be inundated, as shown in Figure 42.

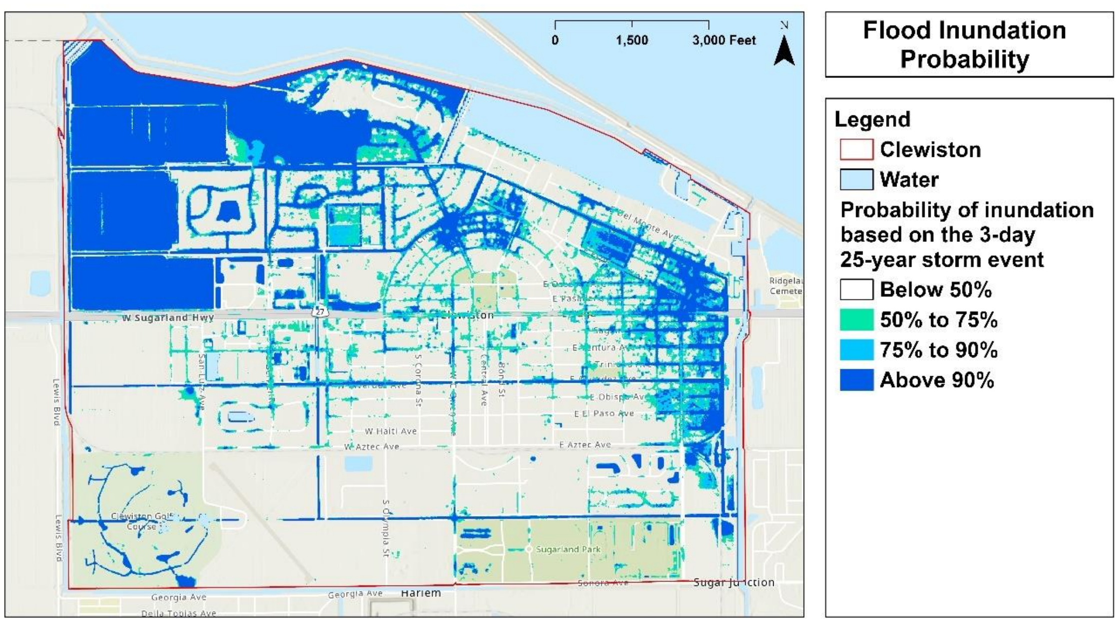


Figure 41. Flood risk based on the 3-day 25-year storm in Clewiston

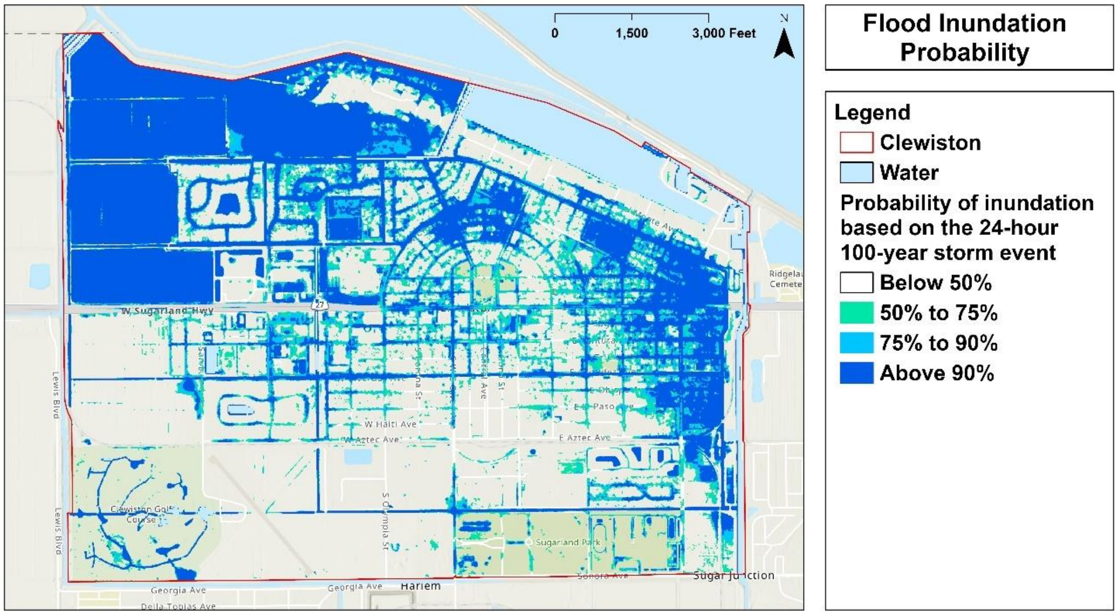


Figure 42. Flood risk based on the 1-day 100-year storm in Clewiston

3.11 Comparison

The CASCADE 2001 model is paired with GIS to compare the predicted flood response at three nested levels of drill-down modeled separately based on the scale, including the 8-digit HUC level (Caloosahatchee Watershed), the 12-digit HUC level (Ninemile Canal Subwatershed), and the local municipal level (City of Clewiston, Florida). Additionally, the FEMA 100-year floodplain delineations are used as reference maps to determine how similar the FEMA flood maps are to a storm event that can be readily modeled, allowing for validation of the model and justification for simulating other storm events or flood scenarios.

Therefore, the goal is to evaluate drill-down modeling and FEMA flood maps by comparing them to the results from the three levels of analysis and to one another. This statistical comparison is an objective method to measure the following quantitatively:

- How the predicted flood extent changes with drill-down modeling
- Which infrastructure explains the differences observed at each scale
- How similar the FEMA flood maps are to the 1:100 storm event

CASCADE 2001 incorporates several contributing factors of flooding, including low land elevations, high groundwater levels, poor soil storage, heavy rains, and controlled drainage. Understanding these model inputs will provide insight into how the study area was characterized, ultimately explaining the impact of scale for determining flood risk in a community from the CASCADE 2001 model. In other words, it is possible to determine how the scale of data and drill-down modeling efforts change the predicted flood extents. For example, of interest is that as the drill-down occurs, more localized infrastructure will matter, and any data gaps at the community level, such as unavailable stormwater system models with a missing inventory of local drainage infrastructure, may disrupt accuracy. Table 10 shows the CASCADE 2001 input parameters based on the modeling scale to explain the differences observed at each scale.

Table 10. CASCADE 2001 input parameters based on the scale of modeling

Scale of Modeling	Caloosahatchee Watershed (8-digit HUC level)			Ninemile Canal Subwatershed (12-digit HUC level)	City of Clewiston (Local/Community level)
	Tidal	West	East		
Area (ac)	263,865.00	349,730.00	267,244.00	22,024.26	2,886.66
Low Elev. (ft)	0.67	1.60	9.98	9.83	13.12
High Elev. (ft)	56.00	64.00	41.00	25.42	19.02
Soil Storage (in)	0.65	1.37	1.08	1.47	1.46
Concentration (hr)	27.76	19.08	11.84	4.58	2.58
Initial Stage (ft)	0.67	1.60	9.98	13.83	13.63
3d 25y Rainfall (in)	10.64	10.01	9.16	9.10	8.97
1d 100y Rainfall (in)	11.36	10.56	10.24	10.59	10.46
Infrastructure	Caloosahatchee Estuary; Gulf of Mexico	Caloosahatchee River; Franklin Lock & Dam (downstream)	Lake Okeechobee; Caloosahatchee River/C-43 Canal; Moore Haven Lock & Dam (upstream); Ortona Lock & Dam (downstream)	The boundary of Ninemile/C-21 Canal (north), Industrial Canal (east), L-1/L-1E Canal (south), and Sugarland DD Canal 4 (west); SFWMD/USACE drainage operations & staging	Local Clewiston DD Canals 1 through 7 and Lopez Canal (connection/outlet to C-21 Canal and Industrial Canal); U.S.-27/Sugarland Highway; South Central Florida Express railroad; Topography (sheet flow drainage); shallow swales & few street inlets

CASCADE 2001's spatiotemporal output of floodwater levels provides a prediction for the high headwater height during the applicable design storm, mapped as a GIS layer to identify the extent of flooding. Modeling was conducted separately at each scale corresponding to the three nested levels of drill-down; therefore, the spatial overlap of these study areas makes it possible to determine how the predicted flood elevation and extent change with drill-down modeling. Clewiston is the overlapping area that is common to all three model scales. Hence, the predicted flood response at each scale of modeling was compared to determine the flood elevation and extent for the same location (i.e., Clewiston).

For the 3-day 25-year flood simulation, the watershed and subwatershed scales yield nearly identical results for Clewiston's predicted flood response. This is because both levels of modeling utilize the same regional datasets without highly localized drill-down modeling. In other words, the only difference is the boundary condition for determining input parameters so that the subwatershed model simply uses a geographic subset of the larger dataset that covers the entire watershed. Therefore, given approximately equal predictions, a subwatershed level of modeling may not provide a clear advantage over a watershed-wide analysis covering a much larger area without additional data requirements.

However, differences are observed as drill-down occurs. The local municipal scale of modeling utilizes Clewiston-specific inputs within a small boundary and employs the most downscaling techniques and local infrastructure. This provides a better prediction for the flood risk potential in Clewiston. For Clewiston's predicted flooding based on the 3-day 25-year storm, the high headwater height saw a vertical difference of ½ inch, which changes the extent of flooding by approximately 25 acres between the three levels of analysis. Table 11 shows each scale's results based on the 3-day 25-year storm for the area within Clewiston's boundary only.

Table 11. Clewiston's predicted flooding (3-day 25-year) at each scale of modeling

Scale of Modeling	Caloosahatchee Watershed (8-digit HUC level)	Ninemile Canal Subwatershed (12-digit HUC level)	City of Clewiston (Local/Community level)
High Headwater Height (feet)	15.82	15.83	15.86
Flooded Area (acres)	1,013.96	1,020.33	1,039.15
Percentage of Flooded Area	35.15%	35.37%	36.02%

The 1-day 100-year flood simulation led to a greater difference between the three scales where the predicted high headwater height saw a vertical change of 1.9 inches, which corresponds to a flood extent of 114 acres. In this case, the watershed scale of modeling appears to overpredict flooding while the subwatershed and local model results are in good agreement, producing identical results. The difference may be due to the storm event and how the drainage structures handle the flooding caused by increased rainfall received in a shorter duration. For example, the regional operations/staging of the Caloosahatchee River having a greater influence on the watershed-level results and overshadowing local infrastructure explains the difference observed between scales. Further study on the influence of different design storm events is needed to explain why the watershed scale of modeling tends to underpredict or overpredict, while local drill-down modeling consistently produces the best flood prediction.

Therefore, of interest is whether the local scale of modeling provides better answers for flood prediction because of the additional infrastructure and downscaling techniques. Table 12 shows each scale's results based on the 1-day 100-year storm for the area within Clewiston's boundary only. The 1-day 100-year storm modeled using CASCADE 2001 is most comparable to FEMA's 100-year floodplain delineations, often used as reference maps in studies to validate predicted flood extents from a model (Afshari et al., 2018). Initial comparisons indicate that the watershed scale of modeling does overpredict flooding while the identical results produced by the subwatershed and local model closely match the FEMA flood maps. Therefore, drill-down modeling does provide better detection of localized flood risk due to the increased data quantity and quality incorporated into the CASCADE 2001 model.

Table 12. Clewiston's predicted flooding (1-day 100-year) at each scale of modeling

Scale of Modeling	Caloosahatchee Watershed (8-digit HUC level)	Ninemile Canal Subwatershed (12-digit HUC level)	City of Clewiston (Local/Community level)
High Headwater Height (feet)	16.27	16.11	16.11
Flooded Area (acres)	1,313.04	1,198.95	1,198.95
Percentage of Flooded Area	45.52%	41.56%	41.56%

An objective is to determine how similar the FEMA flood maps are to a storm event that can be readily modeled, allowing for validation of the model and justification for simulating other storm events or flood scenarios in new study areas. Hence, the comparative analysis in this study utilizes the Jaccard Index as a spatial similarity measure between the predicted flood extent from CASCADE 2001 modeling and the existing

FEMA maps based on the 1-percent annual chance flood (100-year event). The Jaccard Index quantifies how strong the spatial overlap, or similarity, is between their flooded areas based on a value ranging from zero (0 = no overlap) to one (1 = identical). The result indicates how close or similar the FEMA flood maps are to the 1:100 storm event that can be readily modeled in CASCADE 2001.

For reference, Figure 43 shows the FEMA flood map in Clewiston based on the 1-percent annual chance flood (100-year event). However, it is important to note that the FEMA flood maps are not observed inundation extents, and it is unclear which data and methods are used in FEMA's map development (Jafarzadegan and Merwade, 2017). Additionally, the FEMA floodplain delineations are not necessarily tied to a particular model, leading to a subjective approach, as flood damage, repetitive loss property, and insurance-related aspects are also considered when developing maps for communities to prepare for various potential issues that might occur concurrently in the identified hazard areas.

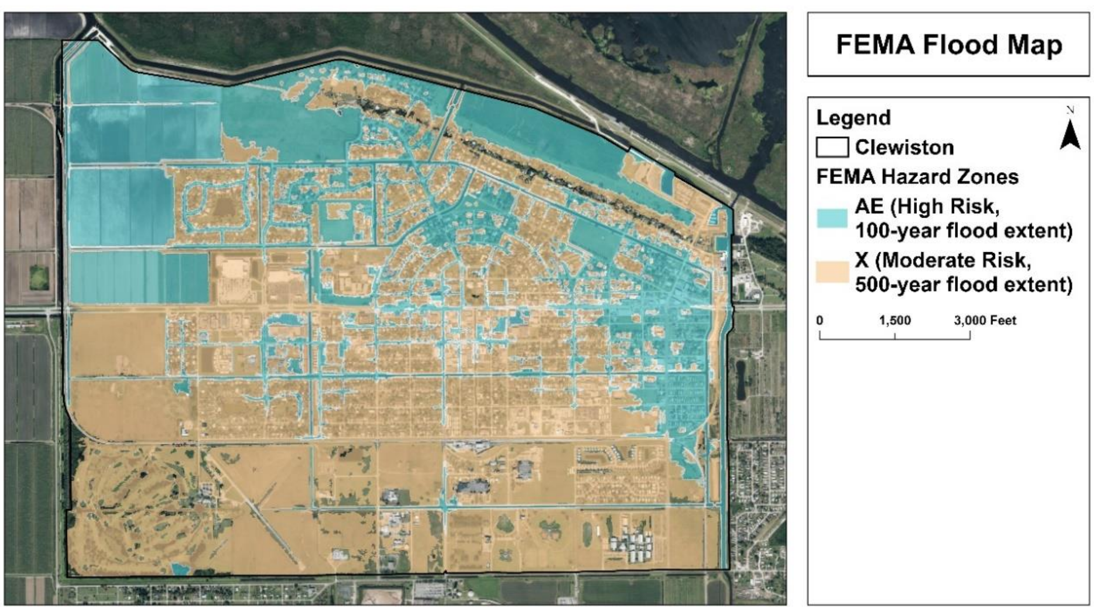


Figure 43. FEMA Flood Map in Clewiston (Effective 2020)

Of interest is whether the model captures flooding in areas where it matters most: urban areas. In other words, this flood risk screening tool should work well in developed areas. Hence, Table 13 shows the Jaccard Similarity computed based on the drill-down to the municipalities in the Caloosahatchee Watershed to assess how closely they match up with the FEMA flood maps where it matters most. This also quantifies the differences observed with downscaling, where the flood prediction improves to match the FEMA flood maps as drill-down occurs. In all urban areas, there is a greater than 70% similarity between the FEMA flood maps and the 1:100 storm event modeled using CASCADE 2001. The model prediction achieves the highest spatial similarity in Clewiston and Fort Myers with 75.0% and 88.6%, respectively.

Table 13. Jaccard Similarity Index computed between the CASCADE 1:100 and FEMA 100-year flood maps for major urban areas in the Caloosahatchee Watershed

Location	**Jaccard Similarity**
Fort Myers	0.886
Clewiston	0.750
Cape Coral	0.723
LaBelle	0.718

By visualizing the differences, the CASCADE-derived and FEMA flood maps share a high similarity in urban areas and adjacent to large water bodies; however, major differences are observed along lower order streams and the many wetlands and undeveloped areas in the Caloosahatchee Watershed. One explanation for this is based on the assumptions of the model. CASCADE 2001 only accepts a single value for each input parameter calculated as a zonal statistic defined by the boundary condition. For example, the zonal average soil storage (inches) input assumes that all land within the study area boundary has a uniform soil storage capacity. The implication is that the model drains areas such as wetlands that would not drain in reality. Additionally, CASCADE 2001's output for the maximum floodwater elevation is associated with the LiDAR-derived elevation datasets using GIS to develop flood maps. This reliance on topography causes the model to miss localized flooding in areas with potential hazards if they have ground surface elevations above the predicted floodwater elevation. Hence, the water features in Figure 16 are used as ancillary data to assume isolated and disconnected water bodies, wetlands, and frequently inundated lands not captured by the model are already full of water.

These findings suggest that the watershed-level screening analysis of flood risk is not geared toward undeveloped and isolated areas. Hence, further research is needed to calibrate the model for better flood detection in agriculture, rangeland, upland forests, disconnected water bodies, and wetlands. However, the drill-down modeling solution presented in this study provides the necessary degree of local relevance to capture nuisance-destructive flood potential with excellent detection because of the community-specific model inputs, additional infrastructure, and downscaling techniques.

4: CONCLUSION

Defining flood risk due to compounding hydrographic influences is the central concern of this document. Modeling and assessing vulnerability focused on the combination of a high water table, heavy rains, and impervious conditions that can lead to localized nuisance flooding events. Through a previous survey with local officials, the number of days of continuous nuisance flooding that the public will tolerate before that flooding is considered destructive is about four days (E Sciences, 2014).

For a large study area, small parts may actually be at risk. The point is to identify where further study might be needed. A screening tool accomplishes this goal applied to the subwatershed scale to designate areas that are susceptible to periodic flooding events. Vulnerability can be identified utilizing the information collected and analyzed. The question raised in this study was whether the large-scale screening tool would provide useful locally relevant results compared to FEMA flood maps, and how much local infrastructure and drill-down modeling impacted the results.

Three advanced GIS methods for downscaling the flood risk screening tool are presented, including the following: using multiple linear regression to map groundwater table elevations from sparse monitoring wells and LiDAR-derived DEM data, using supervised object-based classification of land cover to map impervious surfaces from spectral imagery, and using the GIS-based Arc Hydro tools to delineate catchments and drainage flow paths/outlets from elevation data when local stormwater system models are unavailable.

By combining readily available spatial and hydrologic data, a modeling protocol is developed to represent possible driving factors of flooding such as low-lying areas, a high groundwater table, poor soil storage, and heavy rains. By utilizing a well-established flood simulation model, CASCADE 2001, the maximum headwater heights of floodwaters during the 3-day 25-year and 1-day 100-year storm events were determined based on the unique characteristics and drainage structures of the Caloosahatchee Watershed to identify areas of concern that are particularly vulnerable to flooding. Furthermore, the risk associated with the Caloosahatchee Watershed's flooded area was classified as the probability of inundation to improve the identification of critical target areas that are subject to further study through drill-down modeling. Identifying these areas of concern that are highly susceptible to flooding will assist local efforts to prioritize funding for future mitigation and resiliency planning to protect vulnerable communities and infrastructure.

The comparative analysis in this study explains the impact of scale for determining flood risk in a community by comparing the predicted flood response at each level of modeling in the same location (i.e., Clewiston). The findings indicate that a watershed-level screening analysis of flood risk captures most flooding. However, the flood prediction improves to match the FEMA flood maps as drill-down occurs at the subwatershed or local scale. For all urban areas in the Caloosahatchee Watershed, there is a greater than 70% similarity between the FEMA flood maps and the 1:100 storm event modeled using

CASCADE 2001. This indicates that the model works well to capture flooding in developed areas where it matters most, although further research is needed to calibrate the model for better flood detection in undeveloped areas or isolated and disconnected water features at the watershed level. The drill-down modeling solution presented in this study provides the necessary degree of local relevance to capture nuisance-destructive flood potential with excellent detection because of the community-specific model inputs, additional local infrastructure, and downscaling techniques.

Gaps and insufficient resolution in the available technical data and pertinent information challenge the increasing need for adequate data to downscale a model. For example, there may be sparse observations of groundwater levels, inadequate detail of land cover datasets for classifying pervious and impervious land, or missing local stormwater infrastructure information that presents challenges. Without such data and information, it may be impossible to construct a small-scale model that produces locally relevant results. Hence, utilizing advanced GIS methods to extract required model parameters from limited data is one possible solution to combat these issues with downscaling.

Several challenges of downscaling were addressed; for example, it is then necessary to determine which data are needed, available, and relevant to construct a model at different scales. Finally, once downscaling is better understood, flood risk mapping and scenario modeling can support the development of comprehensive action plans that address flood resilience in the context of watershed master planning and the Community Rating System.

APPENDICES

Appendix A. Datasets

Table A-1. List of datasets collected by FAU (2020)

Data Category	Dataset Name	Original Source	Spatial Coverage/ Resolution	Temporal Coverage/ Resolution	Physical Location on Server	Dataset size and Format	Native or FAU Processed dataset
Topography	USGS_NED	USGS	Part of Florida, Raster data in 3m	Created by USGS, various years	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\LiDAR_DEM\DEM_3m	40.9G bytes, raster images	Native
	USGS_DEM	USGS	Florida, Raster data in 10m	Created by USGS, various years	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\USGS_DEM	22.6 G bytes, raster images	Native
	DEM_3m_merged	USGS	3m in tiff	Various years	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\LiDAR_DEM\DEM_3m_merged	186G bytes, raster images	FAU Processed
Groundwater	FL_GW	South FL Water Management District	Florida, Excel	Daily, 1980-2020	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_GW\South Florida District	140 M bytes, excel	Native
Surface Water and Tides	Tidal	NOAA's Tides and Currents CO-OPS SOAP Web Services	State of Florida, Excel	Every 6 minutes since 1920, excel	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\Tidal\	1.37 G bytes, excel	FAU Processed
Soil	FL_Soil	FY2019 USDA Soil SSURGO gSSURGO) Database https://sdmdataaccess.nrcs.usda.gov/	Florida, Raster data is in 10m	Released by USDA in 2019	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_soil Processed data for water holding capacity ratio is at: \\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_soil\aws0_150_whc1.tif	107G bytes, both vector and raster	FAU Processed

Data Category	Dataset Name	Original Source	Spatial Coverage/ Resolution	Temporal Coverage/ Resolution	Physical Location on Server	Dataset size and Format	Native or FAU Processed dataset
Land Cover	USGS_LC	USGS	Conterminous United States, raster format, 30m derived from satellite	Created by USGS in 2016 (Most recent)	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\USGS_LC\NLCD_2016_Land_Cover_L48_20190424	20G bytes, raster	Native
	Impervious Surface	USGS	Florida, 30m derived from satellite	Created by USGS in 2016 (Most recent)	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\Impervious\NLCD_2016_Impervious_descriptor_L48_20190405\	24.6G Bytes, Raster Image	FAU Processed
Drainage Structures	AHED_Structures	South FL Water Management District	Part of Florida, Point Shapefile	Created by SFWMD, Updated in 2018	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\Flood_structures\SFWMD\AHED_Structures	1.33 M bytes, Vector Shapefile	Native
Precipitation Records	FL_NOAA14_Precipitation	NOAA Atlas 14 Database	Florida, raster in 800m	Most recent release from NOAA	\\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_NOAA14_Precipitation\se25y3d_inch.tif	34 M bytes, raster images	FAU Processed, 3 day-25 year and 3 day-100 year

Table A-2. Explanation of data usage from Table A-1 (List of datasets collected by FAU)

Dataset Name	**Description**
d2minwte_ft	Depth in feet to the local minimum water table created by the expression “dem_resample” minus “minwte_ft”
d2wte_ft	Depth in feet of the unsaturated zone soil layer created by the expression “dem_resample” minus “wte_ft” and using the conditional function to reassign negative values to zero
dem_ft	Digital elevation model (3-meter cell size) with vertical units in feet created by mosaicking available 3-meter data obtained from the \\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\LiDAR_DEM\DEM_3m_merged\MERGED folder and 10-meter DEM data to fill gaps obtained from the https://viewer.nationalmap.gov/basic/ website
dem_resample	Resampled digital elevation model for calculations (10-meter cell size) with vertical units in feet created by resampling “dem_ft” raster dataset
impervious	Binary land classification of 0 = impervious surfaces, and 1 = pervious surfaces obtained from \\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\Impervious\ImperviousBinary\Binary_Impervious_OK.dat
inundation	Probability of inundation (flood risk) Z-score surface created using maximum headwater heights of 6.94, 10.53, and 15.82 feet and the “dem_ft” raster dataset clipped to the Tidal, West, and East Subwatershed feature class in the expression [headwater height] minus [DEM] divided by 0.46
minwte_ft:	Local minimum water table with vertical units in feet created using the Empirical Bayesian Kriging function to run an interpolation with the observed surface water stations DBHYDRO data and pseudo-station point elevations
rain_25y3d_in	Estimated precipitation for a 3-day 25-year design storm obtained from \\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_NOAA14_Precipitation\se25y3d_inch.tif
ssc_inch	Soil storage capacity in inches created by the expression “d2wte_ft” times “whc_ratio” times “impervious” times “water” times 12
water	Binary classification of 0 = water, and 1 = land obtained from \\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_Waterbodies\Water_Raster\Binary_Water.tif
whc_ratio	Water holding capacity ratio surface obtained from \\engsynws01.eng.fau.edu\Project_mastercopy\Datasets\FL_Soil\aws0_150_whc1.tif
wte_ft	Water table elevation with vertical units in feet generated using a multiple linear regression equation of “wte_ft = (0.9748 * minwte_ft) + (0.0363 * d2minwte_ft) + 1.8391”

Appendix B. Ninemile Canal Subwatershed and Clewiston

Ninemile Canal Subwatershed

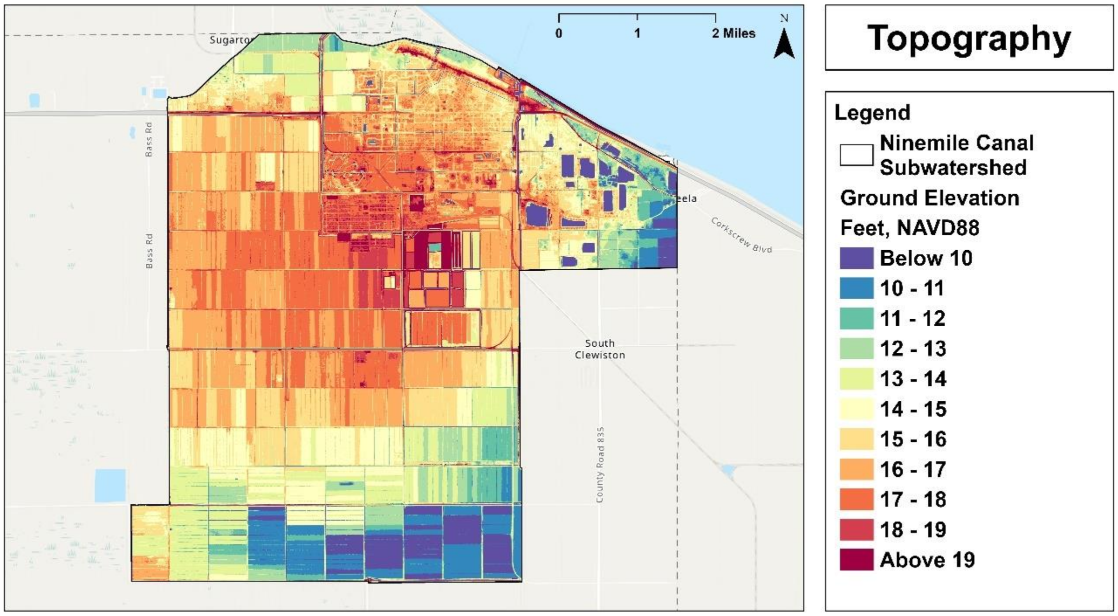


Figure B-1. Surface Topography of the Ninemile Canal Subwatershed

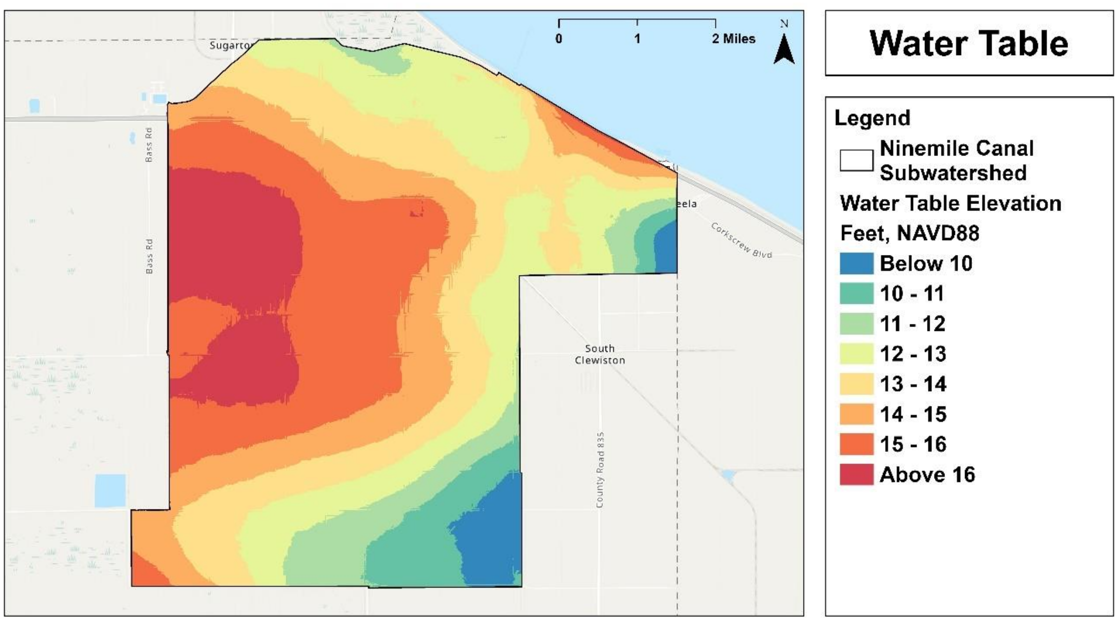


Figure B-2. MLR-generated water table elevations in the Ninemile Canal Subwatershed

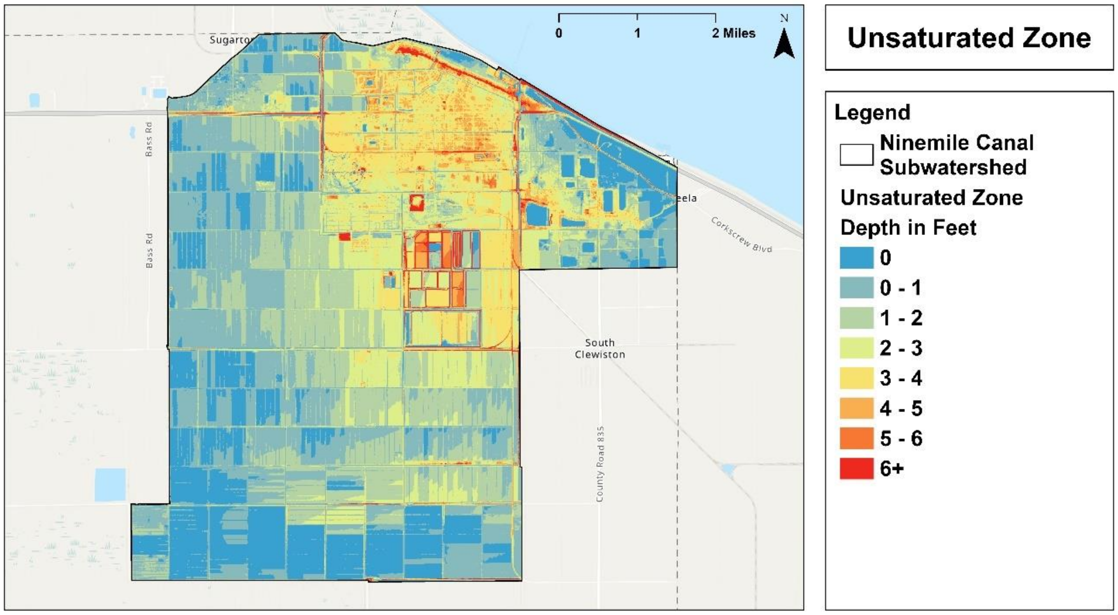


Figure B-3. Unsaturated Zone Depth in the Ninemile Canal Subwatershed

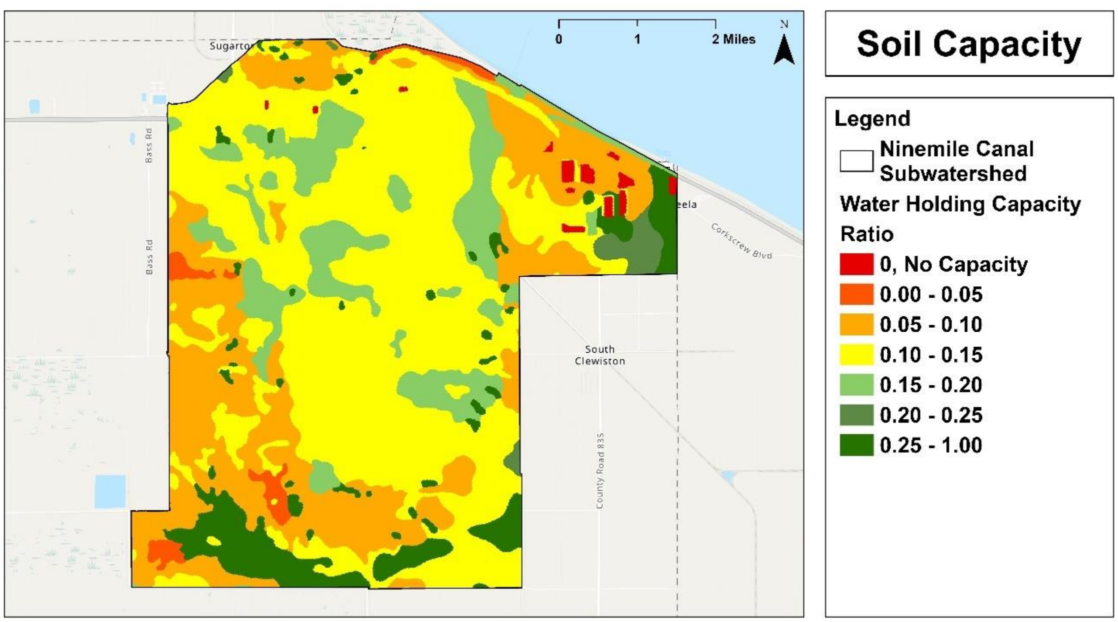


Figure B-4. Soil Water Holding Capacity in the Ninemile Canal Subwatershed

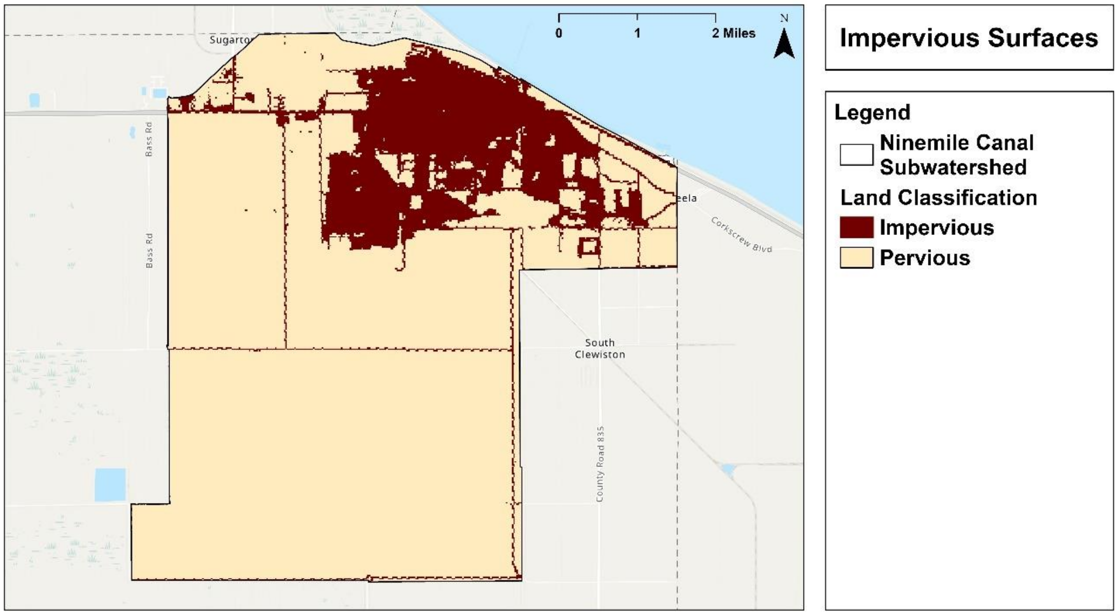


Figure B-5. NLCD 30-meter impervious layer in the Ninemile Canal Subwatershed

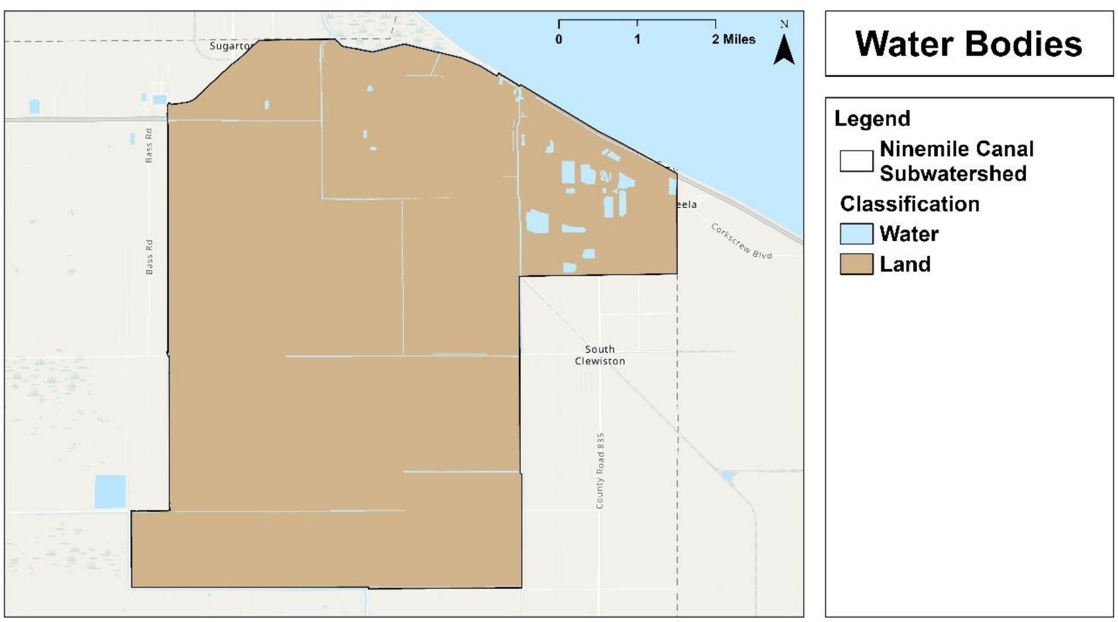


Figure B-6. Water Bodies in the Ninemile Canal Subwatershed

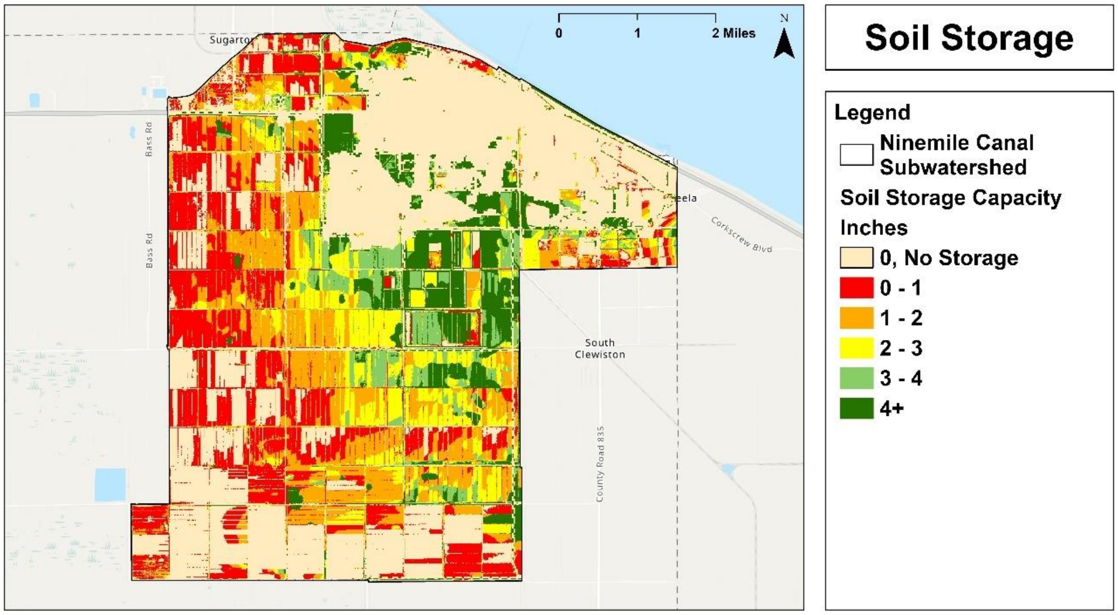


Figure B-7. Soil Storage Capacity in the Ninemile Canal Subwatershed

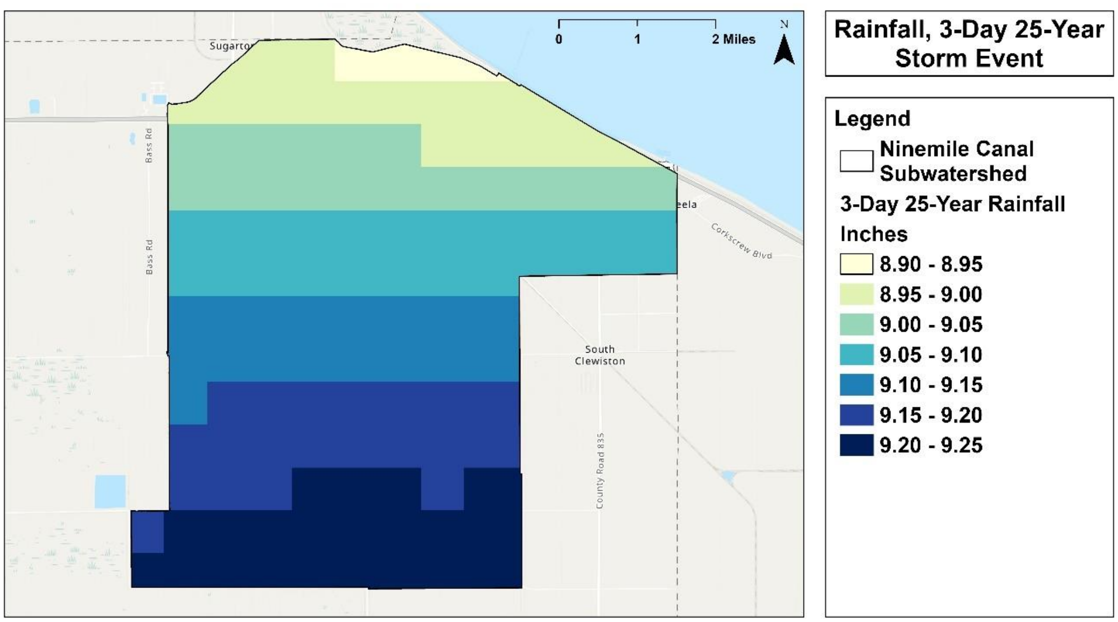


Figure B-8. Rainfall for a 3-day 25-year Storm in the Ninemile Canal Subwatershed

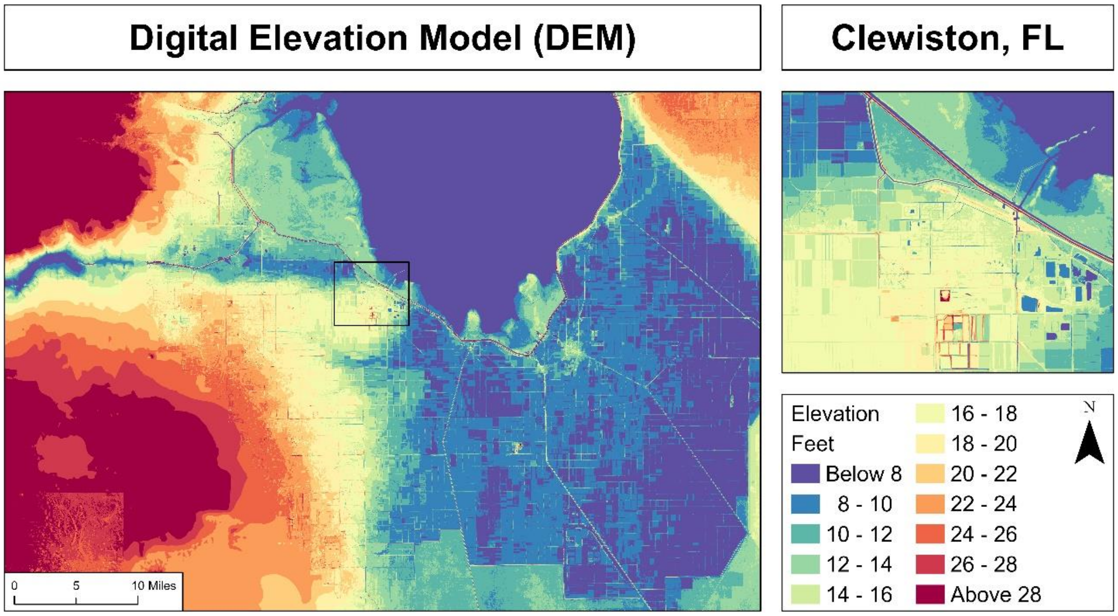
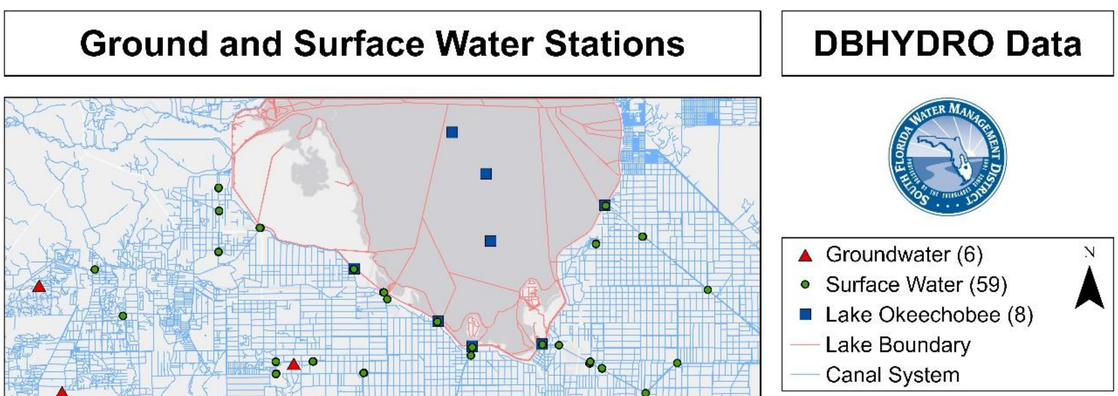


Figure B-9. Surface Topography in the City of Clewiston



Station	ft NGVD	ft NAVD	Date
C-1075	30.82	29.54	29-Oct-2017
HE-517	10.99	9.75	29-Oct-2017
HE-856	28.29	26.96	29-Oct-2017
HE-860	26.48	25.13	29-Oct-2017
HE-1069	19.55	18.24	29-Oct-2017
HE-1077	28.93	27.65	29-Oct-2017

Figure B-10. Station-based Observation Data in the City of Clewiston

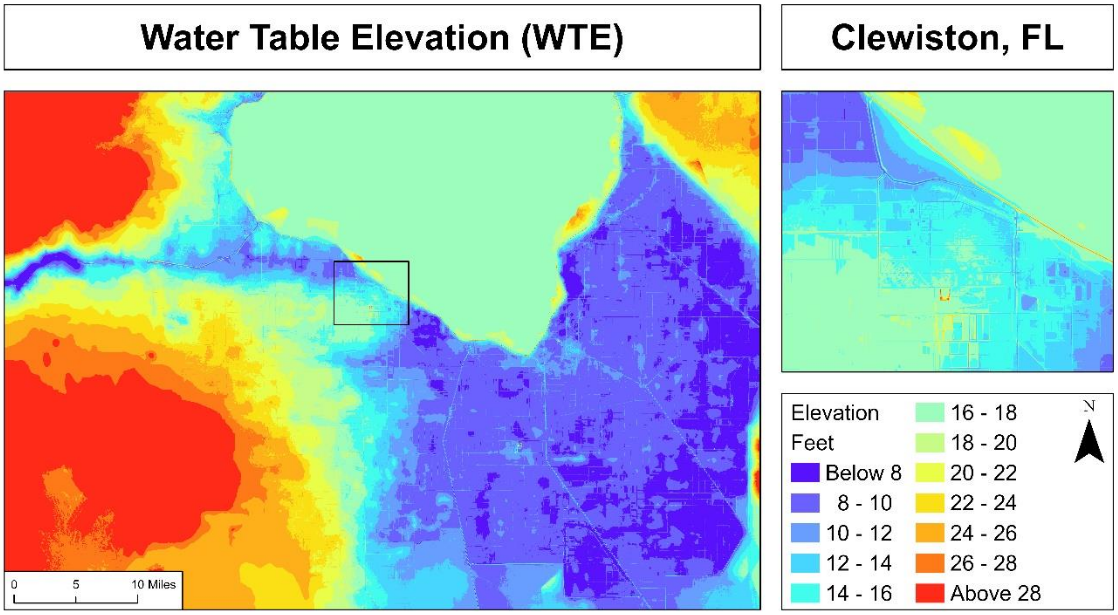


Figure B-11. MLR-generated Water Table Elevation in the City of Clewiston

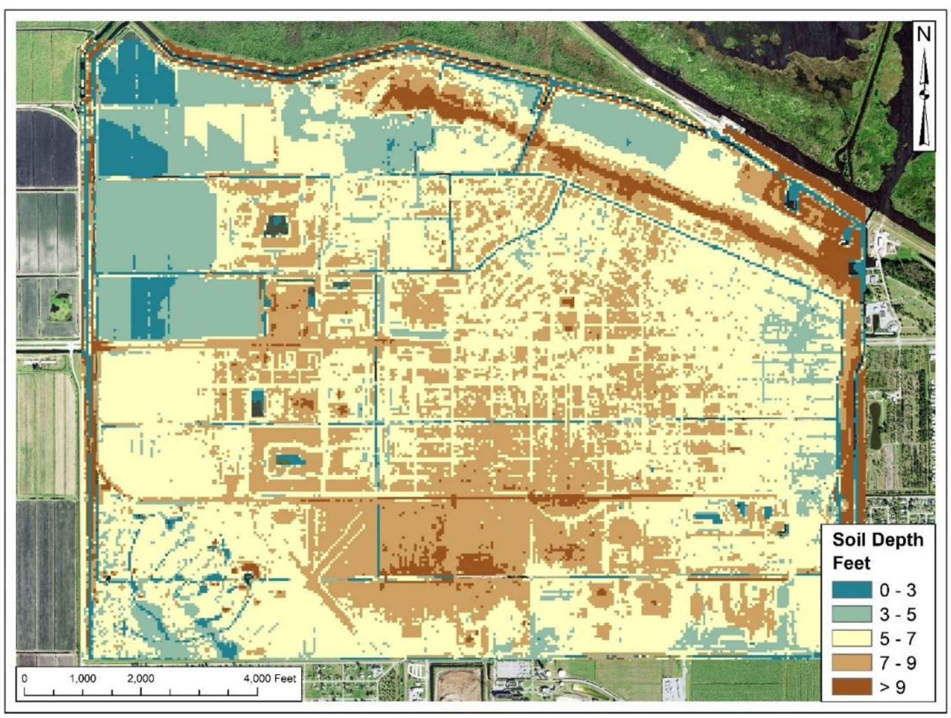


Figure B-12. Unsaturated Zone Depth in the City of Clewiston

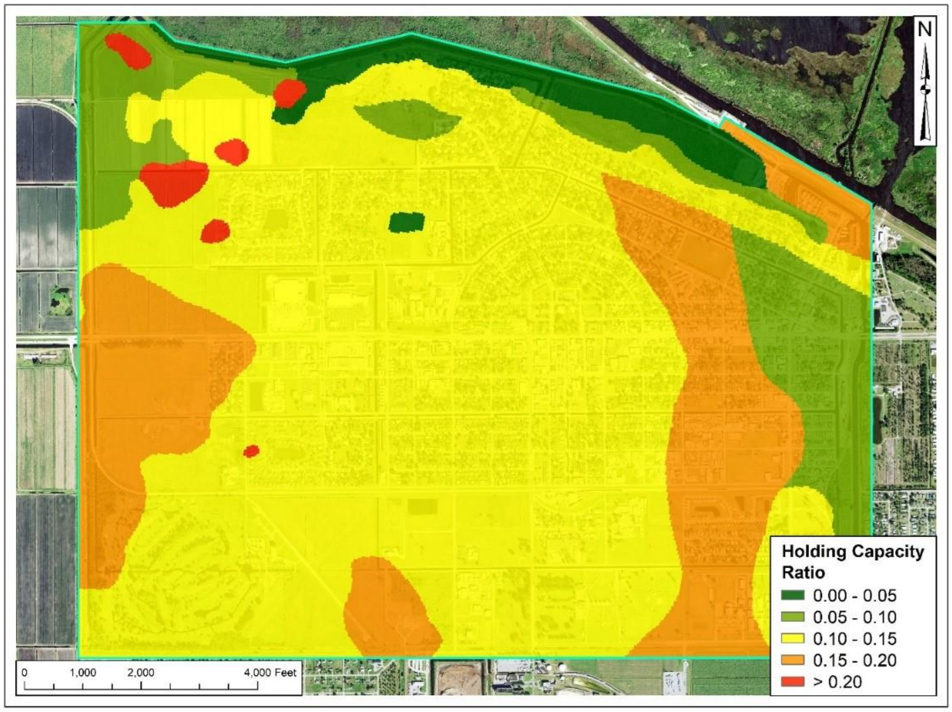


Figure B-13. Soil Water Holding Capacity in the City of Clewiston

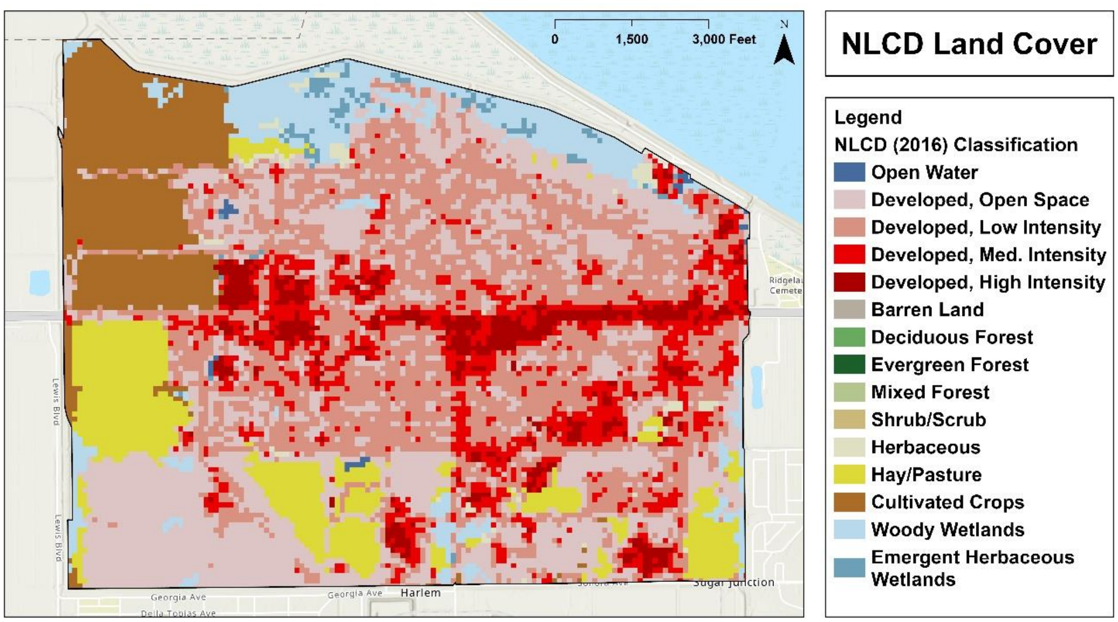


Figure B-14. NLCD 2016 Land Cover in the City of Clewiston

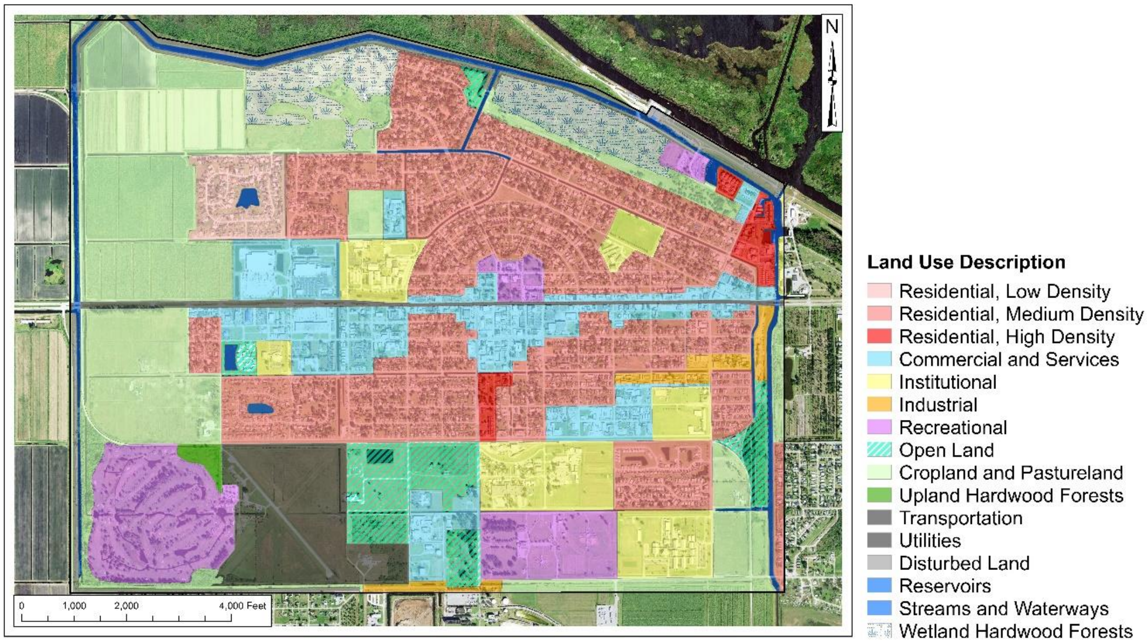


Figure B-15. SFWMD 2014–16 Level-2 Land Use Land Cover in Clewiston

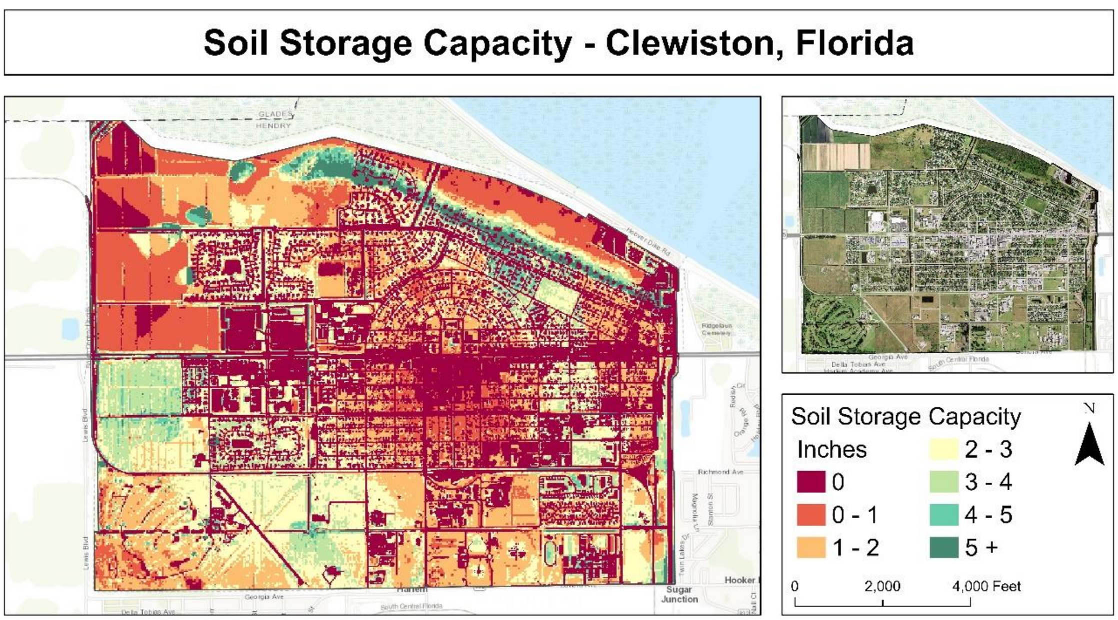


Figure B-16. Soil Storage Capacity in the City of Clewiston

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