Appendix

Outline of Modeling for Watershed Master Plan

CENTER FOR WATER RESILIENCY AND RISK REDUCTION
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Disclaimer

This document is a watershed master plan that rolls up the results for all HUC12 subwatersheds affecting the community. This document refers to regulatory provisions that contain legally binding requirements. However, this document does not impose legally binding requirements. Local government decision-makers retain the discretion to adopt or modify the approaches described in this document. Adoption of the suggestions or recommendations herein will not necessarily constitute approval during Community Rating System (CRS) cycle verification visits. Interested parties are free to raise their opinion about the appropriateness of the application of the guidance to a situation, and FDEM will consider whether the recommendations in this guidance are appropriate in that situation to make changes to this guidance document in the future.

EXECUTIVE SUMMARY

As a part of a meeting with ISO representatives, FAU was asked to provide some added detail to the modeling process. This appendix serves as that information. Per these discussions, the following information was asked for:

1. *Demonstration that each watershed plan that has analyzed the impact of sea level rise and/or fully developed watersheds on your community during a 100-year event. To meet the WMP1 criteria for modeling, ISO requested a copy of each watershed plan that demonstrates that the Subrecipient has analyzed the impact of sea level rise and/or fully developed watersheds on your community during a 100-year event. To be credited, the plan must have a plan to control the impacts of the 10-year event and the 25-year event on the community. Credit for onsite control of the 10-year event and the 25-year event or the 100-year event is an acceptable method of controlling the impacts.*

   This involves several issues:

   1. *Explain the model and how it reaches conclusions (basically how the model works)*
   2. *Explain sea level rise scenarios as applicable of 5 ft and greater*
   3. *Explain how 100 year storm event is assessed*
   4. *Explain drilldowns and solutions from drilldowns in Sections 5.2-5.4*
   5. *Explain how existing infrastructure is used*
   6. *Explain how and what assumptions were used for the future condition*
   7. *Show implementation of solutions to resolve flooding in at least 1 HUC12*
   8. *Link capital plan with solutions in #7*
   9. *Determine the volume of detention*

RESPONSE: All of these are related to the modeling so this lengthy appendix was developed from FAU's Phase I effort. ISO indicated that they were ok with using the 1 day 100 year event in place of the 1-day 25-year event and requested that the sea level rise scenarios include king tides which was done. Sea level rise (as applicable, king tides + sea level rise and 1-day 100-year storm events (and the combination for all 3 as applicable) were performed for the community. This is explained in Sections 2.3 (surface water and tides) and 2.7 Rainfall events in this document, and in Chapter 2 and 4 of the plans for the community. Note some communities have limited data on infrastructure, and in many circumstances they do not control the operation or maintenance of the infrastructure that does exist.

2. *The community and must have aa adopted plan to control the impacts of the 10-year event and the 25-year event on the community. Note, to be credited, the plan must have been adopted and implemented by the community*

RESPONSE: The plans will be adopted once ISO approves the draft plan. Each community has at minimum, a 1-day 25-year storm event control requirement within their current ordinances and regulations. Permits from the water management districts are used to enforce these requirements. Note there are state-wdie requirements, and then a Part2 to the environmental resource permitting system specific to each district to control flooding. This regulatory framework is very different than most other parts the the county and is related to the potential for tropical events to disrupt communities. As a result, the concept throughout the state is that new development does not exacerbate current conditions. In urban areas, the move is to create more retention that currently exists, as opposed to creating more impervious areas because downstream (and upstream) flooding has been ongoing challenges for decades. The regulatory framework is outlined in Chapter 3, including a summary table.

3. *WMP requires an explanation on how the plan manages future peak flows and the volume of runoff from new development so that it doesn't increase over present values. A community must demonstrate that its watershed management plan and associated regulations prevent increases in peak flows at all points within its watershed(s) and downstream. ISO notes that credit for onsite control of the 10-year event and the 25-year event or the 100-year event is an acceptable method of controlling the impacts.*

RESPONSE: The 1-day 100-year event was modeled for all communities, in addition to king tides and 5 feet of sea level rise where applicable, as was the 1-day 10-year and 1-day 25-year events. The concept was to determine where flooding was increased in response to added rainfall or where tipping points occurred in coastal communities. See Section 2.3 and 2.7 of this document and Chapter 3 for application. Note, ISO was ok with using the 1 day 100 year event in place of the 1-day 25year event and requested that the sea level rise scenarios include king tides which was done. Also 3.1.2.

1. *WMP 4 requires an explanation about how the plan manages the runoff from all storm scenarios and where to the 1-day 25-year event and identification about where to find that in the plan itself. Refer to specific regulations or standards. Each scenario that is greater than 1-25 should include solutions for the flooding. This part of the plan and the local community input should be a part of this. The sections of the plan need to be identified.)*

RESPONSE: See chapter 4 for a step by step of how the model works and a comparison to other models in Chapter 2. The benefit of CASCADE 2001, as used and modified by FAU and the South Flroida Water Management District is that is builds on HEC-HMS and adds groundwater, tides and the intensive GIS needs for the CRS credits, and merges all the data into a program whereby flooding can be identified and the risk for same applied. FAU has modified the outputs to address the probability of flooding so that added effort can be focused on the critical needs areas. Note FAU included, as a part of the modeling exercise, critical land uses, a means to prioritize projects and a probability function, none of which are part of other models

5. *Explain drilldowns and solutions from drilldowns in 5.2/5.3*

RESPONSE: The drilldowns are a remodeling at a smaller scale, of the areas identified in Chpater 4 as being most at risk to flooding. As indicated in Hidle et al 2024, the methods used by FAU is scalable without losing significant accuracy (a zoom from a HUC 8 to a 4 sq mile community yielded 1 inch difference in flood elevation, which is within the z-score for risk). However, remodeling allows the project team to test solutions, which the larger scale does not given that for larger scale areas, large scale infrastructure is the driver, whereby at the local level, localized infrastructure matters more. Note Fau does not assume there are maintenance issues with the infrastructure, which is an unlikely conditions, but determining what the actual conditions will be during a future storm event is not possible to postulate.

6. *Explain future condition usage*

RESPONSE: FAU used a algorithm to create future land use based on current regulations and project land use patterns form local communities (see Section 2.5), as applicable to each community

RESPONSE:

7. *Explain how infrastructure is used*

RESPONSE: Communities pick infrastructure that is acceptable, based on suggestions from FAU and the “Periodic Table of Solutions” during the process. Certain communities may find certain solutions to be unacceptable today. FAU takes a long-term view of this which is why the conclusion section outlines longer term issues. The periodic table of solutions is included in every plan. Some solutions work under certain conditions only -i.e. green and natural solutions tend to work for surge, not sea level rise. Increase land protection is a policy decision that can be made from this plan. The capital plan reflects current efforts. In some cases, the plan illuminates problem areas not clear to the community so budgeting will need to occur in subsequent years. In some cases, there are no solutions. Note that form most coastal plants, modeling indicates that a tipping point exists between 2-3 ft of sea level rise, as this is the point where most current sea walls will be overwhelmed since the average height is only 3-3.5 ft in most coastal communities. Therefore, the following should be long-term policy changes for the community:

1. Conduct neighborhood studies on flood-prone areas to determine where pumping stations may be needed. Note regional pumping by the SFWMD and USACE will be needed to solve the long-term flooding trends
2. Implement policy changes to increase finished floor elevations over time in response to changes in sea level rise. A start would be to increase the finished floor elevation minimum height for all new construction to 2 ft freeboard above the FEMA floor elevation.
3. Upon reaching 1 ft of sea level rise above current levels, increase the finished floor elevation again by one foot and continue that pattern. An increase of 1 ft in sea level is likely at least 30 feet away. Since housing averages less than 50 years before demolition and rebuilding in Florida, this would permit a gradual increase in finished floor elevations without negatively impacting an excessive number of residents at any one time.
4. Establish ongoing funding to implement stormwater infrastructure programs. This could include State Revolving Funds which can be used for stormwater projects

Note the 2-3 ft sea level rise scenario is not immediate and it is well beyond the 5 year life of the watershed plan. Hence many solutions do not need to be implemented until such time as the need exists. In addition, many solutions can be implemented as redevelopment of communities occurs, as opposed to expensive hard construction paid for by local governments today. The key is regulatory control for the future.

8. *Show implementation of solutions / Link capital plan with solutions*

RESPONSE: See drilldown solutions in each plan – these are outlined in the respective plans (Chapter 5.2 and 5.3 in most cases) and the associated capital element for the paln.

9. *Explain flooding*

RESPONSE: Flooding is probability based (see based on water levels and the Fau infused AI tools for predictive modeling. These can be converted to depth grids, however the accuracy of the Lidar data suggest that flooding may not be present in all placed flooding is indicated, and vice versa. Hence those “hazy” areas are indicted with less than 100% probability, but not zero probability.

10. *Volume of detention*

RESPONSE: The volume of detention is a function of the basin. Because of the flat surface in Florida, especially along the coast, detention is a challenge. Mor important is the push to move water offshore vial pumping station, or to prevent incursion via raised sea walls. The volume detained can be gleaned fr Chapter 4

11 . *Explain how the plan manages the runoff from all storm scenarios up to and including and where to find that in the plan itself. Refer to specific regulations or standards.*

RESPONSE: See Chapter 3

The issues requested by ISO for the relevant WMP 1-8 are included in the appendices and the plan. Note none of the Florida communities qualify for WMP8 or WMP7 so those will not be discussed.

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List of Acronyms

3DEP	3D Elevation Program
AADT	Annual Average Daily Traffic
AWS	Available Water Storage
BMAP	Basin Management Action Plan
BWA	Biggert-Waters Flood Insurance Reform Act of 2012
CAAP	Climate Adaptation Action Plan
CERP	Comprehensive Everglades Restoration Plan
CFU	Colony Forming Units
CPA	Community Planning Act
CRS	Community Rating System
CWA	Clean Water Act
DEM	Digital Elevation Model
DSS	Data Storage System
EMAP	Environmental Monitoring and Assessment Program
ESRI®	Environmental Systems Research Institute, Inc.
FAC	Florida Administrative Code
FAU	Florida Atlantic University
FDEP	Florida Department of Environmental Protection
FDEM	Florida Division of Emergency Management
FDIC	Federal Deposit Insurance Corporation
FDOT	Florida Department of Transportation
FDPA	Flood Disaster Protection Act of 1973
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Studies
FLUCCS	Florida Land Use, Cover, and Forms Classification System
FMP	Floodplain Management Plans
FTA	Federal Transit Administration
FTP	Florida Transportation Plan
IDF	Intensity Duration-Frequency
IPH	Inches Per Hour
LMS	Local Mitigation Strategy

FRR	Flood Risk Reports
GIS	Geographic Information Systems
GO	General Obligation
GPS	Global Positioning System
GW	Ground Water
HUC	Hydrologic Unit Code
IPCC	Intergovernmental Panel on Climate Change
LEED	Leadership in Energy and Environmental Design
LiDAR	Light Detection and Ranging
LOS	Level of Service
MEOW	Maximum of the Maximum Envelope of High Water
MFL	Minimum Flows and Levels
MINWTE	Minimum Water Table Elevation
MLR	Multiple Linear Regression
MOM	Maximum of the Maximum Envelope of High Water
MPO	Metropolitan Planning Organization
MRLC	Multi-Resolution Land Characteristics Consortium
MS4	Municipal Separate Storm Sewer System
NCDC	National Climatic Data Center
NCSS	National Cooperative Soil Survey
NCUA	National Credit Union Administration
NeXRAD	Next-Generation Radar
NFIA	National Flood Insurance Act
NFIP	National Flood Insurance Program
NLCD	National Land Cover Database
NOAA	National Oceanographic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
NRI	Natural Resources Inventory
NWFWMD	North West Florida Water Management District
NWI	National Wetlands Inventory
OCC	Office of the Comptroller of the Currency
QL2	Quality Level 2
RCAP	Regional Climate Action Plan

RDA	Rural Development Administration
RiskMAP	Risk Mapping, Assessment, and Planning
RMSEz	Vertical Root Mean Square Error
SAR	Synthetic Aperture Radar
SCS	Soil Conservation Service
SFHA	Special Flood Hazard Area
SFRCCC	Southeast Florida Regional Climate Change Compact
SFWMD	South Florida Water Management District
SJWMD	St. Johns River Water Management District
SLOSH	Sea, Lake and Overland Surges from Hurricane
SQL	Standard Query Language
SRESP	Statewide Regional Evacuation Study Program
SRF	State Revolving Fund
SRWMD	Suwanee River Water Management District
SW	Surface Water
SWFWMD	South West Florida Water Management District
SWIM	Surface Water Improvement and Management
SWPPP	Stormwater Pollution Prevention Plans
TMDL	Total Maximum Daily Loads
ULDR	Unified Land Development Regulations
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WMD	Water Management District
WMP	Watershed Master Plan
WTE	Water Table Elevation

1.0 DEFINING THE WATERSHED PLANNING PROCESS

The purpose of this document is to outline the process for modeling watersheds for communities interested in producing or adopting a watershed master plan for the purposes of reducing local flood risk and maximizing Community Rating System (CRS) credits. To this end, the Florida Division of Emergency Management contracted with Florida Atlantic University in late 2019 to develop a mechanism for modeling watersheds throughout the state and to develop a template to be used for watershed master plan development using the Florida Division of Emergency Management's Bureau of Mitigation for Hazard Mitigation Grant Program DR-4337-004-P. The tasks relevant to the modeling were as follows:

> "Task 2.2 – Determine an appropriate methodology for selection and prioritization of potential funding recipients under the Watershed Master Planning Initiative Pilot Program. The Sub-recipient will develop a screening tool and apply it to selected basins from the 29 Florida Total Maximum Daily Load (TMDL) Basins diagram to designate areas that are susceptible to periodic flooding events. Utilizing the information collected and analyzed in Task 1, the Sub-recipient with input from FDEM will determine an appropriate study scale for WMPs (e.g., watershed vs sub-basin vs sub-sub-basin or river vs tributary, etc.). In order to prioritize sub-basin level vulnerability, the development of a flood risk scoring system or relative needs index with appropriate criteria will be required. A basic total risk score can be created with stakeholder input based on a weighted composite score of likelihood of failure and consequence of failure (Scott and Smith 2019).
>
> Deliverable 2.2: A report summarizing the screening tool methodology, flood risk scoring system, and preliminary justification for the basins selected for validation.
>
> Task 2.3 – Validate screening tool. Conduct the first run of the screening tool for at least one coastal watershed (basin with a direct marine boundary), such as Basin 28: Lake Worth Lagoon – Palm Beach Coast to confirm that the screening tool is functioning properly. Comparison with repetitive loss property maps (in GIS) will be used to assess accuracy. Initial screening results derived from lower resolution data will be evaluated by local stakeholder groups. The screening tool will highlight areas that are "Vulnerable," "Potentially Vulnerable," or "Less Vulnerable" using the definitions of the Army Corps of Engineers and delineated by Romah (2012). The screening tool will focus at a tile level coarser than 3 m × 3 m.

The Sub-recipient will validate the methodology for non-coastal watersheds (basins without direct marine boundaries), at least one inland area, such as Basin 20: Kissimmee River or Basin 25: Lake Okeechobee will be selected to represent non-coastal scenarios. The inland areas will use the boundary conditions derived from the coastal areas.

Deliverable 2.3: A report summarizing the results of screening tool method validation and maps for selected coastal and non-coastal watersheds.

Task 2.4 – Validate higher resolution scale screening methodology for determining most vulnerable areas. “

Based on the basin-wide effort in Task 2.3, the Lidar data can be reduced to 3 m × 3 m tiles for high-resolution screening for more localized areas of the basins. This is very data intensive and time-consuming but will assist in identifying vulnerable focus areas within the larger watershed context. In this task, the basins analyzed in Task 2.3 will be re-evaluated by the Sub-recipient at a higher resolution. Additional criteria that may be applied include but are not limited to the following: amount, number, and distribution of flood insurance claims; number and concentration of Repetitive Loss and Severe Repetitive Loss properties; pace and distribution of development pressures; and/or number of flood insurance policies in the study area. Water quantity will remain the focus at this screening level. Water quality would occur at a more detailed and local level; therefore, is beyond the scope of this task.

FDEM with assistance from the Sub-recipient will submit data and results from this effort to local stakeholders and the local water management district for input as a part of a stakeholder meeting to be arranged by FDEM. The comments will be included in an updated run of the screening tool. Note Tasks 2.3 and 2.4 may be performed concurrently if the resolution permits.

Deliverable 2.4: Maps of the more specific areas screened.

Task 2.5 – Apply screening tool to remaining watersheds

Concurrent with Task 2.3, the Sub-recipient will apply the screening tool at low resolution for remaining watersheds to identify most vulnerable areas.

Deliverable 2.5: A map of each watershed highlighting critical area(s.

TASK 3 – TEMPLATE DEVELOPMENT

Task 3.1 – Create a guidance document for screening tool implementation.

Based on the results of Task 2, the Sub-recipient will develop a guidance document/instruction manual that outlines how to implement the screening tool methodology and flood risk scoring system for users.

Deliverable 3.1: Guidance document – complete - delivered via Dropbox to FDEM.

Task 3.2 – Create a template for watershed master plans (best practices guidance document).

Based on the data gathered from Tasks 1.1 and 1.2, the Sub-recipient will create a template to identify best practices for WMP integration into existing Local Mitigation Strategies and provide support data and mapping to initiate the process for community uprating. Note that much of the data will be gleaned from Task 2 activities. As a part of the template, the Sub-recipient will collect and organize best practices for achieving CRS points. The Sub-recipient will present and discuss the information to the FDEM before proceeding with development of a draft plan for a community chosen by the parties herein.

Deliverable 3.2: Best practices document outlining the Florida-specific framework and technical assistance for the Watershed Master Planning Initiative Project to include elements for riverine and coastal scenarios."

The main outcome of this grant program was to assist the Florida Division of Emergency Management (FDEM) to increase adoption of watershed master plans by communities in the State of Florida to improve the CRS ratings and reduce flood insurance premiums. Based on the basin-wide effort in Task 2.3, the available topographic Lidar data across the State permits the use of DEM tiles for high-resolution screening at the regional and at the more localized areas of the HUC8 and HUC 12 subbasins. Basing the modeling on this level/scale of data for larger regions is very computer intensive and time-consuming, but will assist in identifying vulnerable focus areas within the larger watershed context and permitting drill-downs into areas identified as being the most at-risk. In other words, intense data can serve both regional and localized scales without the need to reprocess the data tiles. Flood risk can then be scrutinized where it matters most, while setting those less likely areas aside.

The following sections outline the data needs and general sources used to acquire or access data, followed by a discussion of how the data is used to create flood risk models. Of note, FAU's preference has been to provide flood risk, and opposed to depth grids because of the ability to work with people who claim flooding (or not) occur regularly, and to address the accuracy of the Lidar data collected (coastal areas are often +/- 4.6 inches).

1.1 Purpose of the CRS Watershed Master Planning Process

Per the CRS Coordinator's Manual, the "objective of watershed master planning is to provide the communities within a watershed with a tool they can use to make decisions that will reduce the increased flooding from development on a watershed-wide basis." Successful watershed master plans:

1. Evaluate the watershed's runoff response from design storms of various magnitudes and durations under current and predicted future conditions,
2. Assess the impacts of sea level rise and climate change,
3. Identify wetlands and other natural areas throughout the watershed,
4. Protect natural channels,
5. Implement regulatory standards for new development such that peak flows and volumes are sufficiently controlled,
6. Include specific mitigation recommendations that should be implemented in order to ensure that communities are resilient in the future, and
7. Have a dedicated funding source like a stormwater utility in place in order to implement the mitigation strategies recommended by the plan.

The CRS Coordinator's Manual notes that "there is a large amount of documentation that must be assembled in order to take credit for this element. In addition, the impact adjustment map communities must create requires a large amount of data and some GIS expertise." In addition, "If parts of the watershed are outside the community's jurisdiction coordination with the other communities is required. In addition, hydrologic modeling is required to determine the present and future runoff conditions." This situation is present in virtually every community. To wit, the minimum standard that is required is "that runoff from all storms up to and including the 25-year event be managed, and ensure that future peak flows do not increase over current rates. In addition, some coastal communities are required to evaluate the effects of sea level rise." "One strategy for reducing the effort associated with implementing this CRS element is working with neighboring communities that share watersheds. Working with other communities can help to maximize credits for the CRS element because of the way the impact adjustment is calculated."(https://floodsciencecenter.org/products/crs-community-resilience/element-profiles/452-b-watershed-master-plan/).

1.2 Overview of the Watershed

By definition, the WMP process focuses on a specific watershed, which is a geographic area that is defined by a drainage basin. A watershed master plan should address a geographic area large enough to ensure that implementing the plan will address the major sources and threats of impairment to the basin and its waterbodies under review. Although there is no rigorous definition or delineation of this concept, the intent is to avoid focus on single waterbody segments or other narrowly defined community or neighborhood areas that do not provide an opportunity for addressing larger scale watershed stressors in an efficient manner. The United States Geological Survey (USGS) created a nationwide system based on surface hydrologic features, referred to as hydrologic units, which are part of a watershed mapping classification system showing various areas of land that can contribute surface water runoff to designated outlet points, such as lakes or stream segments. These units are arranged in a nested, hierarchical system identified using a unique Hydrologic Unit Code (HUC), forming a standardized system for organizing, collecting, managing, and reporting hydrologic information across the nation. Hydrologic unit codes (HUC) are developed using a progressive two-digit system where each successively smaller areal unit is identified by adding two digits to the identifying code the smaller unit is nested within. USGS designates drainage areas as subwatersheds (including smaller drainages) numbered with 12-digit hydrologic unit codes (HUCs), nested within watersheds (10-digit HUCs). These are combined into larger drainage areas called subbasins (8 digits), basins (6 digits), and subregions (4 digits), which make up the large regional drainage basins (2 digits).

Subwatershed << Watershed << Subbasin << Basin << Subregion << Region

This system divides the country into 21 regions (2-digit), 222 subregions (4-digit), 370 basins (6-digit), 2,270 subbasins (8-digit), ~20,000 watersheds (10-digit), and ~100,000 subwatersheds (12-digit) (USEPA, 2008). describes the system's hydrologic unit levels and their characteristics, along with example names and codes.

Table 1. HUC codes and levels (USEPA, 2008)

Name	**Digits**	**Average size (square miles)**	**Number of HUCs (approximate)**	**Example code (HUC)**
Region	2	177,560	21	17
Subregion	4	16,800	222	1706
Basin	6	10,596	370	170601
Subbasin	8	700	2,200	17060102
Watershed	10	227 (40,000 –250,000 acres)	22,000	1706010201
Subwatershed	12	40 (10,000 –40,000 acres)	160,000	170601020101

To meet the goals of developing a watershed master plan, the subwatershed scale was chosen (the HUC-12 level) and the result mosaicked to a community level map. Each HUC12 is included in the plan appendices. In many cases, the HUC12s needed to be divided further because of riverine branching, structures and other infrastructure.

1.2.1 Hydrologic Boundaries

A "watershed" is defined by the National Oceanographic and Atmospheric Administration (NOAA) as an area of land that channels precipitation to creeks, streams, and rivers, and eventually to outflow points (2020). One way to identify watershed boundaries is to use a topographic map. Information on the physical and natural characteristics of the watershed will define the watershed boundary and provide a basic understanding of the watershed features that can influence watershed sources and pollutant loading. The concept is to identify the outlets and mark the elevation points to construct a boundary or ridge line following the highest ground between the waterways while crossing perpendicular to topographic contour lines, as shown in Figure 1.

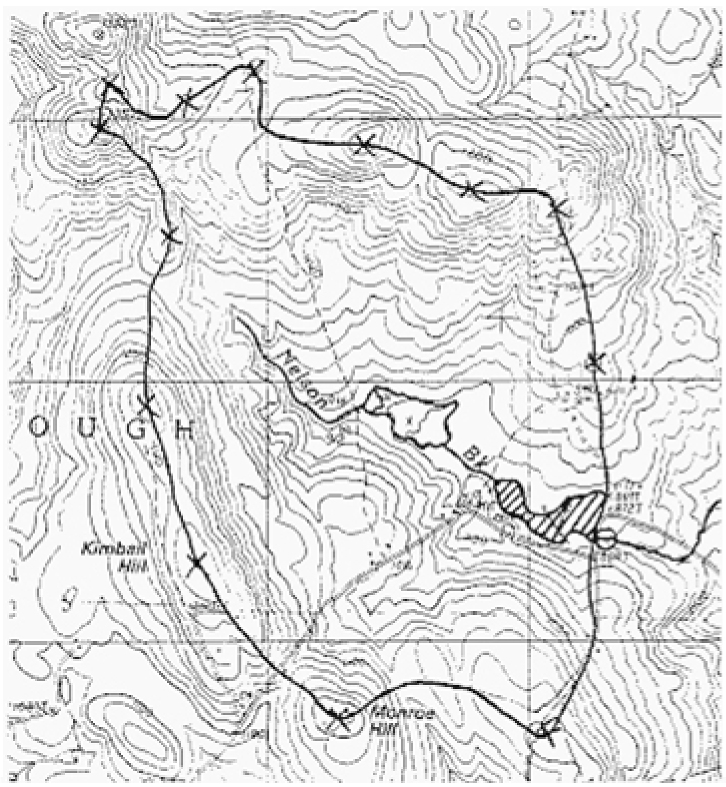


Figure 1. An example of a USGS topographic map used to define a watershed (https://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs144p2_014463.jpg)

A watershed can be relatively small, such as an inland lake, or can encompass thousands of square miles of streams, rivers, lakes, reservoirs, and underlying groundwater. Large watersheds (>50 square miles) are not particularly useful for modeling localized flooding events due to size and complexity. Thus Figure 2 shows how the hydrologic units are nested. The USGS Watershed Boundary Dataset (WBD) describes the hierarchical hydrologic unit data, based on topographic and hydrologic features at a 1:24,000 scale in the United States, except for Alaska at 1:63,360 scale. The data within the WBD have been reviewed for quality control through the 12-digit hydrologic unit, and certified. Although not required as part of the framework WBD, the guidelines contain details for compiling and delineating the boundaries of two additional levels, the 14- and 16-digit hydrologic units, as well as the use of higher resolution base information to improve delineations. Up-to-date information and availability of the hydrologic units were listed at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/ nra/dma/?&cid=nrcs143_021630/, but the portal was inactivated in late January 2025..

Figure 2. Description of how basins are subdivided into smaller subbasins (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset?qt-science_support_page_related_con=4#qt-science_support_page_related_con).

Realistically the model should include areas less than 50 square miles, which means the basis for modeling should be at the HUC12 level. Communities will often incorporate parts of multiple HUC12 subwatersheds to create a more accurate community flood risk map, each HUC12 should be modeled individually and the results mosaicked together. However, HUC12 or smaller is generally of interest at the localized flooding level, not the basin or subregion level like the TMDL maps created by the Florida Department of Environmental Protection (FDEP). Florida has 29 TMDL regions. FDEM originally tasked Florida Atlantic University (FAU) to develop its statewide protocol based on the 29 TMDL regions, which correspond roughly to the HUC-8 basin level. However, for watershed master planning purposes, the HUC-TMDL boundary layer (Figure 3) was modified and is available at cwr3.fau.edu. This map was compiled from the USGS HUC basins and the TMDL boundary maps developed by FDEP. These have also been cataloged by USGS nationally as HUCs at http://water.usgs.gov/wsc/index.html. The appropriate HUC can also be found at the USEPA "Surf Your Watershed" website (http://cfpub.epa.gov/surf/locate/index.cfm).

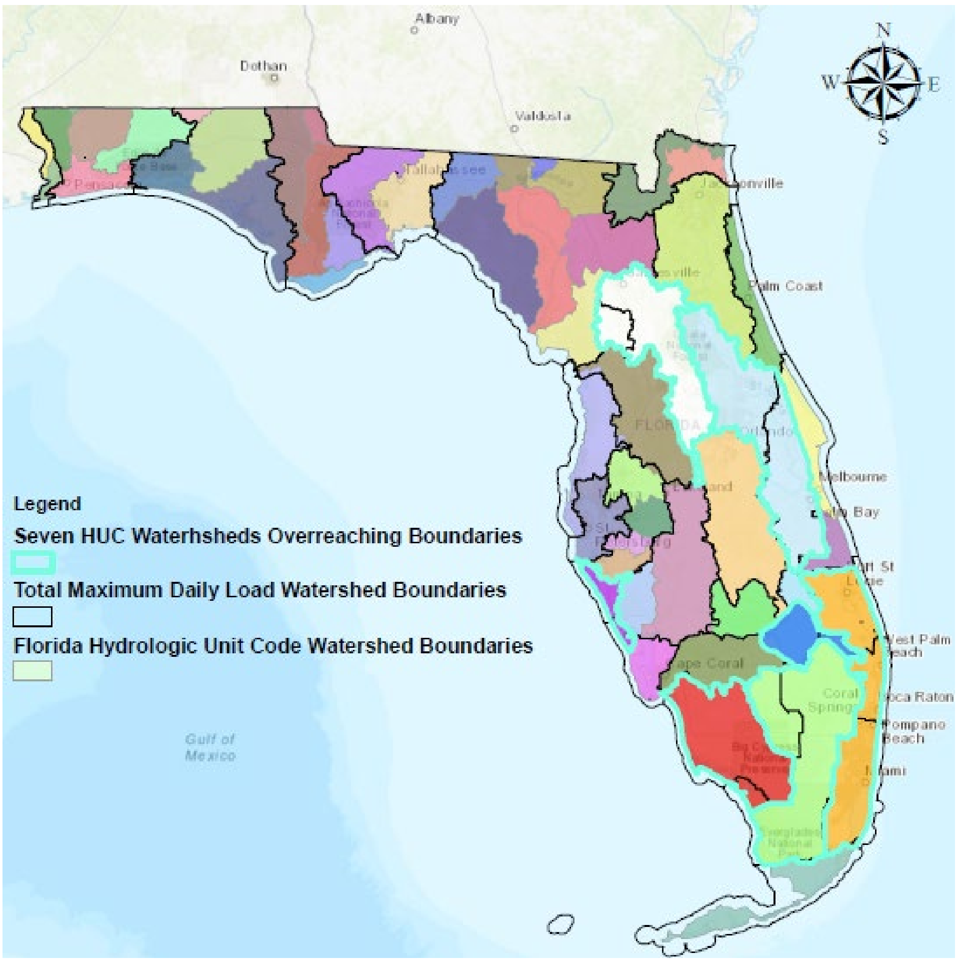


Figure 3. The 2020 HUC-TMDL boundary map such that TMDL regions align with HUC boundaries to better delineate basin-level boundaries for screening tool development as created and revised by FAU

For CRS purposes, the maximum watershed area for a creditable WMP should not exceed 50 square miles, and preferably no larger than 20-30 square miles. As noted, this is the HUC12 level of detail as opposed to the HUC8 level. There are 29 defined HUC8 subbasins in Florida, with hundreds of HUC12 subwatersheds. Subdividing the subject area into subwatersheds or smaller will permit better resolution on localized flood vulnerability to comply with CRS requirements. The 12-digit HUC level 6 map for Florida is shown in Figure 4.

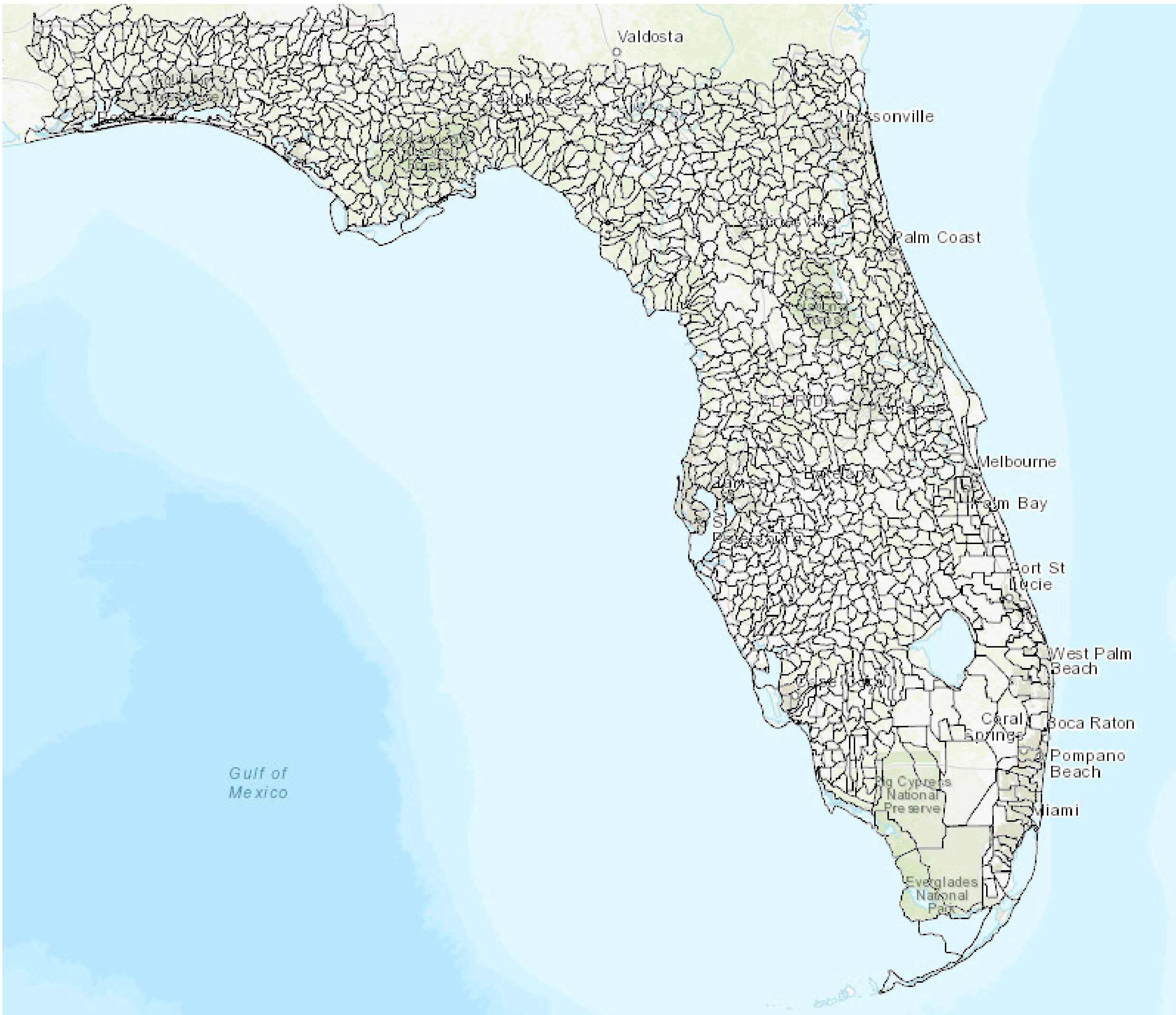


Figure 4. The 12-digit HUC, level 6, Florida subwatershed boundary dataset map (https://drecp.databasin.org/)

In many cases, a community jurisdiction can comprise multiple HUC12 subwastersheds, which are modeled individually and then mosaicked together. Figure 5 shows an example for Homestead, FL.

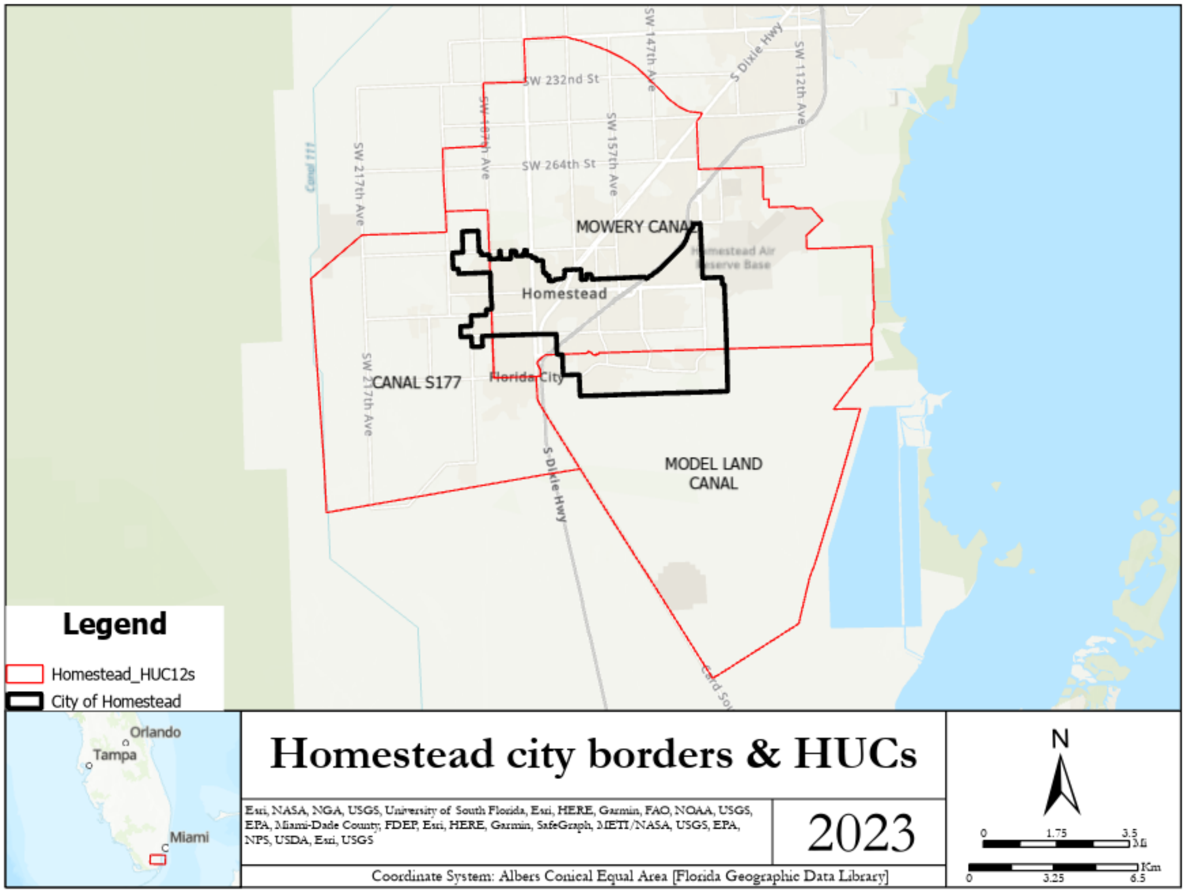


Figure 5. HUC12 subwatersheds for Homestead.

1.2.2 Geomorphological Considerations

Once the boundaries are identified, the next step is characterization of the areas. It is important to note agricultural and industrial activities, urban development, wildlife habitat, protected open space, water recharge zones, and geomorphology of stream/rivers (i.e. streambanks, shorelines, riparian zones, channel dimensions, slope, stream conditions, etc.). Some examples of standard geomorphological protocols include the following:

- USEPA's Environmental Monitoring and Assessment Program (EMAP) (www.epa.gov/emap)
- Vermont's Stream Geomorphic Assessment Protocols (www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro.htm).

1.2.3 Floodplains

A floodplain is a generally flat area of land next to a river. An example of a floodplain from the Suwanee River watershed is shown in Figure 6. Floodplain identification and mapping is important for flood protection of property and reduction of potential damages. Because floodplains are anticipated to flood periodically, local governments are expected to develop regulations that either prohibit development in floodplains or permit development that follows standards that make the structures/property flood resilient.

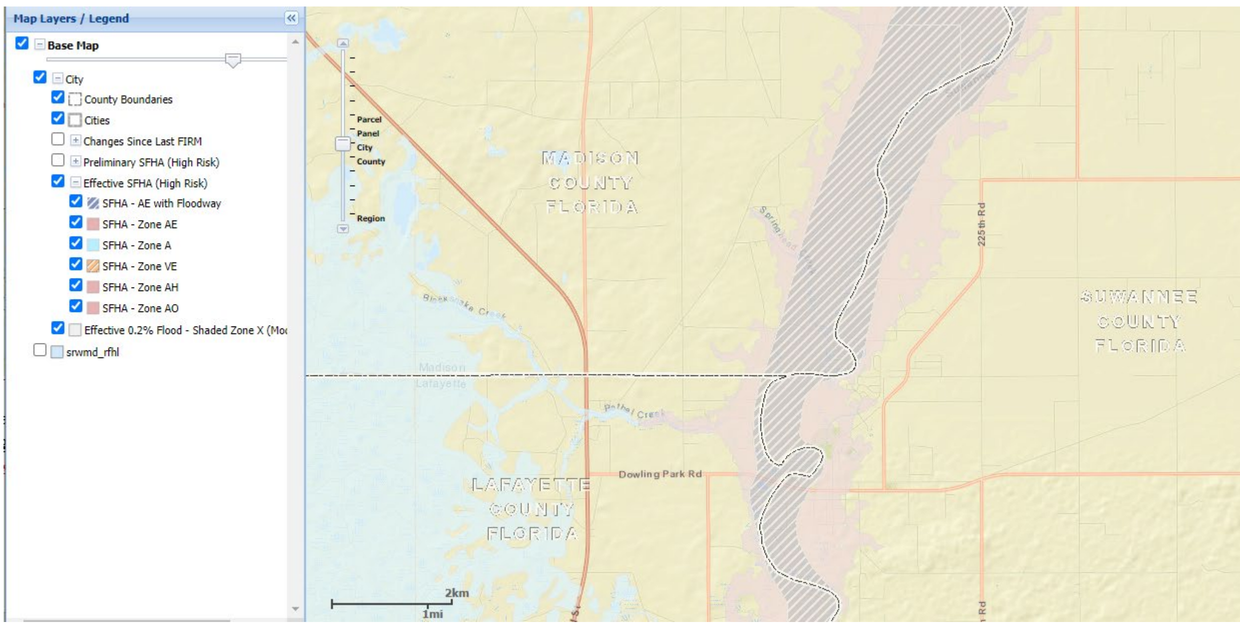


Figure 6. Natural channel of the river (dark line), river floodplain (black hatch) and fringe area (pink shaded area) within flood zones map. Note in Florida, lack of topography makes delineating the flood plain and bluff lines a challenge, but the concept still applies (http://www.srwmdfloodreport.com)

Beyond the floodway is the flood fringe, which extends from the outer banks of the floodway to the bluff lines of a river valley. When a channel receives too much water, the excess flows over its banks and into the adjacent floodplain. Flooding that occurs along a channel is called riverine flooding (black hatched area in Figure 6). Overbank flooding occurs when downstream channels receive more than normal precipitation from their watershed. Excess water overloads the channels and flows out onto the floodplain. Overbank flooding varies with the watershed's size and terrain. One measure of a flood is the velocity of its moving water. Depending on the size of the river and terrain of its floodplain, flooding can last for days and cover wide areas. In urban areas, flash flooding can occur where impervious surfaces, gutters, and storm sewers increase the speed runoff.

1.1.4 Flow Paths and Natural Channels

Natural channels are defined features on the ground that carry water through and out of a watershed. They may be rivers, creeks, streams, or ditches. They can be wet all the time or dry most of the time. Beyond the floodway is the flood fringe that extends from the outer banks of the floodway to the bluff lines of a river valley. ArcHydro is an available extension in ArcMap with a set of tools design to create the catchment drainage areas using a digital elevation model (DEM) as input. The ArcHydro function also permits the delineation of routing and subbasins, which may need to be modeled separately. Figure 7 shows an example map illustrating the flow channels for the Caloosahatchee HUC8 basin based on the modeling by FAU and the drilldown into the eastern HUC12 region.

1.3 Planning Goals and Scope

To ensure the watershed planning effort remains focused, the planning goals and scope of the effort must be clearly defined. If the scope and goals are established early in the planning process, it will become easier to implement and monitor the plan. The goals and scope will also impact the planning horizon, which is typically 5 to 10 years. Factors such as changes to the watershed, development pressure, impacts of climate change, availability of new technologies and mitigation strategies, etc. will make the plan obsolete within a 10-year window or less, requiring periodic updates. Therefore, it makes sense to update the plan before then (e.g., every five years). Some examples of projects implemented to address watershed goals are listed in Table 2. Note that watershed master plans may include water quality goals as well as flood mitigation goals.

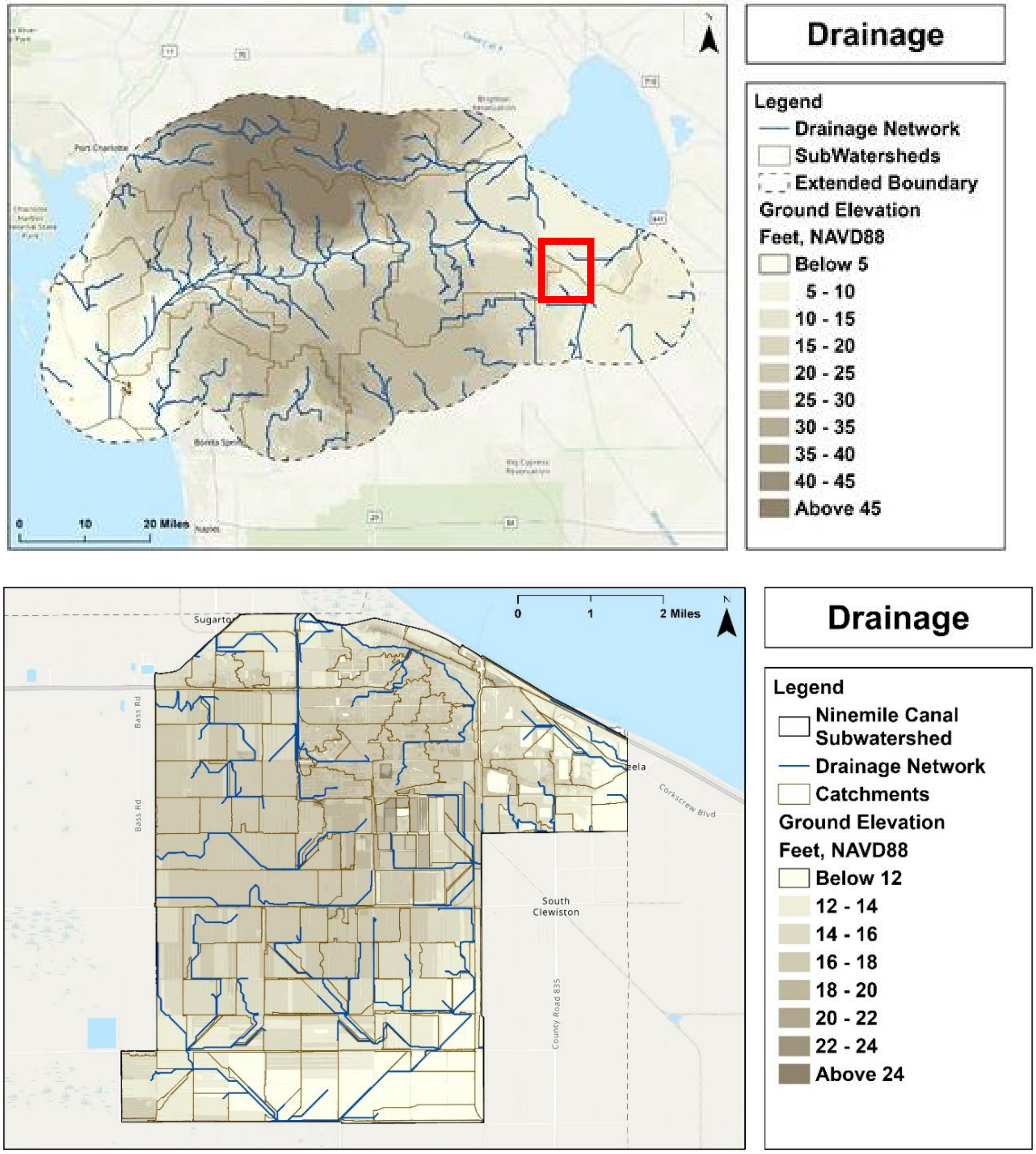


Figure 7. Example of a flow paths map for the Caloosahatchee basin (top) and at the subwatershed level (bottom)

Table 2. Sample goals related to flood protection on a watershed basis

Sample Goal	**Indicator**	**Management/Project**
Reduce Overbank Flooding	Repetitive Loss Claims	Revetment
Restore Wetlands	Wetland Species Population Counts	Restore Water Flow
		Increase Regulatory Protection
		Acquire Properties
Reduce Flood Levels	Repetitive Loss Claims Changes to Flood Maps	Install Pump Stations
		Install Weirs/Gates
		Install Piping
Increase Water Supply	Water Restrictions	Construct Upstream Reservoir

2.0 COLLECTION AND ANALYSIS OF DATA

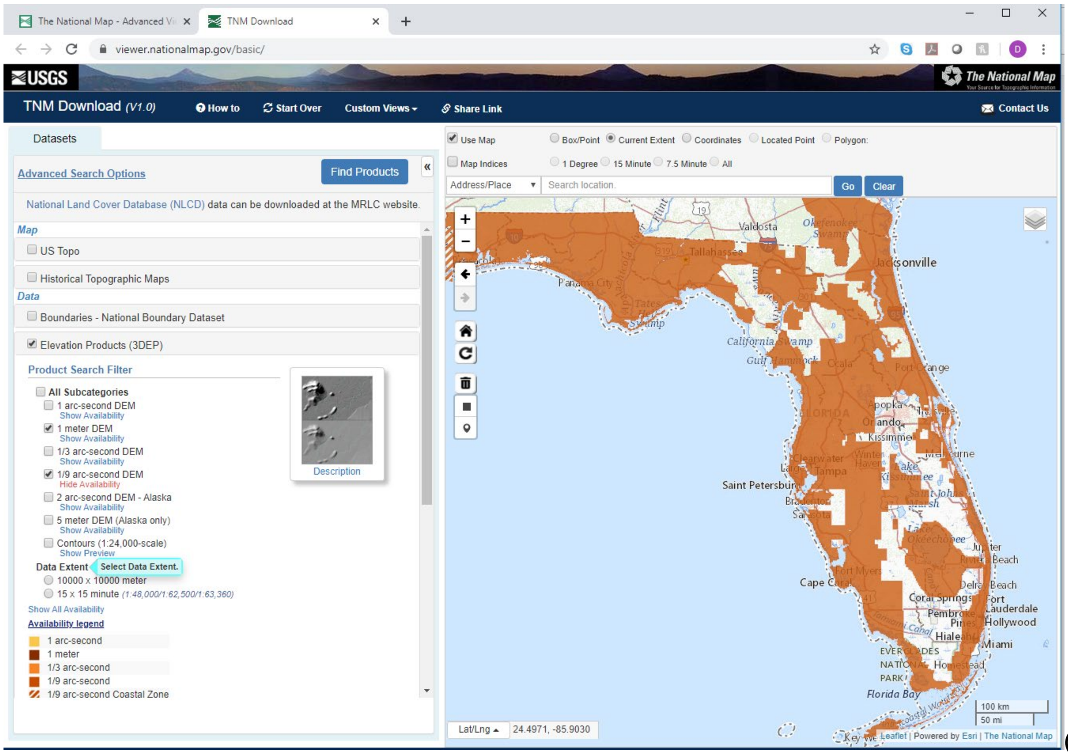
As noted in Chapter 1, intensive data gathering is needed to develop the flood risk modeling results. To accomplish the goal of modeling the state, FAU gathered data from the water management districts on groundwater table elevations and surface water gages, tidal information for coastal areas from NOAA, soil maps from USDA, and topographic data from many sources. The design storm for calculation purposes was the 3-dayn25-year storm, which is the standard used by the SFWMD, along with the 1 day – 100 year and 1-day 25-year events for some communities. Because of the ever-present challenge with tropical weather, most communities are interested in higher risk, so the 1-day 100-year model was performed for all communities. The 1 day 10-year event was also modeled.

2.1 Surface Topography Development

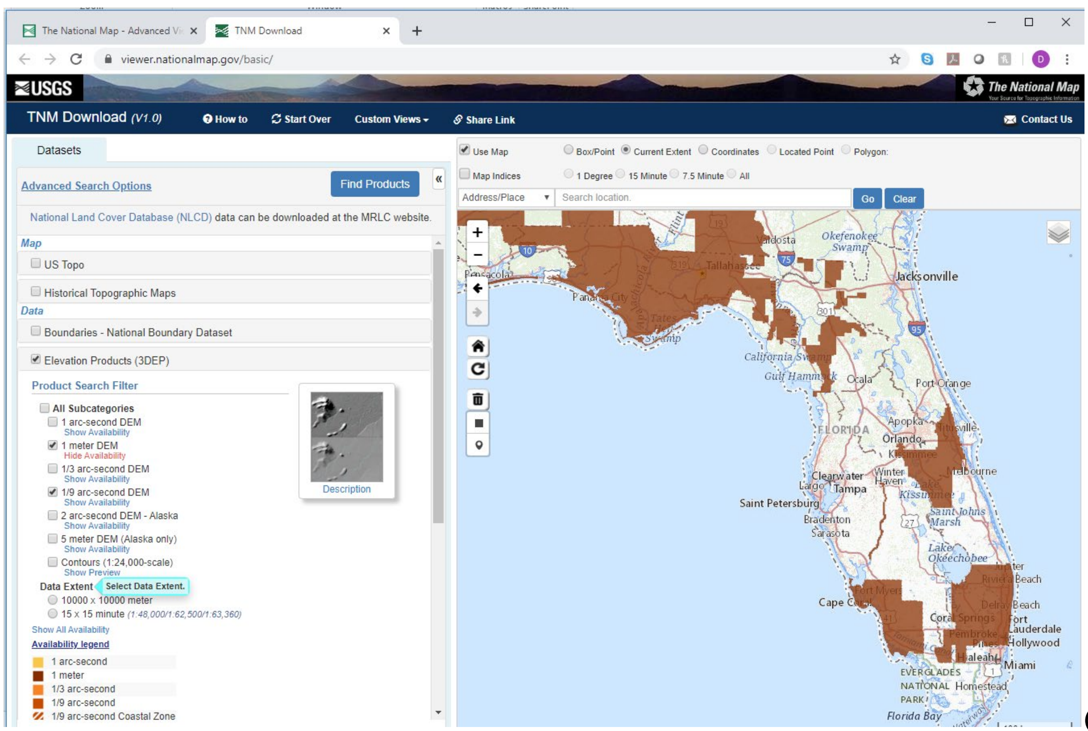
Topography is a key parameter that influences many of the processes involved in flood risk assessment, and thus, up-to-date, high-resolution, high-accuracy elevation data are required. Elevation datasets were obtained from the USGS 3DEP Elevation Products Program available through the National Map Viewer (https://viewer.nationalmap.gov/basic/). All data met the FEMA standard. FEMA has adopted as a standard the Quality Level 2 data as defined in the USGS LiDAR Base Specification v1.2 (Heidemann, 2018), which is provided through the USGS 3D Elevation Program (3DEP) (FEMA, 2016a). In order to meet the requirements for FEMA Risk Mapping, Assessment, and Planning (RiskMAP), 1-meter (2015 to present) and 1/9 arc-second (~ 3-meter) (2010 -2015) LiDAR DEMs were acquired. QL2 lidar specifications are found in the USGS LiDAR Base Specification: Version 1.0 (2012), Version 1.1 and 1.2 (2014), and Version 1.3 (2018) (Heidemann, 2018). Quality Level 2 (QL2) from the National Enhanced Elevation Assessment (NEEA), which serves as the basis for the USGS 3D Elevation Program (3DEP), was developed using airborne LiDAR point density of 2 points per square meter allowing for high accuracy and enhanced resolution of derivatives. The 1-meter DEM has a target non-vegetated vertical accuracy of 19.6 cm at the 95-percent confidence level (Arundel et al., 2015). This accuracy meets the 3DEP Quality Level 2 vertical accuracy threshold of plus or minus (±) 10 cm RMSEz (Arundel et al., 2015). In vegetated areas, the vertical accuracy might be slightly diluted (showing larger RMSEz values) but nevertheless the 1-meter DEM products retain high level of accuracy in all segments. The 3-meter DEM products have a vertical accuracy between 22 cm and 30 cm which meets the specifications of FEMA Elevation Guidance (Document 47) for flood risk analysis and mapping (FEMA, 2016a). The FEMA specifications for vertical accuracy of elevation datasets are shown in (adapted from FEMA 2016a, p. 6). Figure 8 indicates data availability (1-meter and 3-meter DEM) for the State of Florida.

Table 3. FEMA vertical accuracy requirements based on flood risk and terrain slope

Level of Flood Risk and Terrain Characteristics	**Specification Level**	**Vertical Accuracy**	**LiDAR Nominal Pulse Spacing (NPS)**
High flood risk; low-lying flat areas	Highest	24.5 cm / 36.3 cm	≤ 2.0 meters
High flood risk; rolling slopes	High	49.0 cm / 72.6 cm	≤ 2.0 meters
High flood risk; hilly terrain	Medium	98.0 cm / 145 cm	≤ 3.5 meters
Medium flood risk; low-lying flat areas	High	49.0 cm / 72.6 cm	≤ 2.0 meters
Medium flood risk; hilly terrain	Medium	98.0 cm / 145 cm	≤ 3.5 meters



(a)



(b)

Figure 8. Extent of high-resolution DEM datasets available through the USGS 3DEP elevation program for the State of Florida: (a) 3-meter DEM; and (b) 1-meter DEM

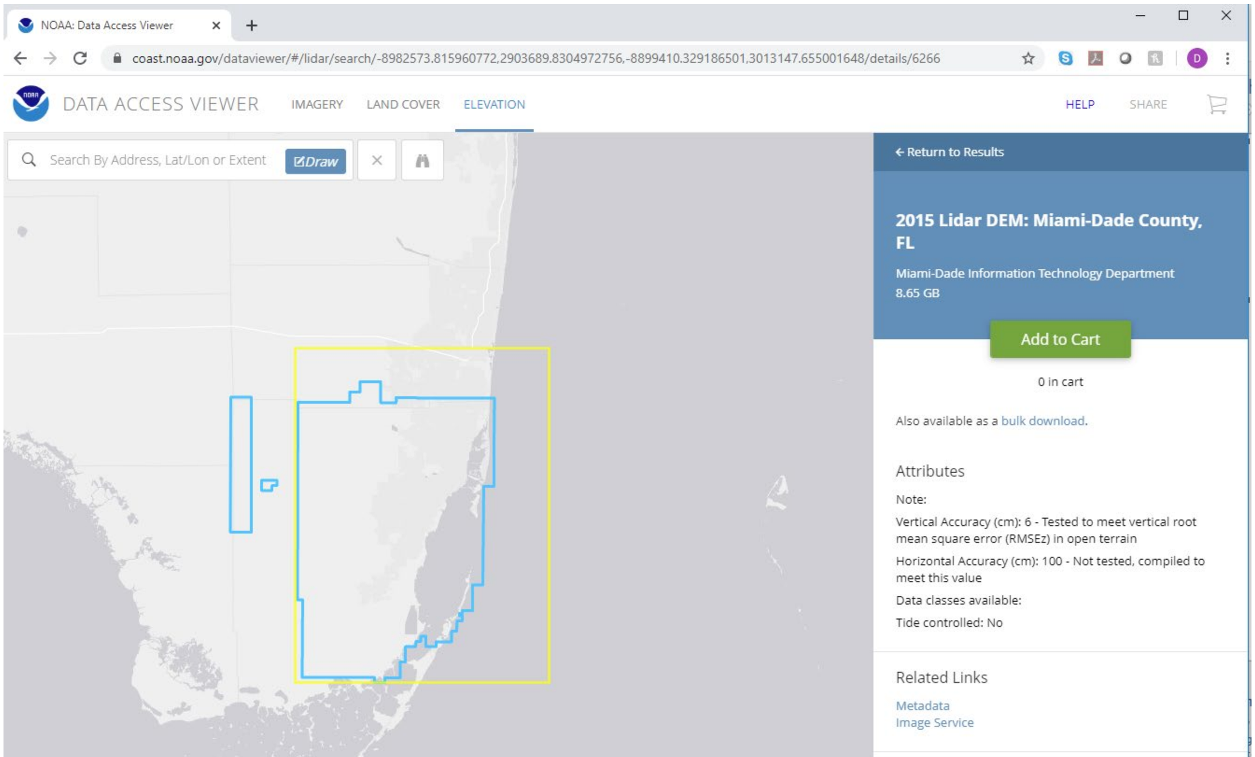


Figure 9. LiDAR DEM for Miami-Dade County downloaded from NOAA Data Access Viewer – the dataset has a vertical accuracy of 6 cm (tested to meet the RMSEz specification for open terrain)

Table 4 Challenges and solutions for Lidar coverage issues Across the state.

Issue Noted	Solution
1. **Extent of coverage**. The available high-resolution datasets (1-meter and 3-meter) do not cover the entire State of Florida. For instance, large swaths of data are missing for the Suwannee River Basin and several of the inland rural counties.	Every effort was made to locate and acquire additional high-resolution datasets that cover some of the gaps in the data downloaded from the main sources. Acquired all 2016 NOAA datasets for use as the default and asked local communities for the most recent data available. Additionally, LiDAR point cloud data (specifically, for the Suwannee River Basin to process at a later date and derive Bare Earth DEM datasets as needed) was acquired.
2. **Completeness of coverage**. While compiling tiles into larger regions, gaps in the data at a pixel level or higher were encountered.	Filling the gaps in a DEM is an important step in DEM processing for hydrological modeling as such gaps may adversely affect the computation of flow direction and flow accumulation as well as the delineation of stream networks and catchments.
3. **Ongoing Updates**. There was an intent to track new datasets throughout the process with the intention of using the most recent datasets, if its quality exceeded that of the prior datasets.	Newer sources of data are periodically checked for this purpose. New and older datasets were merged to capture the most up-to-date data possible.
4. **Reprojection issues**. A slight dilution of vertical accuracy may be introduced through reprojection of source data into the UTM coordinate system (Arundel et al., 2015).	To correct minor artifacts in existing datasets, the following approaches were considered: 1) identify earlier (2007-2008) LiDAR-derived products that cover the missing pixels areas and merge them with the newer dataset; 2) when such data are not available and in compliance with the specification levels described in , the 10-m NED dataset was used to extract the elevations and fill up the gaps. All utilization of the topographic data followed FEMA (2016b) Guidance on Projections and Coordinate Systems for flood risk analysis and mapping.

2.2 Groundwater

Building on prior efforts (Bloetscher et al 2011; ESciences, 2014; Romah, 2011; Bloetscher and Wood, 2016; Zhang et al 2020), for modeling purposes, groundwater levels were conceptualized as an average of the in situ observable extremes (the 99 percentile values were used). 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. 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). 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.

Pertinent groundwater information were obtained from the 5 water management districts, Florida Department of Environmental Protection (FDEP) and other state and local partners to identify watershed characteristics necessary to inform an effective framework for a statewide watershed master planning initiative. Table 5 summarizes the groundwater datasets collected and made available at cwr3.fau.edu. Over 4400 wells were identified and downloaded, but only 35% (n=1500) provided data applicable for screening (surficial aquifer and continuous data collection since 2000). Note that as many as one-third of wells in a given area may not be useful for modeling purposes because they are either offline, stopped recording years ago, temporarily out of service, or other mechanical reasons.

Table 5. Location of groundwater datasets used in this project

Agency	GW Parameter	Date Range	Number of Wells	Source Data Format
SFWMD	Daily maximum	2000 - 2019	844	CSV files downloaded (and processed)
SWFWMD	Daily maximum	2000 - 2019	469	Access database provided by District
SRWMD	Daily maximum	2000 - 2019	197	Data portal (downloaded and processed)
SJWMD	Daily maximum	2000 - 2019	717	Provided by the District for a fee
NWFWMD	Different temporal resolutions (max processed)	2000 - 2019	92	Provided by the District (required processing)
FDEP	Upper Floridan Aquifer water level	2012-2017	1564	FDEP Open Data Portal: https://geodata.dep.state.fl.us/datasets/unconfined-aquifer-wells-well-list-frame/data

Table 6 shows the location of datasets for groundwater. Over 4400 wells were identified and downloaded, but only 1500 provide the right aquifer and correct timeline (since 2000). For example, data points for determining the groundwater-surface used the monitoring well data gathered from DBHYDRO (from South Florida Water Management District), since this repository contains the largest set of monitoring wells.

Table 6. Location of the groundwater datasets

Water Management District	Groundwater Parameter	Source Data Format
SFWMD	Daily maximum	CSV files downloaded (and processed)
SWFWMD	Daily maximum	Access Database provided by District
SRWMD	Daily maximum	Data Portal. Downloaded and processed
SJWMD	Daily maximum	Provided by the District for a fee
NWFWMD	Different temporal resolutions (maximum processed)	Data Provided by the District (required processing)
FDEP	Upper Floridan Aquifer Potentiometric Contours	FDEP Open Data Porta

Wells in north of the South Florida Water Management District (Figure 10) and within the South Florida Water Management District region (Figure 11) were collected be used for data gathering. The groundwater surface elevation (hydraulic gradient) mapping is a critical effort because to krig a groundwater surface elevation, a common date is needed. In addition, adequate well/station-based groundwater data is needed to create a groundwater surface in GIS. Based on the 99th percentile value as noted earlier, the top 2% of values, the 98-100th percentile, are trimmed and then tabulated in ascending order and reviewed to determine a common date. The 99th percentile should avoid hurricanes and other rare storm events but may put a community at higher risk of flooding due to the combinations of high water table elevations, high tides, and rain. The groundwater surface elevation (hydraulic gradient) mapping is a critical effort because to krig a groundwater surface elevation, a common date is needed. First, there needs to be enough well/station-based groundwater data to create a groundwater surface in GIS. Having less than 20 wells that are aerially extensive is insufficient for developing a groundwater layer in GIS using stochastic variance-dependent spatial interpolation (e.g. ordinary kriging). Prior work by Romah (2011) indicates that while different interpolation techniques can be used, ordinary kriging methods are adequate and representative. A subset of available data is used for the creation of a validation dataset, and the rest of the data is used for calibration (i.e. estimation of parameters of the interpolation model). Where the coast is present, the high tide value of the same day as the groundwater 99 percentile was used as a constant head boundary. Note this makes the model conservative (perhaps overly so).

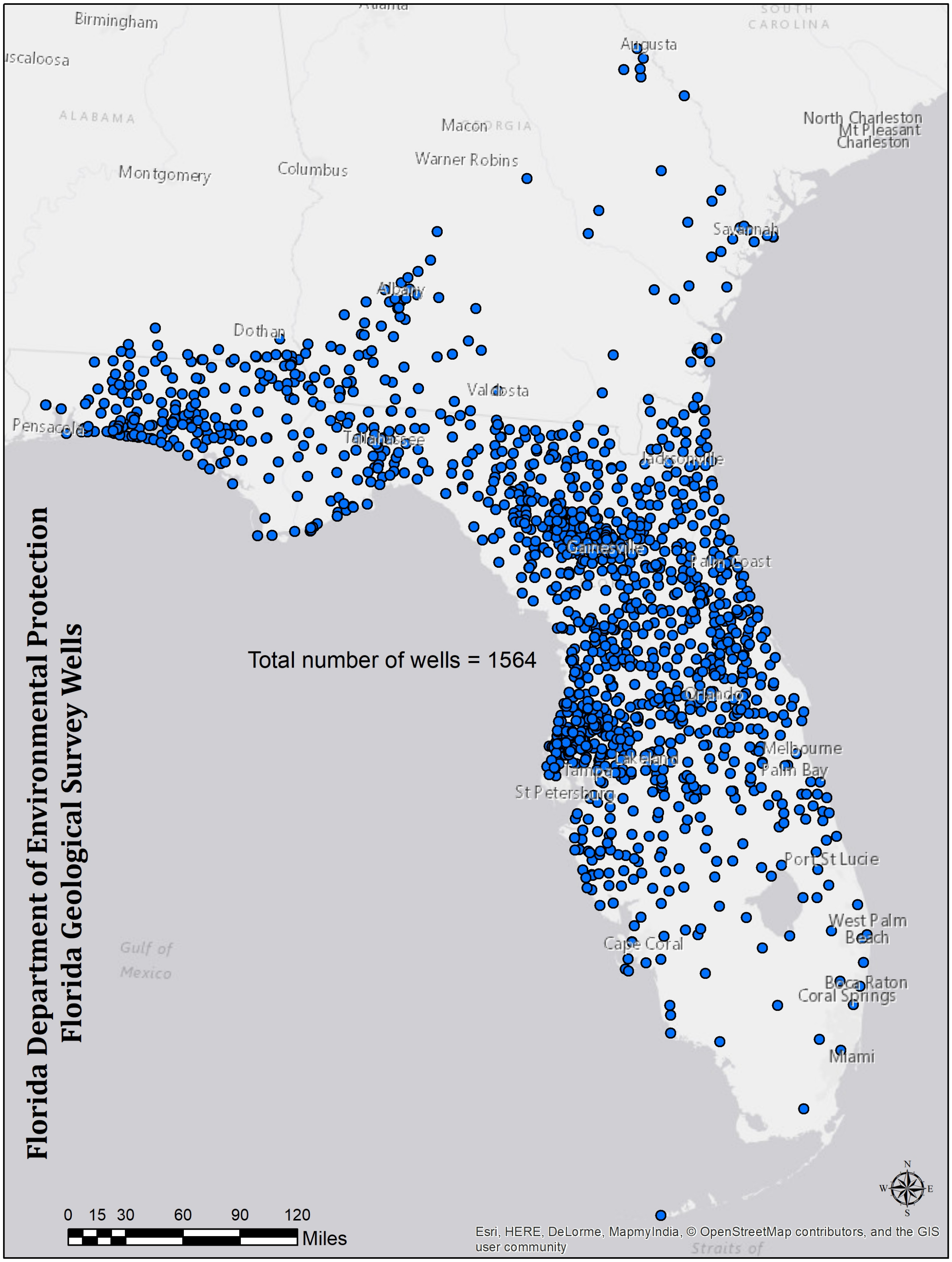


Figure 10. Monitoring wells in Florida Geological Survey wells or other water management district records

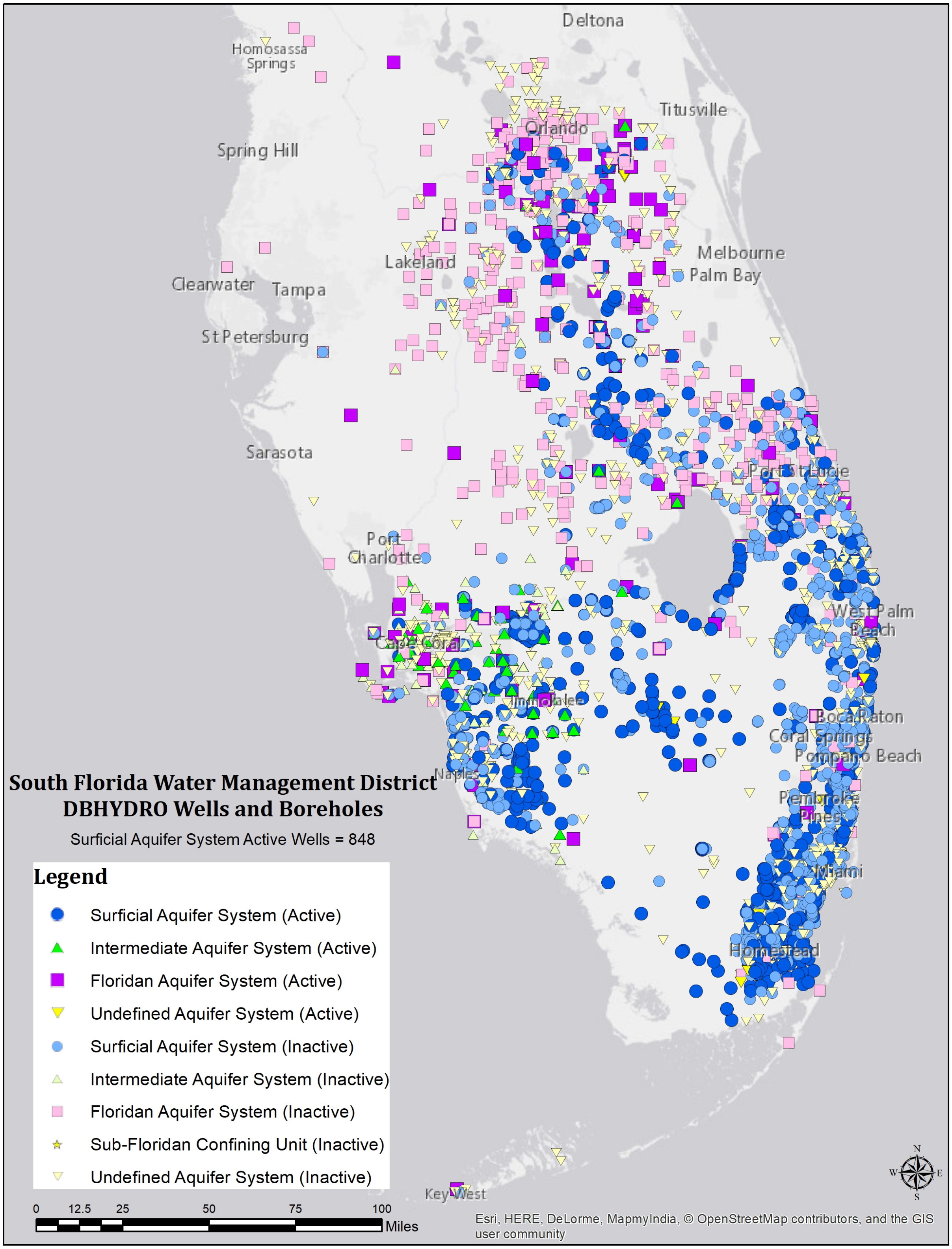


Figure 11. Monitoring wells in DBHYDRO – SFWMD

Outliers and anomalous groundwater levels in the database are initially evaluated, identified and if found to be faulty, are replaced by region-specific mean values based on observations available from the nearest well. Missing date-specific data are estimated using simple temporal interpolation based on observations available in time. If a station (or monitoring well) data contains large amounts of missing data, it is not used in the generation of the groundwater surface. FAU has created groundwater layers for all 29 basins defined in Florida (available at cwr3.fau.edu).

Groundwater plays a vital role when localizing flood-prone areas. The five water management districts (Figure 12), USGS and other agencies continue to monitor the water table elevations. Well information is used to assess the two temporal windows in this area: dry and wet season. For example, in south Florida, the dry season starts in December and ends April, and the wet season starts May and ends in November, creating the ranges of maximum and minimum elevations for each season.

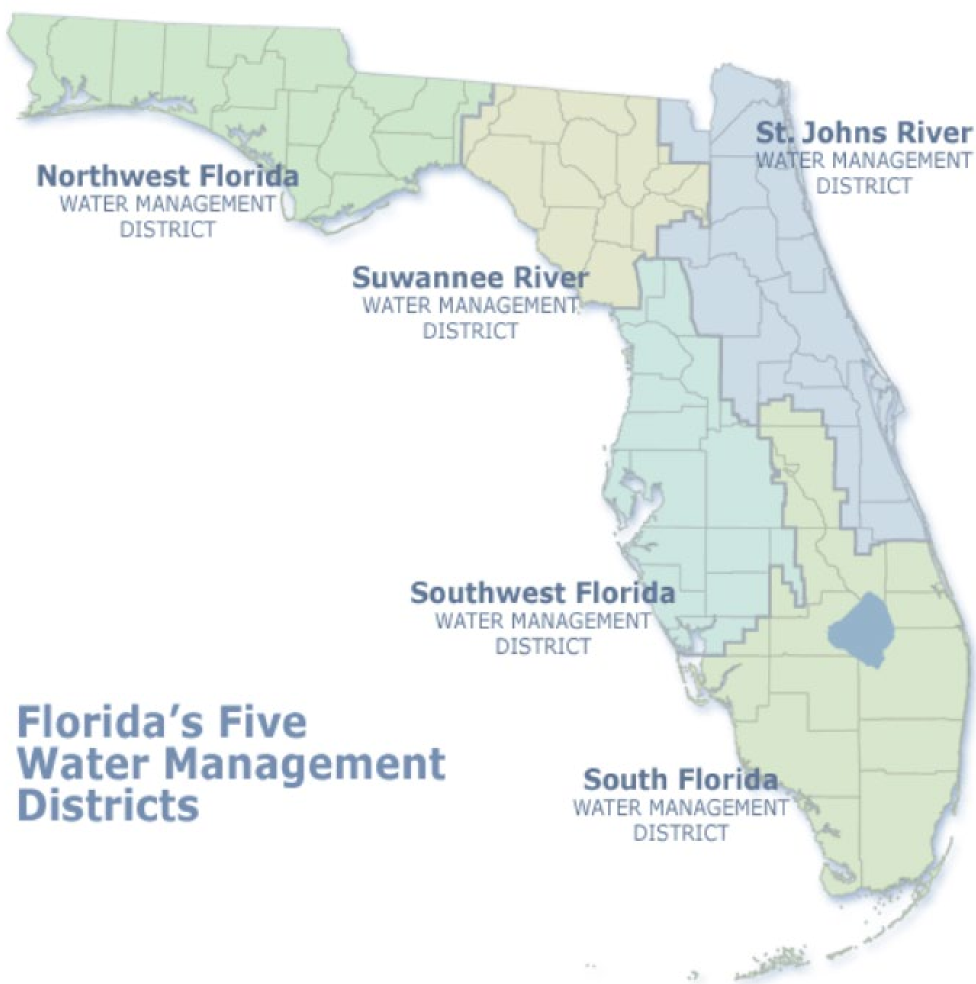


Figure 12. Florida's Five Water Management Districts. (https://www.sfwmd.gov/who-we-are)

Several tests were performed with the wells data only to find the appropriate geostatistical interpolation method from ArcMap 10.7. Deterministic methods use predefined functions of the distance between observation locations and the location for which interpolation is required (for example, inverse distance interpolation). Probabilistic methods have a foundation in statistical theory. These predictors quantify the uncertainty associated with the interpolated values. The requirement of providing information on prediction uncertainty limits the choice of interpolators to statistical ones. Wells inside and outside the boundary area to mitigate the edge effect when creating the surface. Methods to krig the surface included 1) Inverse distance weighted (IDW) with a fixed distance search radius, 2) IDW with a variable search radius, and 3) Empirical Bayesian kriging (EBK). EBK was the method used to create the final groundwater-surface. This method is based on statistical models that include autocorrelation. Kriging not only establishes the surface but offers some inside pre-analysis of the data while setting the parameters of the tool. Kriging is most appropriate when a spatially correlated distance or directional bias in the data is known, as in this case (groundwater/surface water). Note that throughout the State of Florida, spatial groundwater monitoring well density varies considerably, and spatial interpolation of data is required. This is why the kriging procedure is needed.

Dr. Weibu Liu at FAU designed an automated procedure using Python programming in MATLAB to process groundwater data to find the common date by searching the maximum daily record for each well and analyzing the well data collection to filter the dates to the top 95-99 percentile after removing the dates with hurricane or abnormal storm events, improving upon earlier efforts by Romah (2011) and Wood (2016) to find the date using a manual procedure.

NFIP requires consideration of sea level rise to be included in the WMP (see discussion of the issues associated with sea level rise and how this should be accounted for when using the ocean as a constant head boundary under surface waters - section 2.3). For regions with spatially sparse or non-uniform groundwater wells, the groundwater levels are estimated using a multiple linear regression approach from auxiliary variables in addition to the limited ground well observations in a watershed (Zhang et al., 2020 is a publication of this method).

For certain areas of the state, the surface and ground water levels interact as one, and Romah (2011), Bloetscher and Wood (2016), and others have noted that both tides and groundwater are increasing with time. Figure 13 was developed by FAU using the Key West and Virginia Key tidal stations. What was learned was the often reported 10 inches of sea level rise was a finding from 1992, and that an added 4 to

5" of sea level rise has occurred since then. The figure then projects the 2030, 2050 and 2100 value for NOAA, USACE and IPCC AR5 median projections along with the trajectory to the two historical values. Note sea level rise is expected to accelerate in the coming decades and data since 1992 suggests that the trajectory has increased slightly.).

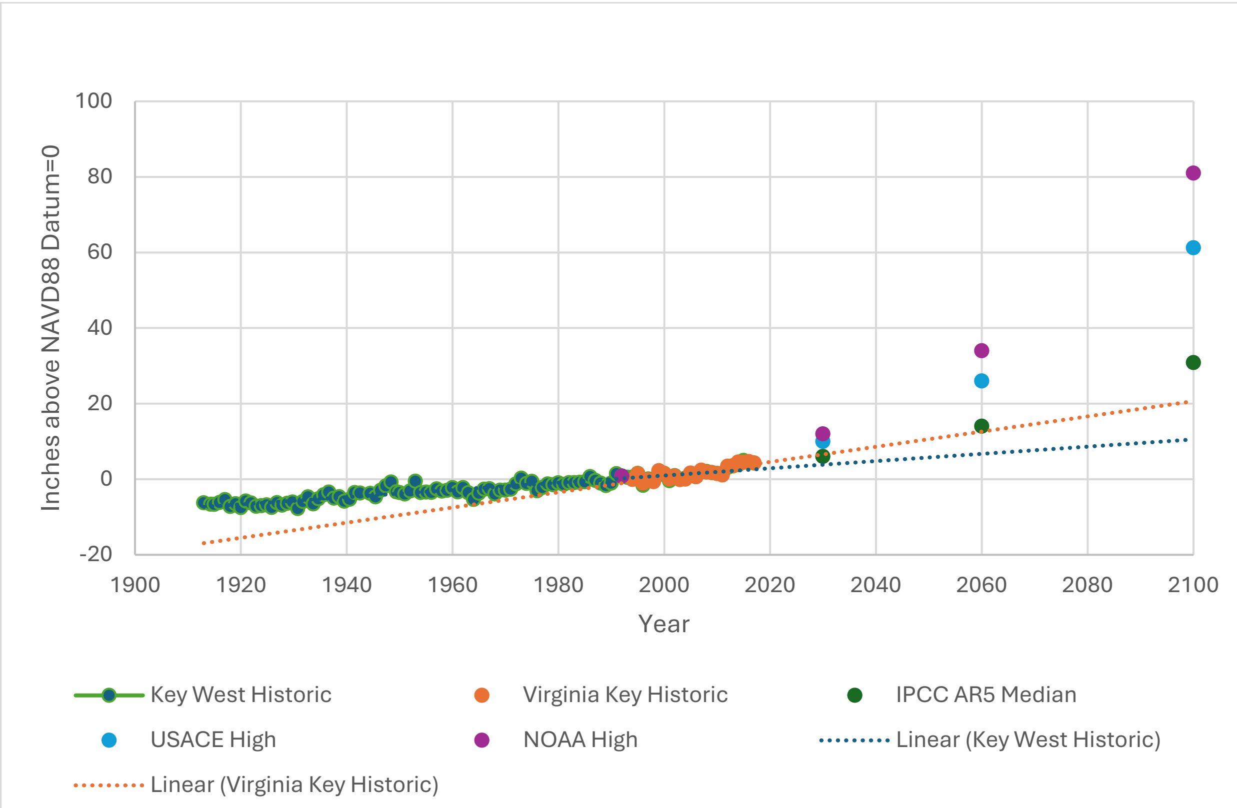


Figure 13. Increasing tides and projected future increase – 99th percentile

Heimlich et al. (2009) project sea level rise at between 2 and 3 ft by 2100 in a study performed in 2008 (Figure 14). This project suggested that looking at milestones as opposed to dates was a better way to prepare for higher seas. In this study 1, 2, 3, 4 and 5 ft thresholds each suggested difference plans and policies be in place to harden local communities. The results were compared to concurrent professionals with respect to predicted sea level rise.

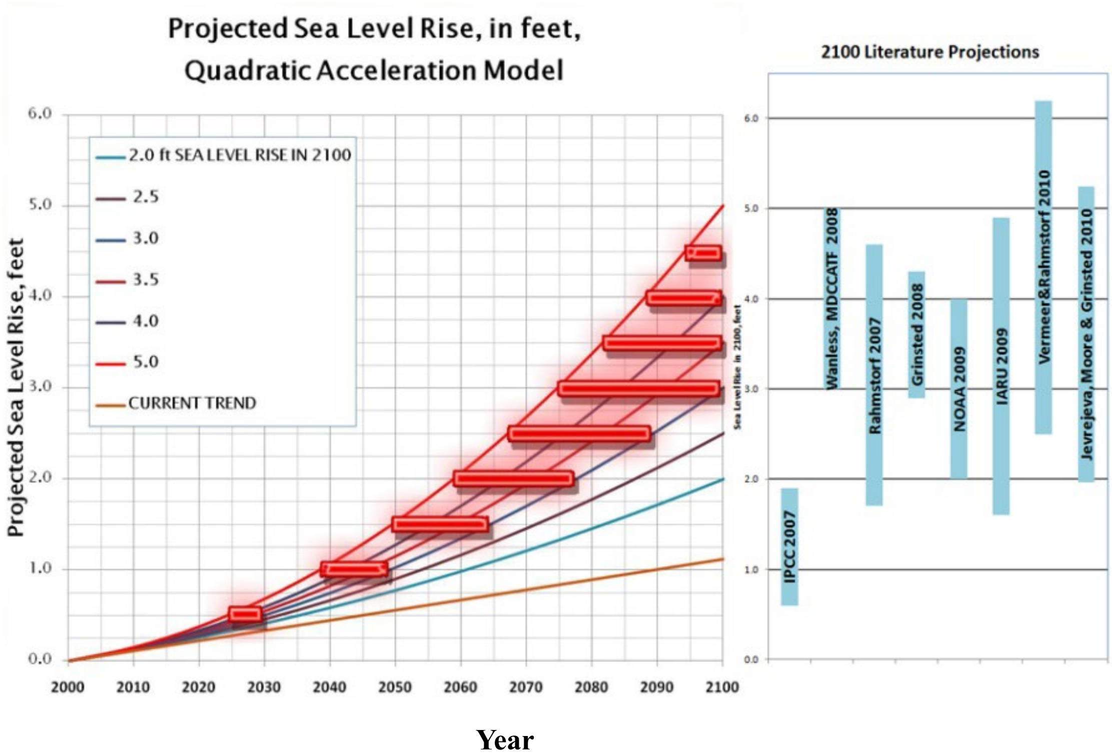


Figure 14. Prediction of sea level rise using a quadratic acceleration equation; The graph outlines the average, and 1 and 2 standard deviations from the average of the current models; The horizontal bars outline the ranges when the sea level rise could occur (Heimlich et al., 2009)

NOAA (2017) outlines five scenarios for sea level rise. The NFIP proposes the use of the intermediate high projection, which is 1.2 meters or 4 ft from current sea level elevations (Figure 15), and the Southeast Florida Regional Climate Compact (SFRCC, 2011) projection recommended by its scientific working group for years 2030 (3” to 7”) and 2060 (9” to 24”). NFIP suggests a projection in excess of 5 feet. The 5 ft plus king tides satisfies this request. FAU’s long term projections are based on 15 inches of sea level rise since 1929 (refer to Figure 13).

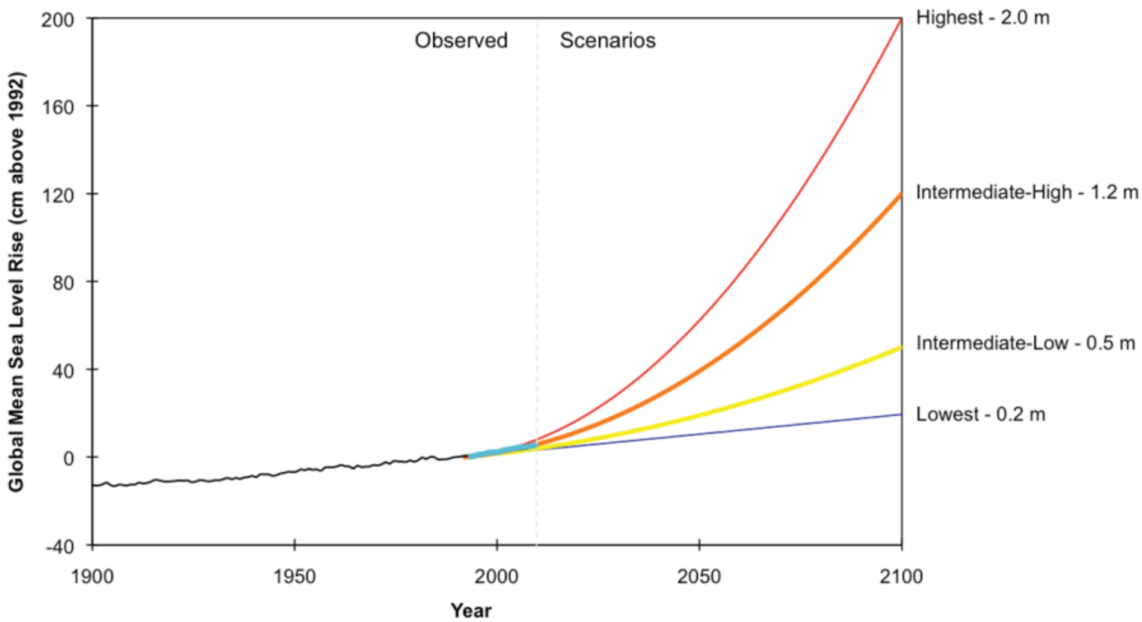


Figure 15. Graphic of sea level rise projections from NOAA (2017) (https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf)

For this project, the groundwater dataset was developed from a date range of 2000 to 2018 plus the tide value for the same date. An example of such a groundwater surface krig is shown in Figure 16.

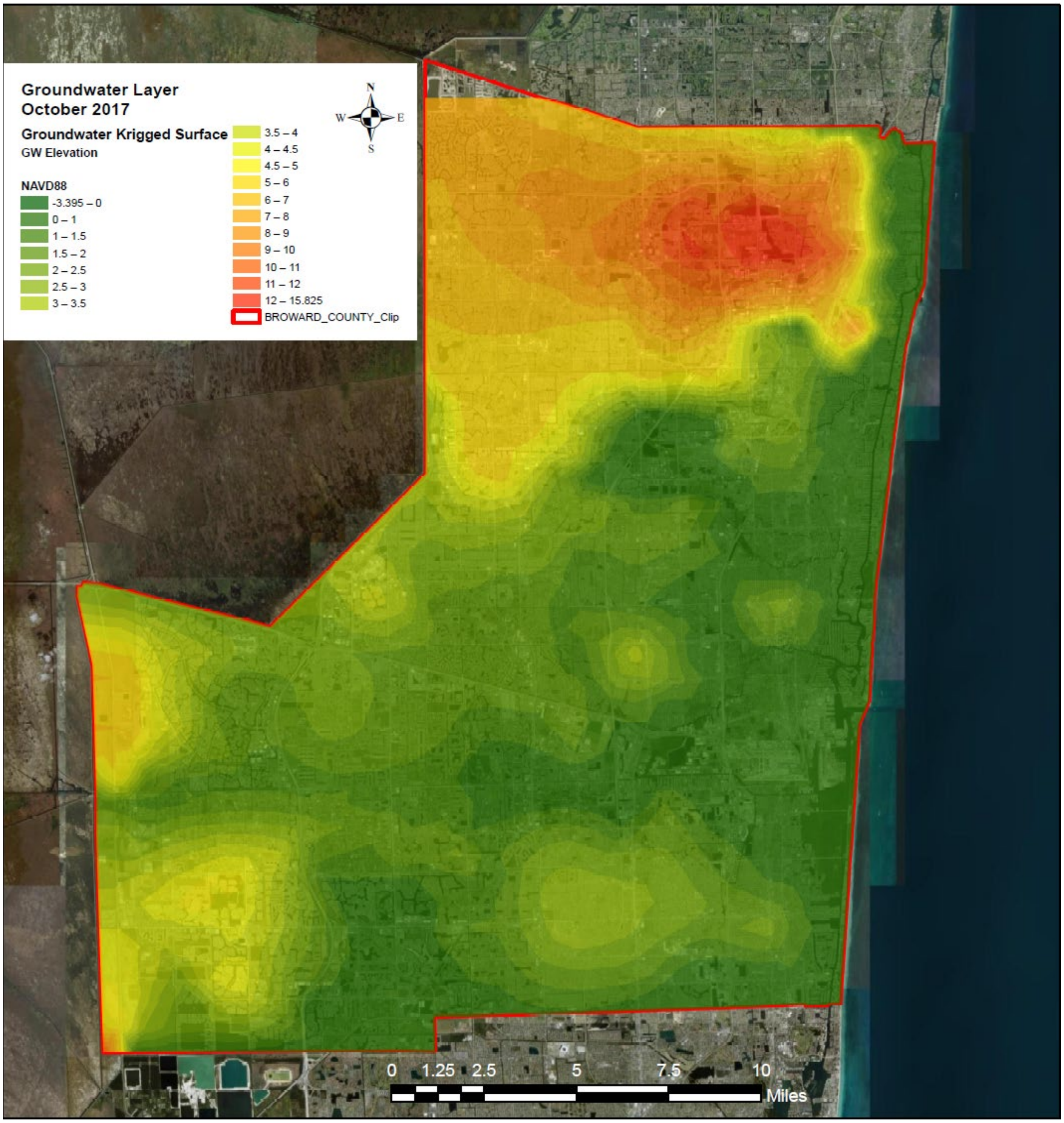


Figure 16. Example of groundwater krigged surface for Broward County. The low levels are wellfields

For example, the common date for south Florida is 10/29/2017, but it is an earlier date in north and west Florida. Once a common date was found, the water levels in all wells are used to create the groundwater surface. Prior work indicates that while different interpolation methods can be used, ordinary kriging (OK) methods work well (Romah, 2012). Table 7 outlines the challenges and solutions for groundwater.

Table 7 Challenges and Solutions for Groundwater

Issues Noted	Solutions
1. In some regions of Florida, the groundwater monitoring well density is not spatially uniform or extensive. Some important areas like the Keys and the Everglades have no well coverage.	Spatial interpolation using a stochastic variance-dependent interpolation (e.g., Ordinary Kriging) can be used to estimate groundwater levels at points of interest or to generate the surface. A subset of available data is used for the creation of validation dataset, and the rest of the data is used for calibration (i.e., estimation of parameters of the interpolation model). Where the coast is present, the coast is used as a constant head boundary.
2. Outliers (very high or low groundwater levels attributed to a variety of reasons) and missing data are noted at some monitoring wells.	Outliers and anomalous groundwater levels in the database are initially evaluated, identified and if found to be faulty, are replaced by region-specific mean values based on observations available from the nearest well. For regions with spatially sparse or non-uniform groundwater wells, the groundwater levels are estimated using a multiple linear regression approach from auxiliary variables in addition to the limited ground well observations in a watershed.
3. Many wells are no longer active.	Missing date-specific data are estimated using simple temporal interpolation based on observations available in time. If a station (or monitoring well) data contains large amounts of missing data, it is not used in the generation of the groundwater surface.

2.3 Surface Waters/Tides

Bloetscher et al. (2012) found that the groundwater elevation would seek high tide as opposed to average tides for a boundary condition. As a result, projecting groundwater levels will indicate infrastructure with a greater vulnerability for flooding where water, sewer, stormwater and transportation infrastructure in low-lying inland areas may be compromised faster due to the loss of soil capacity.

Tidal data can be gathered from NOAA tidal gages and other gages monitored by local governments. The location of tide gages is important to ensure they accurately depict tides, as opposed to inland waters. . Figure 17 shows the NOAA monitored tidal stations across the state. With the exception of the Panama City station, the data and long-term trends are virtually identical for all stations. For most of the coastal areas, it was determined that the 95-100th percentile tides occurred primarily in the September and October timeframe (by listing all tides in ascending order). The tidal peak condition in the peninsula tends to occur with the king tides in the fall, which roughly corresponds to the point when the groundwater levels are also highest in the southern coastal areas of Florida. In north Florida, the highest tides could occur twice per year as a result of runoff conditions in the spring season.

Figure 18 shows the typical annual tides over a 5-year period for Virginia Key as developed by FAU. To set a boundary for the coastal areas, the high tide on the common data should be chosen. North Florida has a lesser difference as winter runoff increases water levels in the spring, but the tidal wave pattern remains the same as it is lunar related. What is obvious is that there is a wave pattern annually, which is the king tides that occur at the end of the wet season (September/October) and during peak tropical storm season. Using the 99th percentile groundwater level along the coast generally matches the king tide pattern. As noted by Romah (2010) and ESciences (2014), the groundwater level consistently is 6 inches above the high tide. Thus, the 99th percentile groundwater level is concurrent with king tide events. Surface water data is gathered from DBHydro and other water management district and USGS sources. Figure 19 shows the process to get to the 99th percentile ground/surface/tidal elevation date (worst case) to be used as an input for modeling. The high tide on the common data is chosen to set a boundary for the coastal areas. The land has relatively flat terrain, and canals and tides control groundwater elevation. For all watersheds and subwatersheds, the outlets need to be defined.

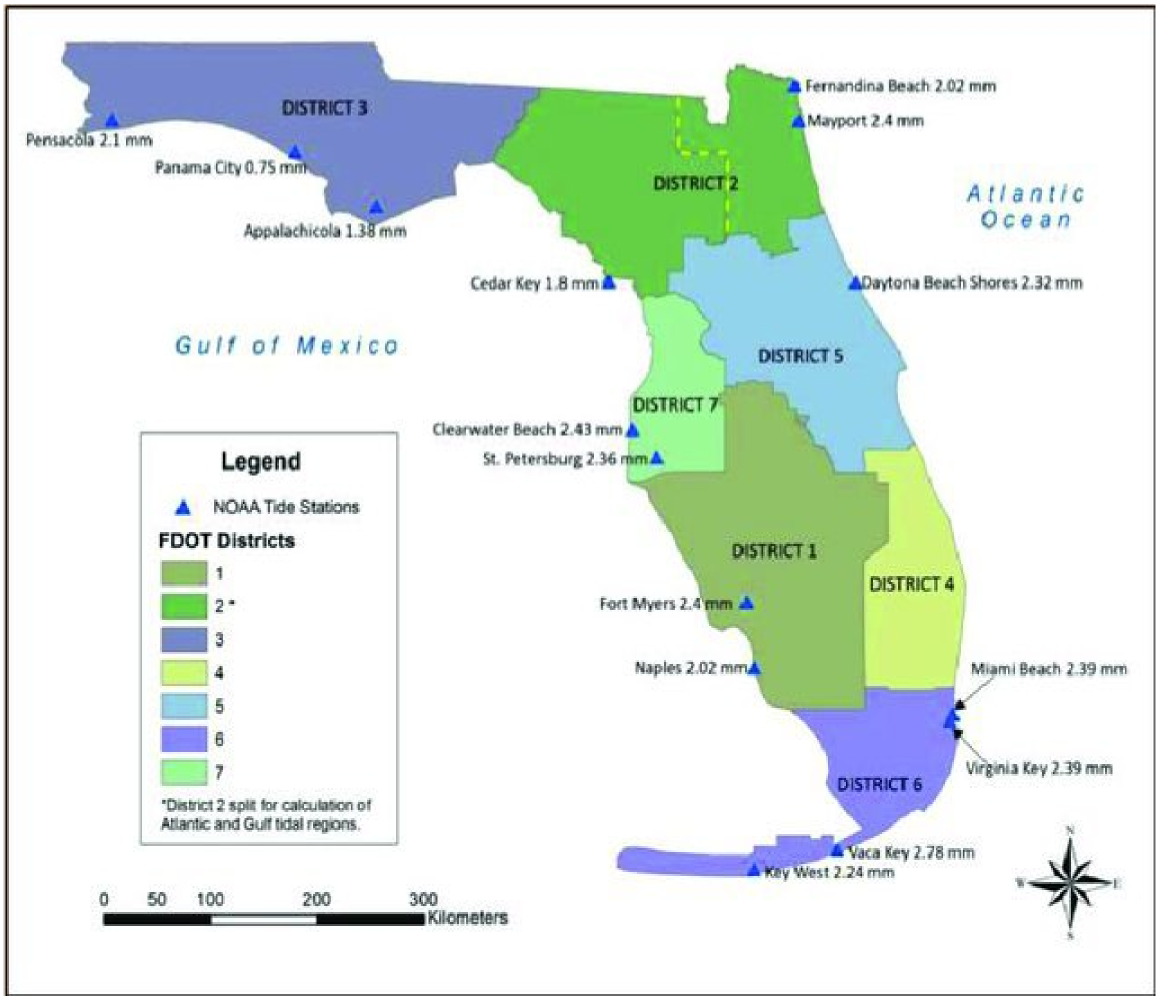


Figure 17. Locations of Florida tidal stations maintained by NOAA in FDOT Districts (https://www.researchgate.net/publication/330637496_Sea_Level_Rise_Projection_Needs_Capacities_and_Alternative_Approaches_Sea_Level_Rise_Projection_Needs_Capacities_and_Alternative_Approaches/figures?lo=1)

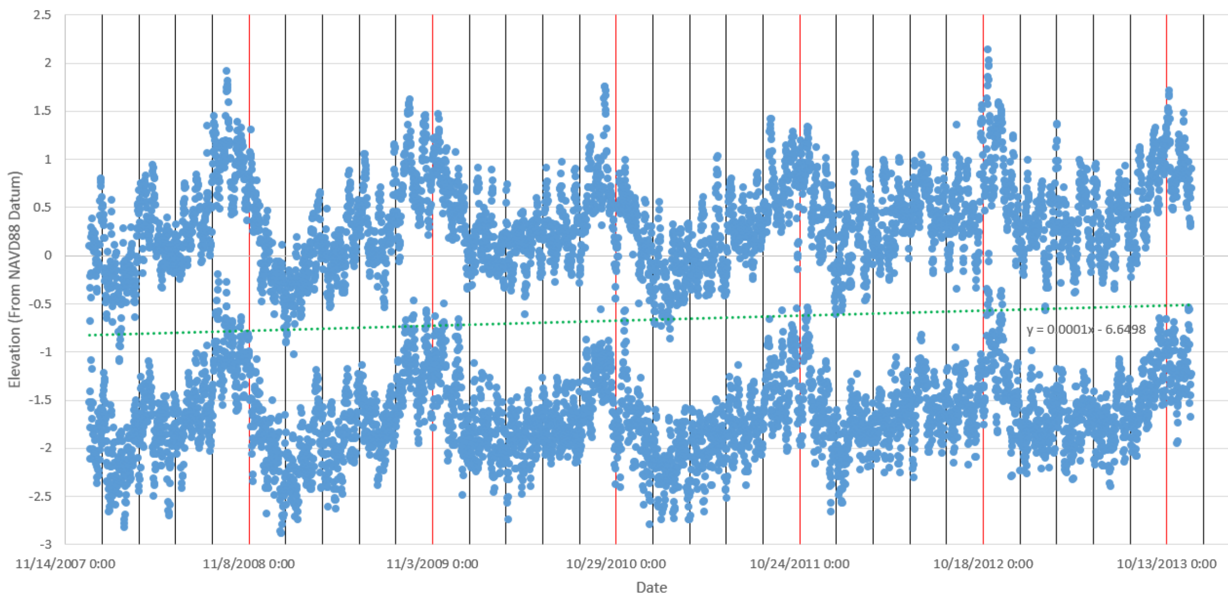


Figure 18. High and low tidal variation for Virginia Key (NOAA2008-2013) over a 5-year period

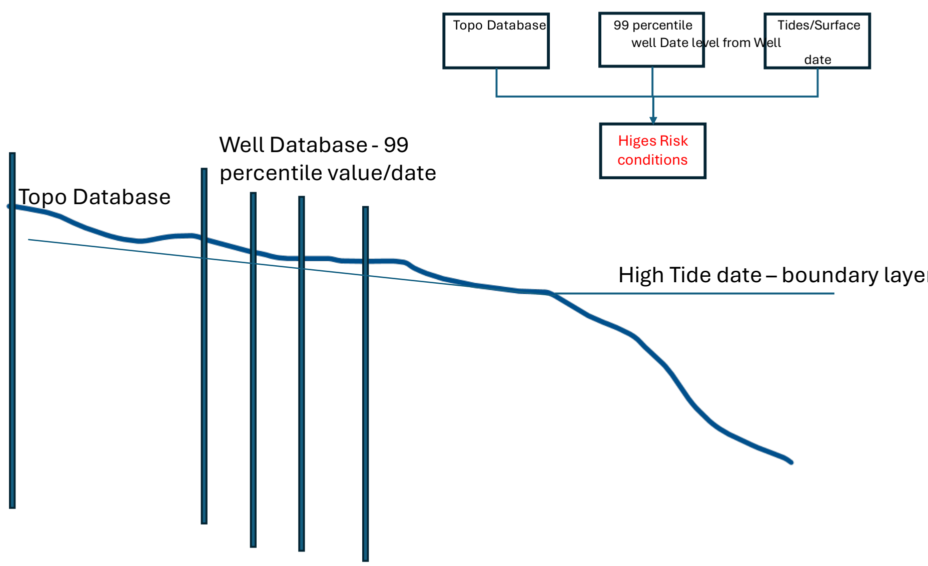


Figure 19. Process to find common groundwater/surface water/tidal elevation data

Figure 2019 is an example of the stream gages provided by the SFWMD. Several water management district staff members offered to provide surface station information for the dates in question upon request. Table 8 outlines the challenges and solutions for addressing surface water and tides across the state (as applicable).

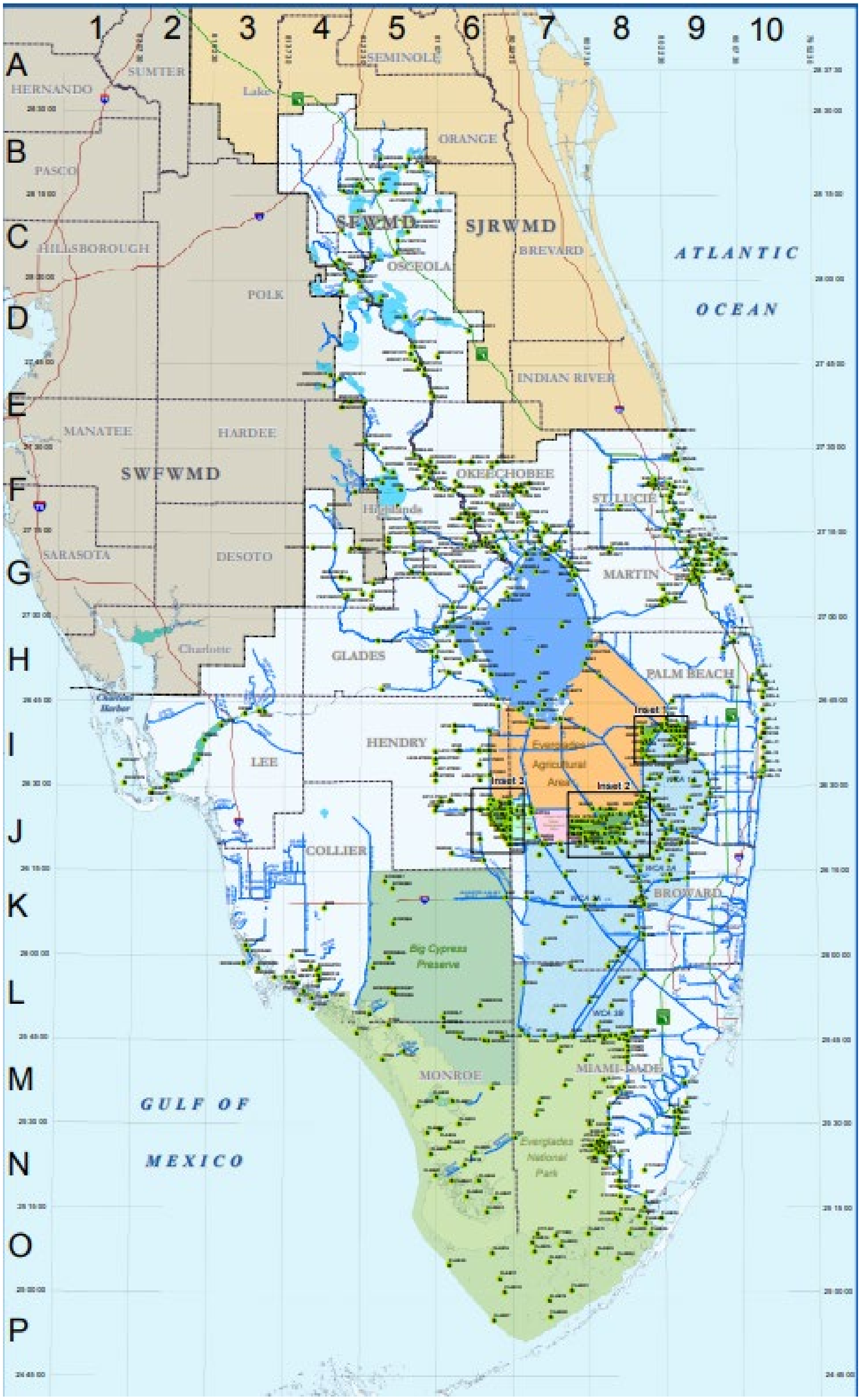


Figure 20. SFWMD stream gage stations for surface water data

Table 8 Challenges and solutions for addressing surface water and tides across the state

Issues Noted	Solutions
1. **Southern Florida Coastal Condition**. The land has limited elevation, and groundwater levels are governed by canals and tides characterized by direct interaction between groundwater and surface water. Bloetscher et al. (2012) found that the groundwater elevation would seek the high tide level as opposed to average tides for the coastal boundary condition. Figure 17 shows the location of tide gages in Florida. These tide gages record high and low tides by cycle each day.	Once a common time period is determined across the majority of wells, canal data can be gathered for that date (and two days prior in the event the canals were deliberately lowered) from the DBHYDRO sites for surface waters. Between stations, an ArcGIS tool permits a line to replicate the canals and establish points in a gradient between stations. The same is true for the ocean but it is a constant head boundary. The canals form boundary conditions for the screening tool on the edges of the basin and affect localized groundwater. Using the water levels in the groundwater and canals, the only remaining boundary was the ocean. The tide issue is easily resolved by using the same date for high tide from the nearest tidal gage. The stream gages can be searched for the correct date using a similar process.
2. **North Florida Condition**. There is no direct interaction between groundwater and surface water, and tidal conditions, groundwater, and surface water are unrelated. There are two possible high groundwater levels: 1) post-rainy season and 2) spring runoff season. Flooding may be more related to stream swell due to upstream runoff than high groundwater levels.	The tidal and groundwater dates need to be obtained using the same method they are for the south Florida condition to determine soil capacity. For points from streams, rivers, canals, and inland water boundaries (e.g., lakes), the elevation of these points are assigned as DEM using extract value to point function in ArcGIS. For points along ocean shorelines, elevations are assigned to the closest tidal station observed elevation using Point to Point spatial join function in ArcGIS. Merge surface station observation data and derived pseudo point elevation data (all are point features with elevation attributes), and then use the merged point dataset to run interpolation algorithms in ArcGIS. Note that the project area has many streams, rivers, etc. Thus we have adequate points to run these interpolators, and each can produce an ideal MINWTE surface.
3. **Hillsborough County Condition.** Coastal areas with topography inland with direct interaction of groundwater and surface water only along the coast.	Current kriging spatial interpolation techniques cannot resolve regions with sparse or no well observations. Thus, an ideal groundwater table map/raster layer cannot be produced. The multiple linear regression (MLR) approach has been well established for groundwater elevation estimation

Issues Noted	Solutions
	(e.g. Seṕulveda, 2003; Chung and Rogers, 2012; Zhang et al., 2002). This technique assumes that the exposed water surface, such as lakes, streams, rivers, and canals, has the elevation of a local minimum water table (MINWTE) in literature. The depth-to-MINWTE can be derived by subtracting MINWTE from DEM. The WTE is estimated via a multiple linear regression model as follows: Eq. 1: $WTE = \beta 1(MINWTE) + \beta 2(\text{Depth to MINWTE}) + \varepsilon$ Where ε = statistical error The tidal and groundwater dates need to be obtained the same way they are for the south Florida condition. Second, for points from streams, rivers, canals, and inland water boundaries (e.g., lakes), the elevations of these points are assigned as DEM using the "extract value to point" function in ArcGIS. For points along ocean shorelines, elevations are assigned to the closest tidal station observed elevation using the point-to-point spatial join function in ArcGIS. Since the value of "depth to MINWTE" is created by subtracting MINWTE from DEM, the conditional function in ArcGIS should be used to set negative values to 0. This is conducted using the raster calculator function in ArcGIS. Before the calculation, 3-m DEM is resampled to 10-m first. An example of Depth-to-MINWTE is displayed in Figure 22.
4. **Inland Condition**. Finding a boundary when not along the coast can create a challenging situation (e.g., Clewiston).	For watersheds with no coastal connection, the challenge is determining if the groundwater and surface waters are linked, and how fluctuations are controlled (versus tides affecting them). This requires obtaining information from adjacent watersheds as a means of smoothing edges within the watershed of interest.

Coastal communities will have the coastal ocean as the outlet. Areas that do not discharge to the coastal ocean will have outlets that become inlets for downstream watersheds. For example, as Figure 21 shows, the Caloosahatchee basin has an inflow from Lake Okeechobee on the east. It also has contributions from various swamps along the river as it flows west. The outlet is the Gulf of Mexico and the east side of Sanibel

Island. A more inland watershed may require a substantially expanded area of investigation to address incoming water and limits on the outlet end. Figure 22 shows how the integrated surface/groundwater/tidal databases can be developed into one map for use with modeling soil sotrage capacity.

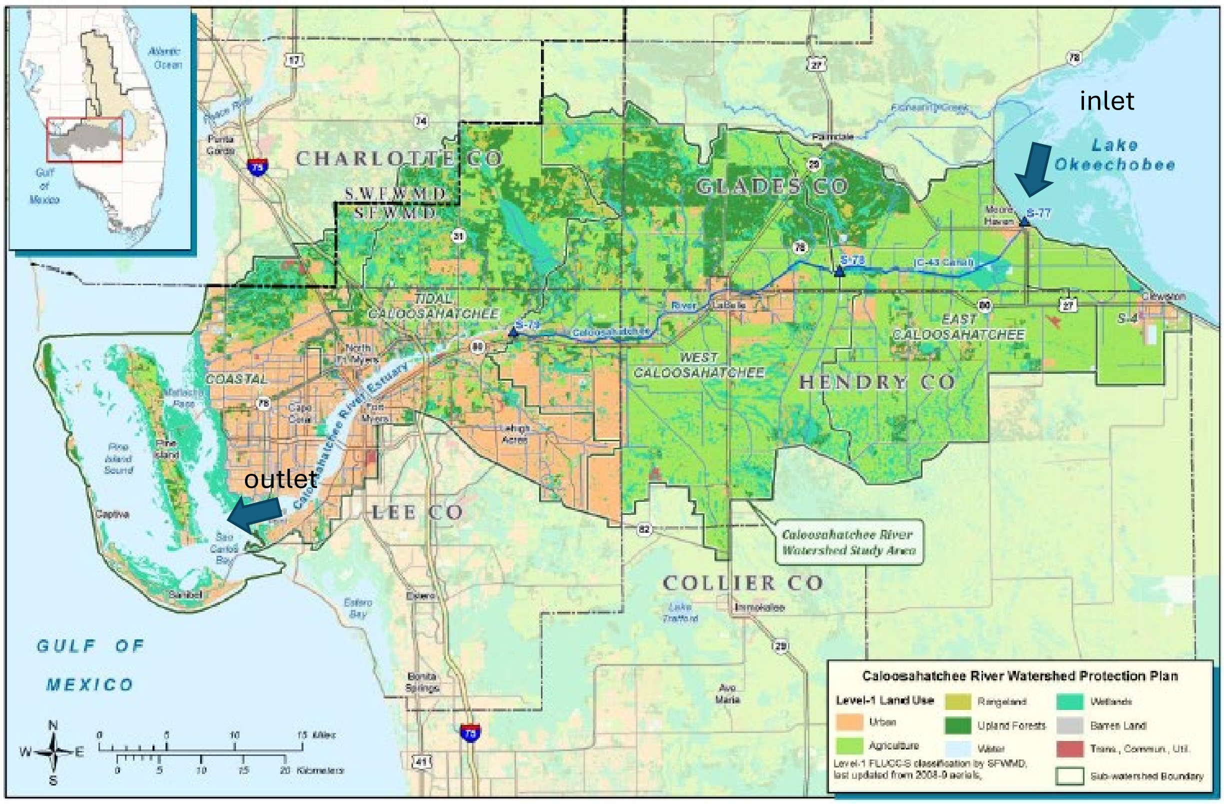


Figure 21. The Caloosahatchee watershed (SFWMD, 2009) inlet and outlet

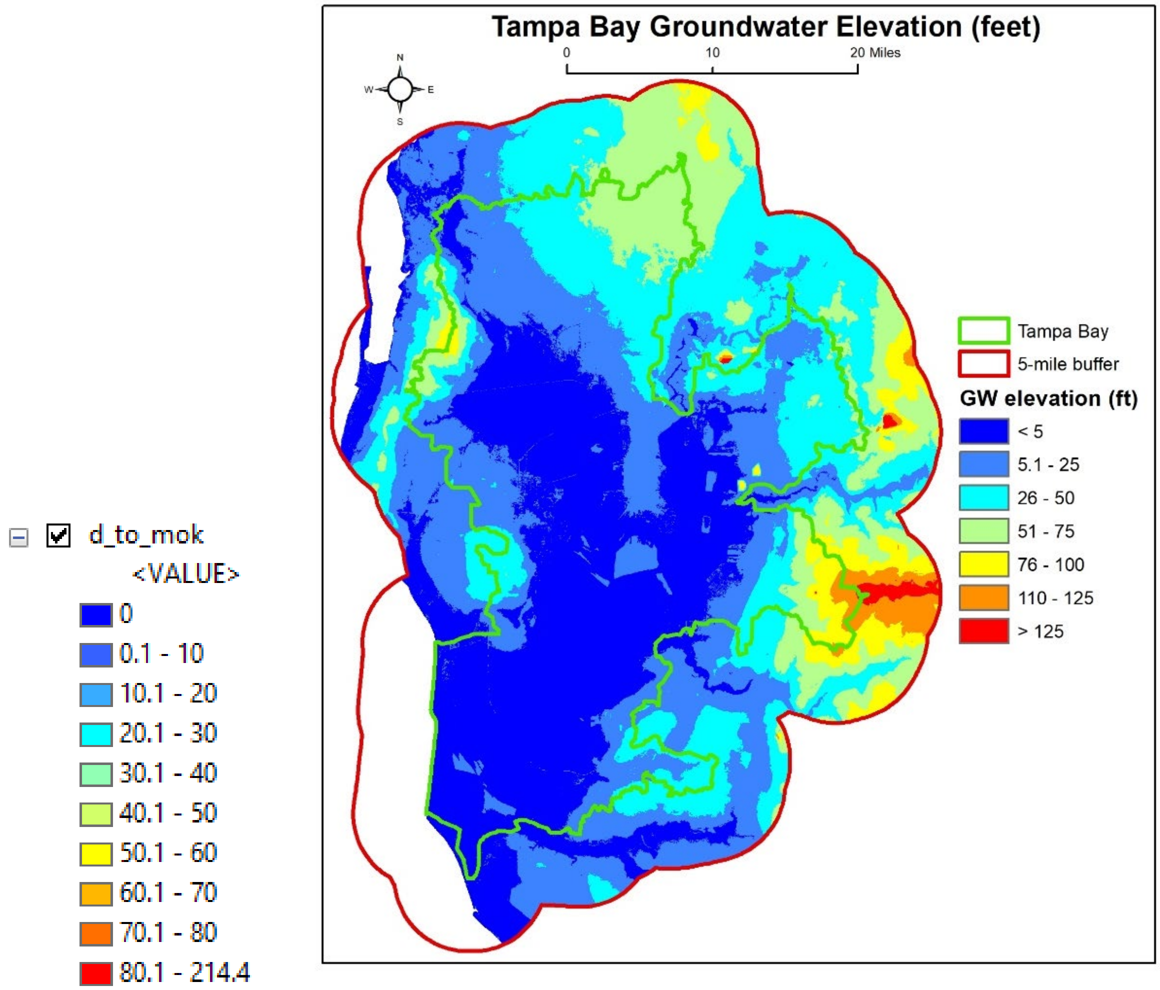


Figure 22. 10-m depth-to-MINWTE. Negative values are assigned to 0.0 because water table cannot exceed ground elevation). Regions with 0 values are expected for water bodies, rivers, streams, canals

ArcHydro is an available extension in ArcMap with a set of tools designed to delineate the catchment drainage areas using a DEM as input. The ArcHydro function also permits the delineation of routing and sub-basins, which may need to be modeled separately. The results from the land cover, water bodies, flood routing, soil capacity, and topography are all inputs used to generate the flood maps. Figure 23 is an example of how this tool can be used to map waterways in a community.

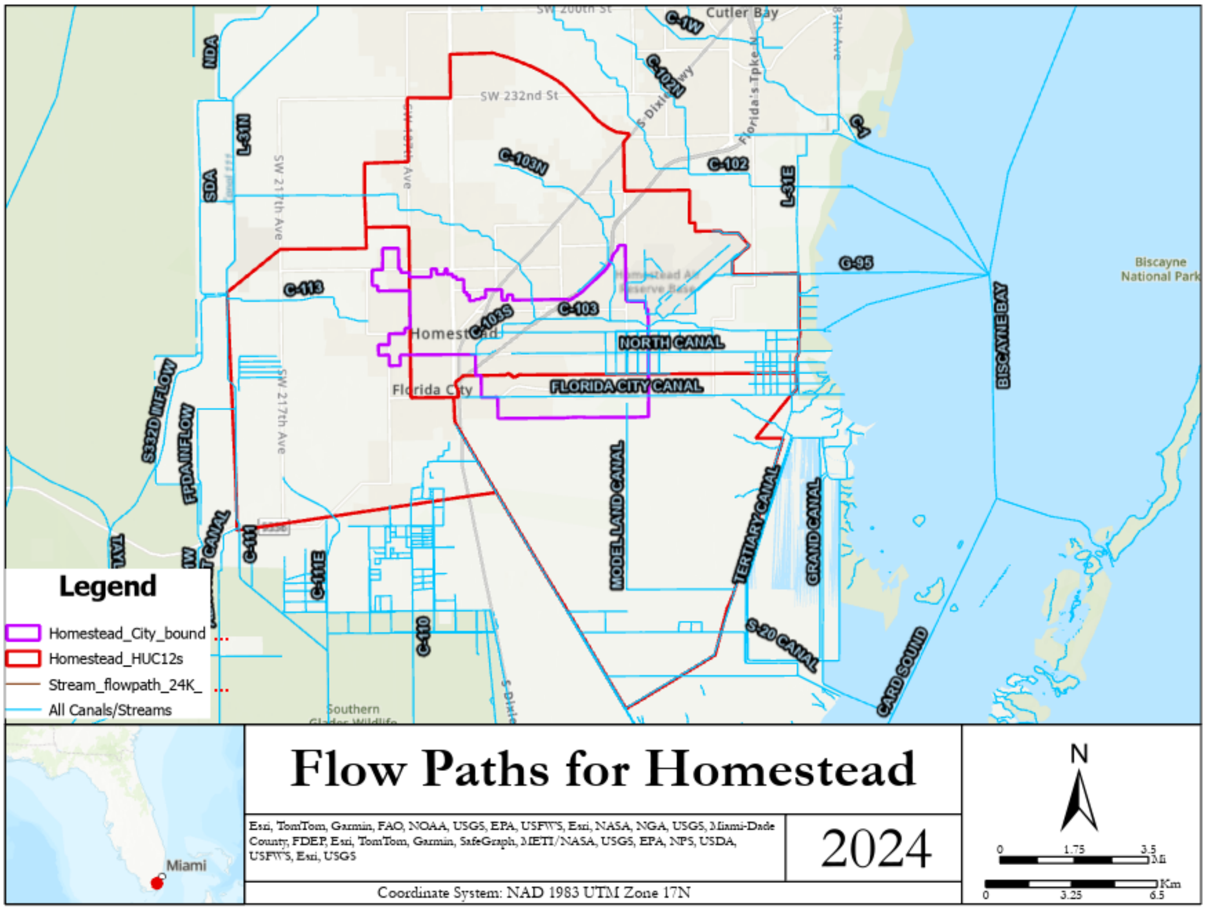


Figure 23. Flow paths for Homestead, FL (SFWMD)

2.4 Soils

Soil storage is available if there is adequate distance between the topographic surface and the groundwater table elevation, and the soil is capable of absorbing the water. Soil data is obtained from USDA or other agencies. Then the soils data needs to be interpreted to determine whether water can be absorbed or will runoff. This is a critical issue for precipitation modeling. The FAU team used the Gridded SSURGO (gSSURGO) dataset from USDA, which is similar to the standard product from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database, but is in the Environmental Systems Research Institute, Inc. (ESRI®) file geodatabase format. A geodatabase file can store significantly more data and thus greater spatial extents than the traditional SSURGO product. This allows for statewide or even Conterminous United States (CONUS) tiling of data. gSSURGO contains all of the original soil attribute tables in SSURGO. All spatial data are stored within the geodatabase instead of externally as separate shape files. Both SSURGO and gSSURGO are considered products of the National Cooperative Soil Survey (NCSS).

An important addition to the new format is a 10-meter raster (MapunitRaster_10m) of the map unit soil polygons feature class, which provides statewide coverage in a single layer. This new addition provides greater performance and important analysis capabilities to users of soils data. Statewide tiles consist of soil survey areas needed to provide full coverage for a given State. To create a true statewide soils layer, some clipping of excess soil survey area gSSURGO data may be required. The new format also includes a national Value Added Look Up (value) table with several new "ready to map" attributes.

Along with these important advantages, the gSSURGO format has a few disadvantages:

- File geodatabases such as gSSURGO are incompatible with the NRCS Soil Data Viewer application.
- The file geodatabase format supports a limited subset of the standard query language (SQL) that the Microsoft® Access® database format or Microsoft® SQL Server® uses.
- Unlike vector layers, the geodatabase cannot store permanent table relates for raster layers.

One important thing to note is the unit of the available water storage. From the user guide of the gSSURGO soil database, it shows that the available water storage (AWS) is in millimeters. However, in the user guide of SSURGO, it mentions that AWS has a unit of centimeters. The FAU team confirmed with Paul F. Reich, who is Geographer of Soil and Plant Science Division USDA-NRCS, that, "the units for Available Water Storage is in cm when using Web Soil Survey, SSURGO, gSSURGO or gNATSGO. One of our guides refers to the National Value Added Look Up (Valu1) table. Within that Valu1 table, the AWS units are in mm." Thus, a conversion was required. Also the maps are 10 m resolution not 3 m. Therefore, a conversion was necessary to use the data.

The available water storage derived for the soil layer (0-150 cm) is shown in Figure 24. It covers most of Florida with a spatial resolution of 10 m. The unit is in cm. The "no data area" is mainly due to a land cover by water body or wetland.

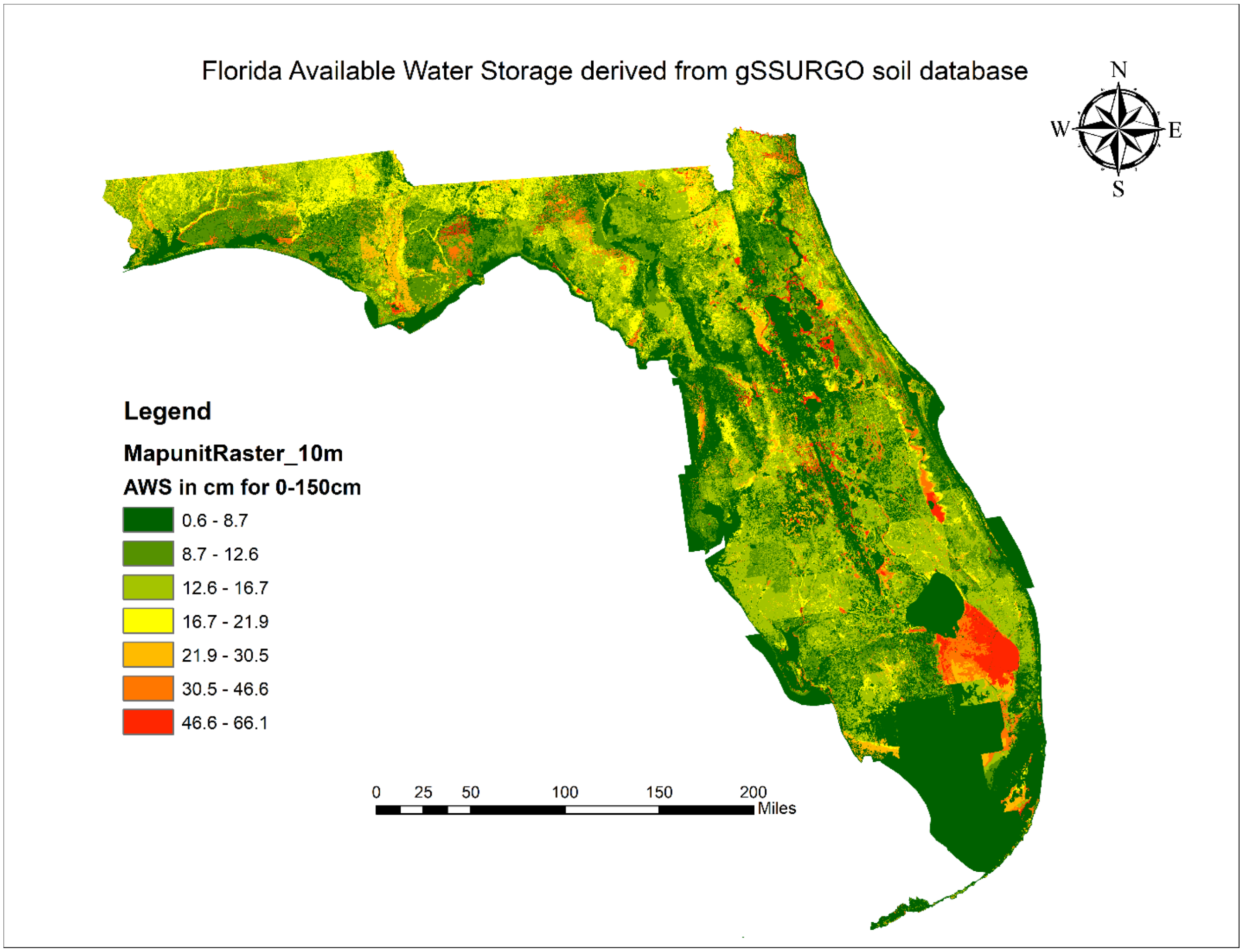


Figure 24. Florida available water storage map

According to the Plant and Soil Science E-Library of University of Nebraska-Lincoln (https://passel2.unl.edu/view/lesson/0cff7943f577/10), water holding capacity refers to the amount of water held between field capacity and wilting point. available water storage (AWS) is that portion of the water holding capacity that can be absorbed by a plant. As a general rule, plant available water is considered to be 50% of the water holding capacity.

The water holding capacity (ratio) is calculated using the following equation:

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

Figure 25 shows the water holding capacity (ratio) map for Florida. Water holding capacity here is dimensionless. Note the tiles were converted to 3 x 3 m.

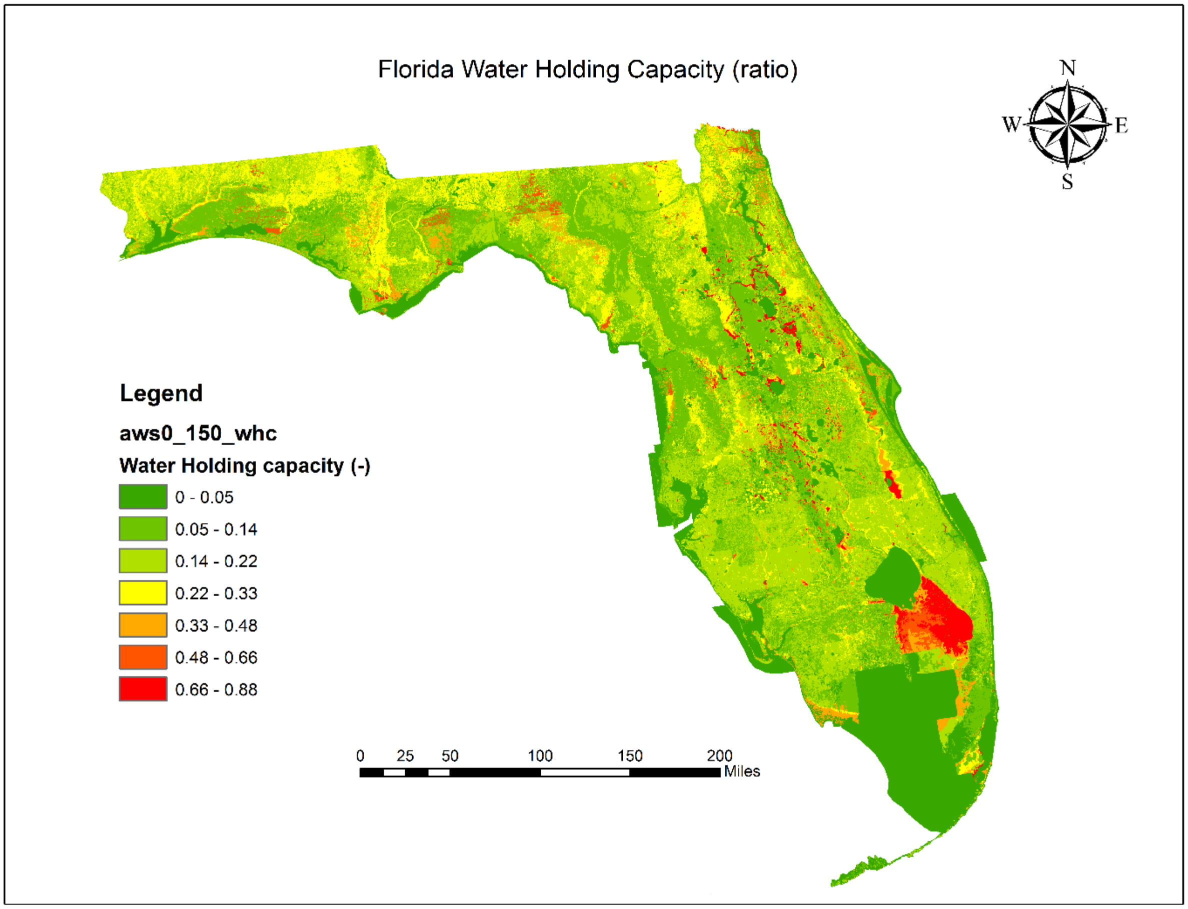


Figure 25. Florida water holding capacity ratio map

2.5 Land Cover

Land cover data aids in determining the extent to which water can infiltrate the soil (natural condition) versus more developed areas, where the land cover type will discourage or impede infiltration. For example, cropland, pastureland, rangeland, forestland, agriculture, developed, federal land, etc. are conditions where the land has considerable ability to infiltrate stormwater runoff. As a result, when modeling runoff from storms, these areas will create less intensive runoff curves. In contrast, developed areas will have more imperviousness, which may vary at the parcel level. For example, residential communities may have less than 30% imperviousness, whereas downtown business districts may have over 80%. In such cases, the runoff curve associated with highly developed areas causes higher peak runoff that occurs faster than that associated with undeveloped properties. Waterbodies are impervious properties per the land use codes.

Land cover is one of the bigger challenges for modeling watersheds. There are multiple sources of data that must be merged in some reasonable fashion. Current land cover changes constantly in response to natural and man-made events, but projecting future land use is what CRS is really interested in. For Flroida, an extensive regulatory framework exists to prevent increases in the runoff curves, requiring the retention of major storm events on site.

Useful sources of data include:

- Current land use maps for local governments
- Future land use maps
- Aerial photography
- Land use databases.

The first 3 are date specific and often provide limited information for pervious or impervious property. Guestimates from local property appraisers is soften the best means to attain these values. For many residential communities, 27-25% imperviousness is a general rule, with future maximums defined as 35-40%. Using 35% - 40% for the future for all residential development, based on land development codes, is the best solution to the problem.

For less developed areas, the National Land Cover Database (NLCD) provides nationwide data on land cover and land cover change at a 30 m resolution with a 16-class legend based on a modified Anderson Level II classification system. The database is designed to provide cyclical updates of United States land cover and associated changes. Systematically aligned over time, the database facilitates understanding the current and historical land cover and land cover change and enables monitoring and trend assessments. The latest evolution of NLCD products is designed for widespread application in biology, climate, education, land management, hydrology, environmental planning, risk and disease analysis, telecommunications, and visualization. While 8 years old, the best application is most undeveloped areas that do not change significantly in such a short period. More urban areas may change significantly.

The U.S. Geological Survey (USGS) has released a new generation of National Land Cover Database (NLCD) products named NLCD 2016. For the conterminous United States, NLCD 2016 contains 28 different land cover products characterizing land cover and land cover change across 7 epochs from 2001-2016, urban imperviousness and urban imperviousness change across 4 epochs from 2001-2016, tree canopy and tree canopy change across 2 epochs from 2011-2016 and western U.S. shrub and grassland areas for 2016. Data are available as prepackaged products, or custom product areas can be interactively chosen using the viewer. NLCD is coordinated through the 10-member Multi-Resolution Land Characteristics Consortium (MRLC).

The challenge is that this data is more than 8 years old and in developing areas, is outdated. As a result, in addition to the NLCD land cover dataset, FAU also collected a statewide land use land cover dataset compiled by the Florida Department of Environmental Protection. This dataset integrates land use land cover data products provided by the 5 Water Management Districts in Florida based on manually interpreted fine resolution aerial photography: North West Florida Water Management District (NWFWMD) 2012-2013, Suwannee River Water Management District (SRWMD) 2010-2011, St. Johns River Water Management District (SJRWMD) 2009, South West Florida Water Management District (SWFWMD) 2009, and South Florida Water Management District (SFWMD) 2004-2005 and 2008-2009. Codes are derived from the Florida Land Use, Cover, and Forms Classification System (FLUCCS-DOT 1999) but may have been altered to accommodate region differences. Two issues arise – some of these datasets are even older than the NLCD dataset and this land use land cover product has a finer delineation of land cover types. One benefit - these datasets can help further refine water bodies and impervious surfaces where soil water holding capacity is zero in our models. These datasets were integrated with future land use to create impervious mapping.

Issues noted:

- Small water bodies and impervious surfaces have not been well delineated in the NLCD dataset but can be delineated by the statewide land use land cover dataset. Large water bodies such as Tampa Bay and canals have not been fully delineated by the statewide land use land cover dataset but delineated by NLCD dataset. Thus, the two datasets can complement each other. The data is 30 m resolution and must be refined to 3 x 3 m.

Solutions:

- The FAU team used the impervious surface from the NLCD2016 to set the soil water holding capacity to zero in model simulations.
- The FAU team used water bodies defined in the statewide land use land cover dataset to set soil water holding capacity to zero in model simulations. Water bodies are re-delineated by using both

NLCD and statewide land use land cover datasets. Note that tiny water bodies may be missing from WMD files.

- The 2016 NLCD Land Cover map for Florida is shown in Figure 26 with an overlay of the county boundaries. The impervious surface mainly includes classes 21, 22, 23, and 24. The 30 m resolution can be re-pixelated to 3 m.

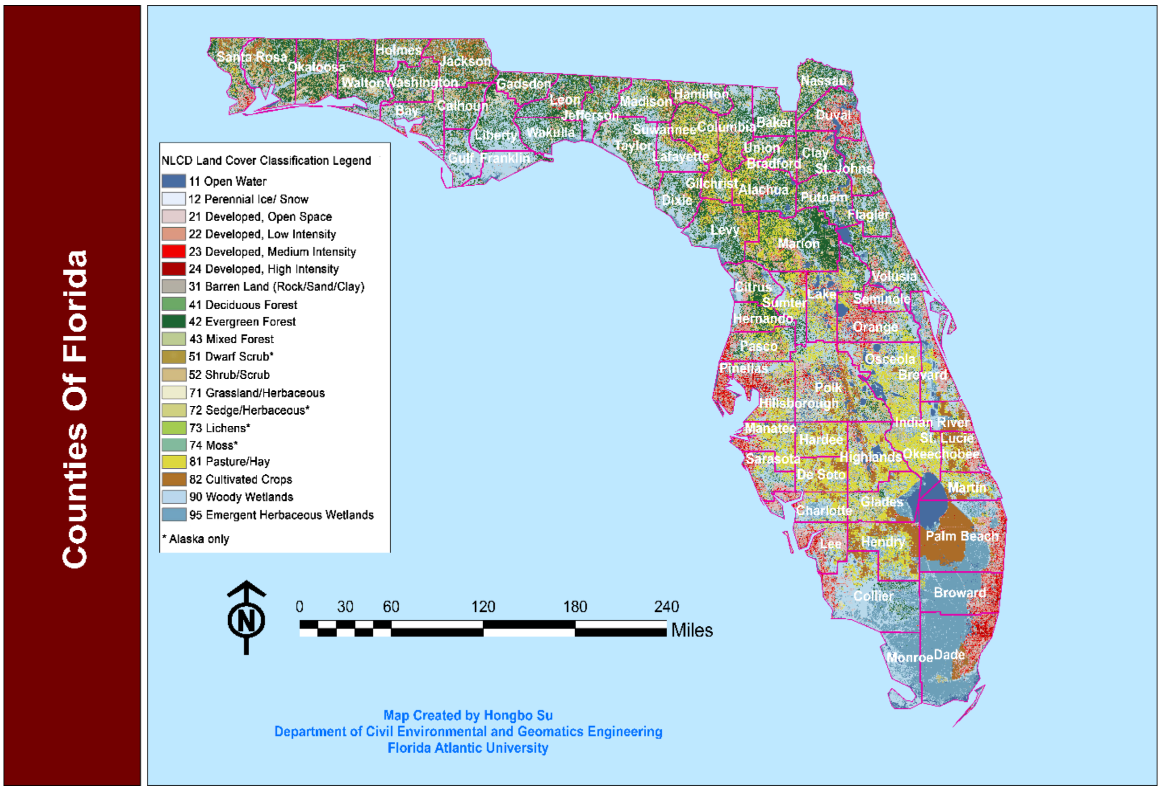


Figure 26. Florida NLCD land cover map

The most recent land use land cover data (2014-2016) from the South Florida Water Management District (SFWMD) are based on a modified Florida Land Use Cover Classification System (FLUCCS). A GIS application and aerial imagery were used to digitize Level-1 and Level-2 land use features through photo-interpretation techniques at the county-level for south Flroida only. Land use features were digitized at a scale ranging from 1:7,000 to 1:12,000. The horizontal accuracy of this dataset is dependent on the source of the aerial photographs taken from 2014-2016, which have varying vertical resolutions between 4-inches and 2-feet. Based on the SFWMD's guidelines for the minimum mapping unit, the smallest wetlands and uplands features captured by this dataset are at least 0.5 acres and 5 acres, respectively. Since the SFWMD dataset is digitized by photo-interpretation on county-based aerial photography, while the NLCD 2016 has a 30-meter resolution derived from Landsat imagery, the NLCD maps appear much coarser and pixelated compared to the SFWMD maps. This level of fine detail may exceed what is available from NLCD2016 and may be preferred for planning purposes. However because the NLCD dataset is dated, current land use maps were gathered for communities when modeling at the HUC 12 level.

Future land use plans normally address what communities expect for development intensity and include regulations to mitigate higher intensity runoff events. The analysis assumes the entire watershed is developed to the **maximum extent allowed by current zoning** derived from the jurisdiction's comprehensive plan. Impervious areas do not permit the infiltration of precipitation to groundwater, and because the water cannot infiltrate, it runs off faster, which means that peak flows to waterbodies and storm sewers occur faster and with higher peak volumes. The result is a disruption of the natural (and potentially the planned) hydrology. Impervious areas include pavement, buildings, and other areas that have been compacted to reduce runoff storage capacity. In other words, developed areas have higher imperviousness compared to natural or agricultural areas.

As commercial and residential areas are constructed in a city, many impervious surfaces, such as streets and roofs, can impact the existing hydrologic system. This urbanization results in an increase in the rate and volume of stormwater runoff. For example, impervious surfaces prevent water from infiltrating the soil, causing the runoff to travel faster than over land. Suddenly, communities and infrastructure are introduced to new flood hazards with new development. However, with proper management of stormwater runoff, cities can counteract this negative impact on the hydrologic system. Using the NLCD 2016 dataset, a layer was created using the following three of the 13 categories to identify impervious areas:

- primary roads in urban areas
- secondary roads in urban areas
- tertiary roads in urban areas

The new layer was then converted to match the 3-m spatial resolution from the DEM and the standard State Plane Coordinate system used by professional land surveyors in Broward (NAD83 Fl East-US foot). Figure 27 is an example of the current land cover for a community (Homestead, FL). There are 3 HUC12 study areas involved.

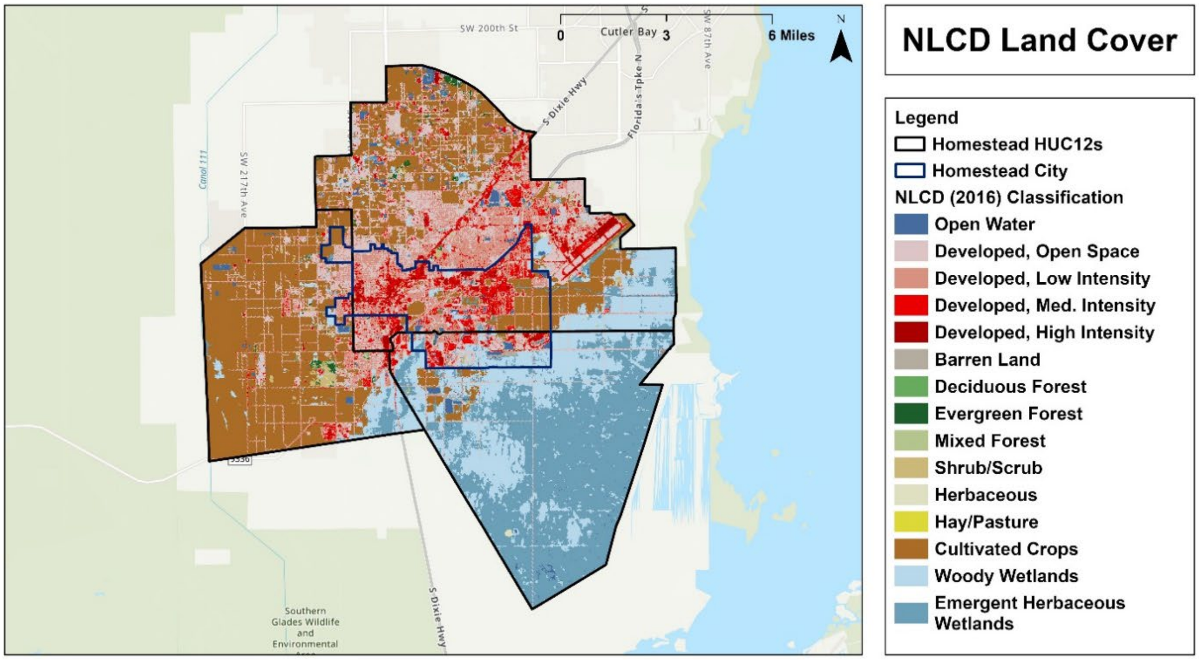


Figure 27. Current Land cover (SFWMD 2014-2016), as generated by FAU CWR3.

Figure 28 is a future land use plan for Homestead, FL. The City is mostly built out today, but the City anticipates that added density will occur with residential development and commercial activity in undeveloped but low-lying properties. However, because the City has limited available land, the density changes are unlikely to have much impact on flooding given that all new projects must comply with the SFWMD stormwater retention requirements to hold the 3-day, 25-year storm event on all new development sites as opposed to allowing the stormwater to flow to City streets.

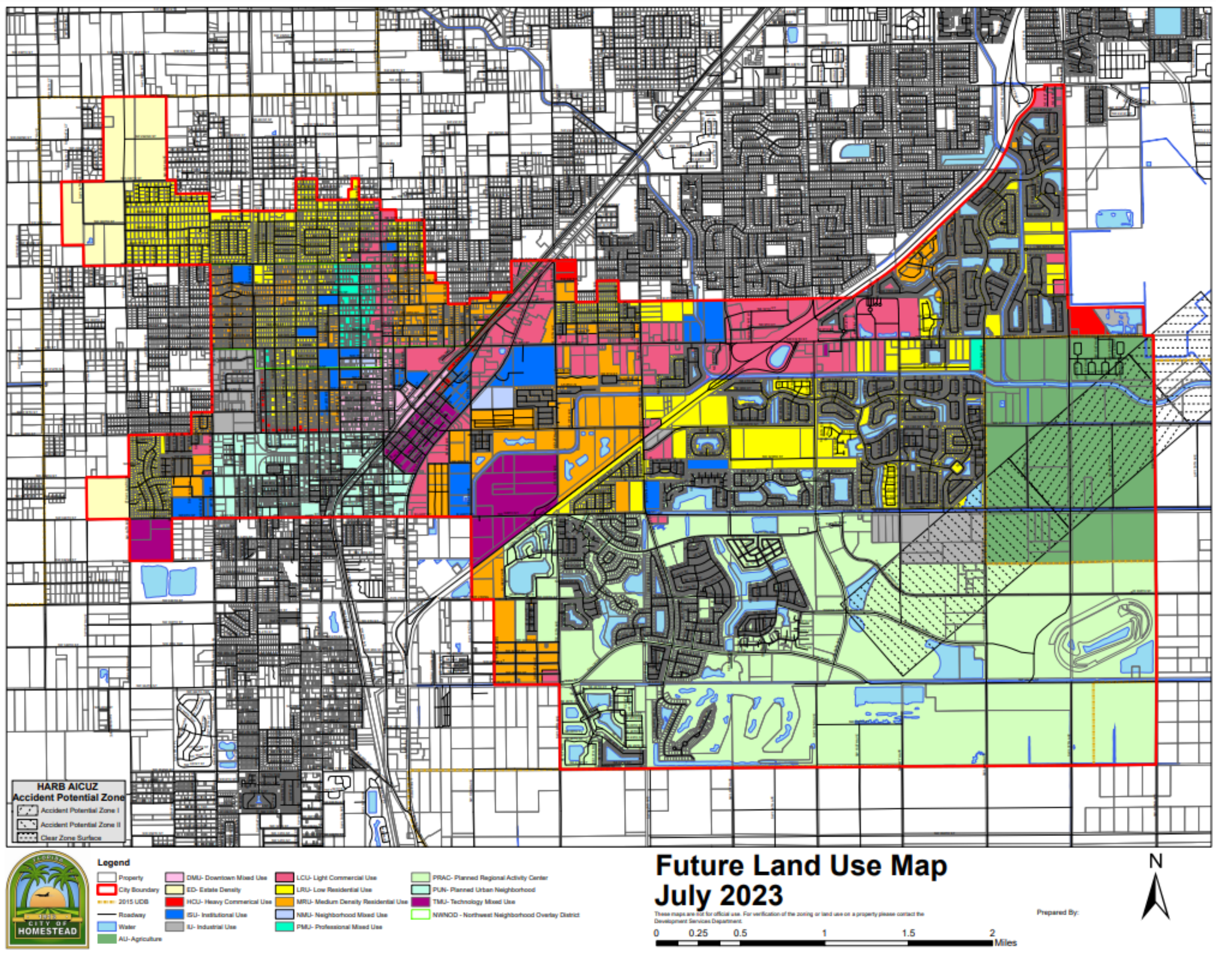


Figure 28. Future land use in Homestead, FL

Since only a limited portion of Homestead was built before these regulations were put into place in 1985, changes to imperviousness will be limited. Note that political and watershed boundaries tend not to line up, complicating development patterns. Political boundaries are important in identifying potential stakeholders within the jurisdiction. Where onsite storage requirements exist (virtually any developed area), those were factored into the future land use assumptions. The future land use map would be translated to the future impervious areas (see Figure 29). Of course, the future land use is still an educated guess and will likely be different than the actual future condition.

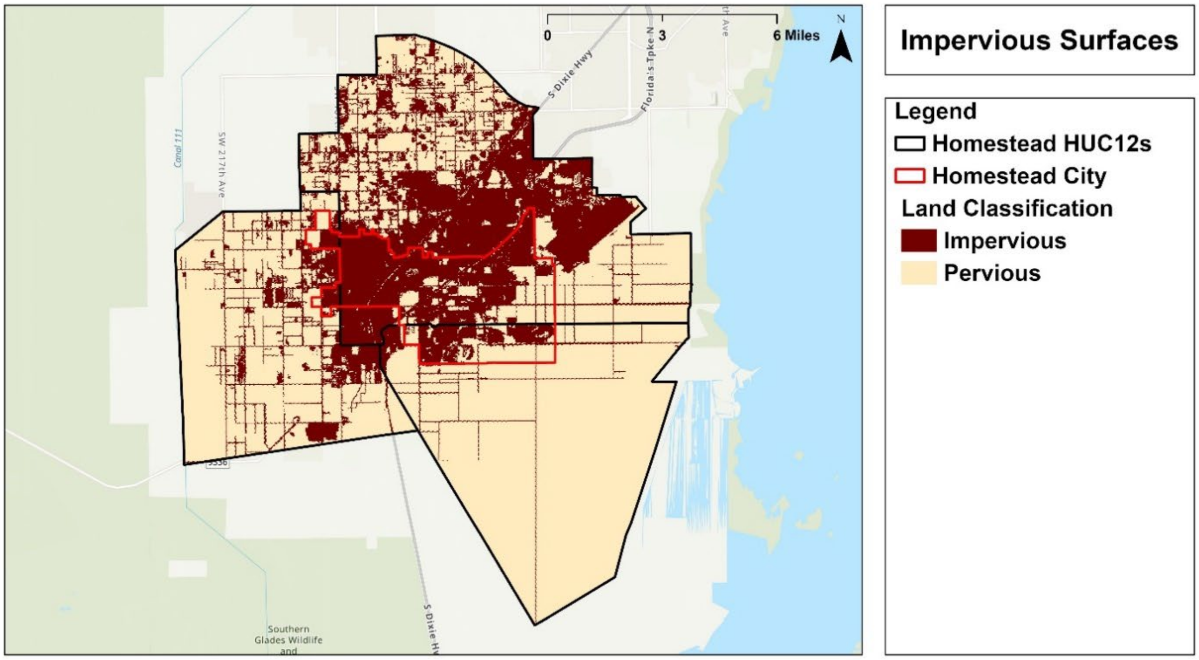


Figure 29. Impervious area map for future land-use for Homestead, as generated by FAU CWR3 (shaded area indicates land use type that is more than 35% impervious)

Waterbodies were defined in the statewide land-use land cover dataset to set soil water holding capacity to zero in model simulations (refer to Figure 30 example). Note that some extremely small waterbodies may be missing from the maps.

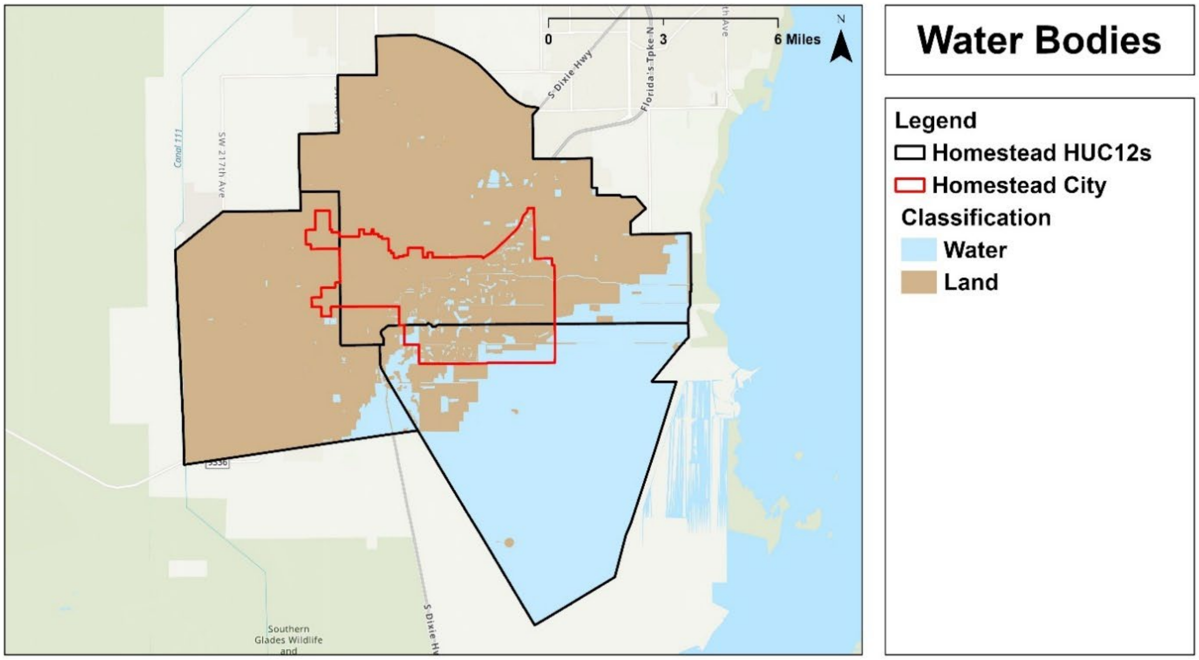


Figure 30. Waterbodies map for Homestead, as generated by FAU CWR3

2.6 Open Space

Open space and reserved areas are important considerations for watershed master planning. CRS credits are available for open space permanently set aside in floodplains. Communities need to provide information on reserved property as a part of WMP4 (as demonstrated with ordinances and easements). Open space is defined as areas exempted from development. Generally, it means one or more of the following qualifiers exist:

1. Valuable for recreation, forestry, fishing, or conservation of wildlife or natural resources
2. A prime natural feature of the state's landscape, such as a shoreline or ridgeline
3. Habitat for native plant or animal species listed as threatened, endangered, or of special concern
4. A relatively undisturbed outstanding example of an uncommon native ecological community
5. Important for enhancing and conserving the water quality of lakes, rivers, and coastal water
6. Valuable for preserving local agricultural heritage
7. Proximity to urban areas or areas with open space deficiencies and underserved populations
8. Vulnerability of land to development
9. Stewardship needs and management constraints

10. Preservation of forest land and bodies of water that naturally absorb significant amounts of carbon dioxide

Figure 31 shows an example of open space reservations (gray areas). Also, the County has certain properties marked in yellow that are held as agricultural in perpetuity (agriculture/conservation). These regions are primarily shown on conservation maps at the County level. Added to this information are the waterbodies, which serve a function related to impervious open space. Agricultural land and other open space land cover will come from the land cover map with an estimate of how much agricultural land will be converted to development in the future.

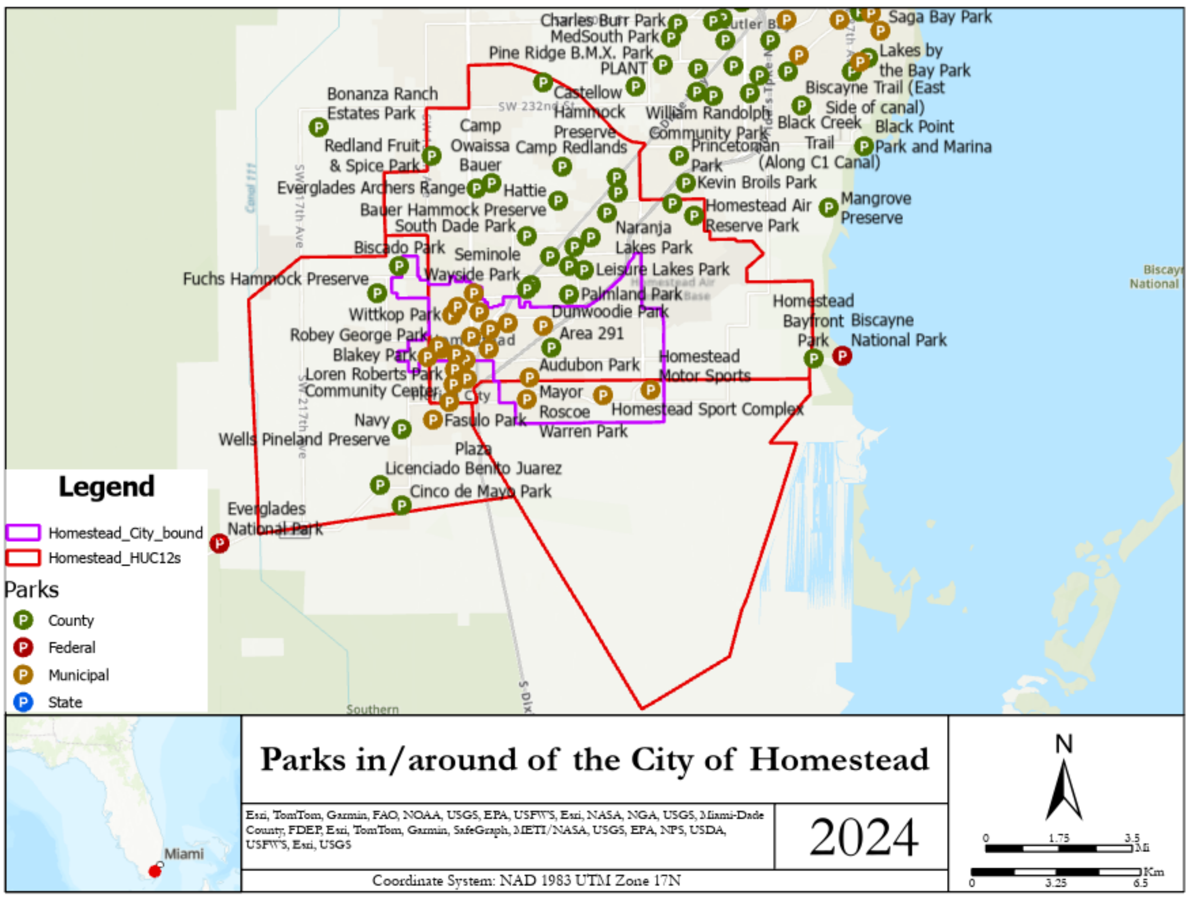


Figure 31. Open areas in the Homestead area

Ecosystem management requires that all aspects of a watershed (e.g. land, water, air, plants, wildlife, etc.) be managed holistically. There are many available resources for assisting in ecosystem management plan development and adapting or integrating those recommendations into the WMP. The need is to identify the key networks of wild landscapes, reserves, buffer zones, and native species habitat to delineate, protect, and restore wilderness corridors, particularly when impacted by human activities and development pressures.

2.7 Rainfall

Relevant precipitation data are needed to understand the local water budget for the watershed and also for modeling purposes. Historical data was obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). Stations within or near a watershed can be found in the NCDC and DBHYDRO databases. Local or regional level stormwater management districts will also collect rain gage data. Hourly or daily precipitation data is required in modeling runoff routing. These precipitation records will provide critical information about wet and dry seasonal variations.

The precipitation data used in screening can be modified for any rainfall event using the accumulated rainfall data table obtained from the NOAA Atlas 14 Point Precipitation Frequency Estimates (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html). Maps of various storm intensities can be developed from NOAA and other sources. See example in Figure 32.

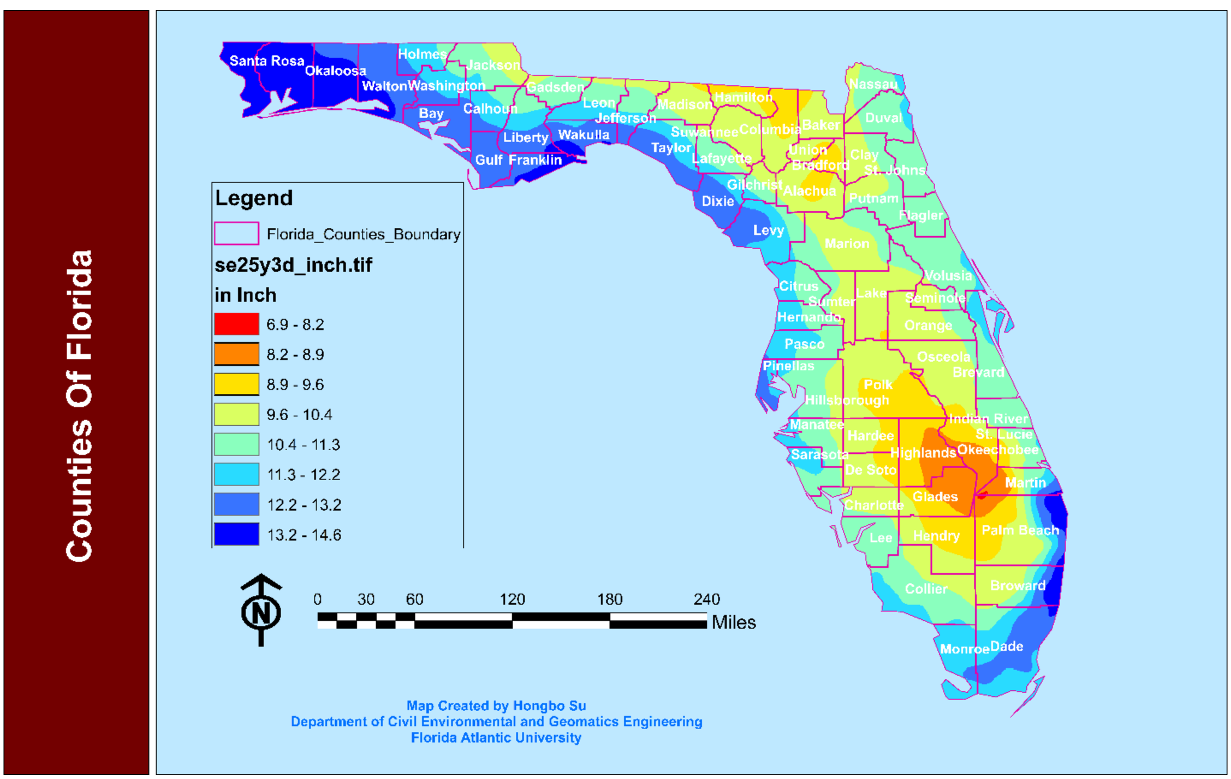


Figure 32. NOAA ATLAS (14) 25-year frequency 3-day duration precipitation

Rainfall used in the screening tool is based on the SFWMD 3-day 25-year storm event but can be modified for any rainfall event using the accumulated rainfall table obtained from NOAA Atlas 14 Point Precipitation Frequency Estimates (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html). Figure 33 shows the 1-day 5-year rainfall map based on the NOAA Atlas 14 dataset for Homestead, FL. Figure 34 shows the 1-day 10-year storm event, Figure 35 shows the 1-day 100-year storm event, and Figure 36 shows the 3-day 25-year storm event, respectively.

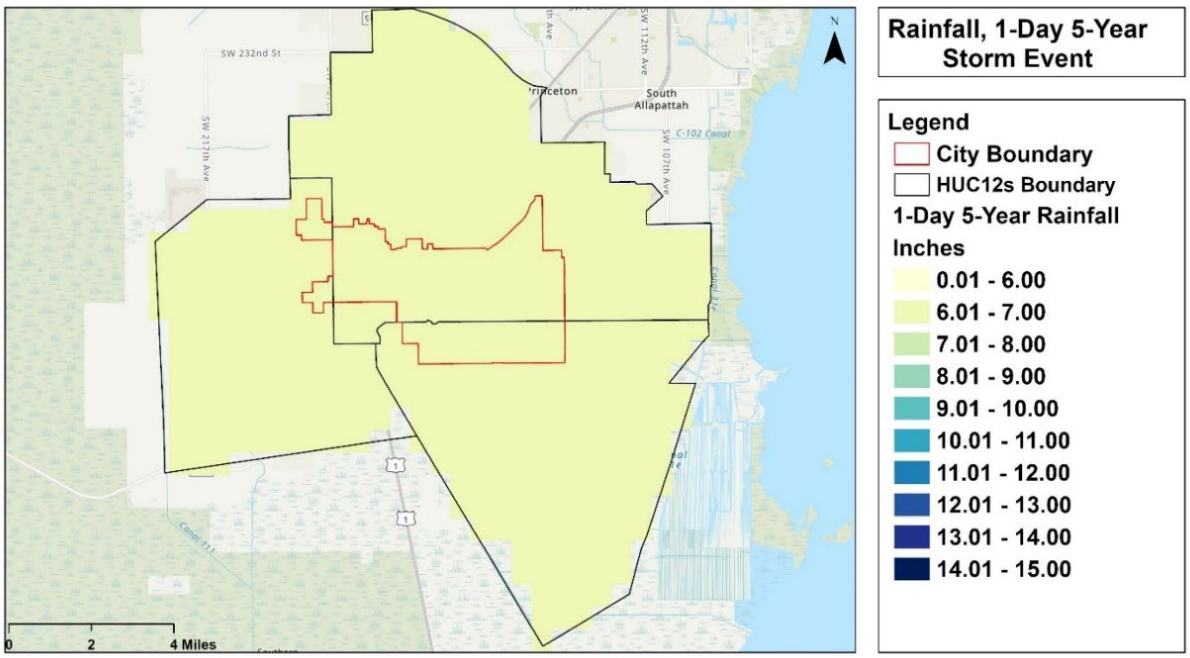


Figure 33. Rainfall distribution map for Homestead for 1-day, 5-year storm, as generated by FAU CWR3

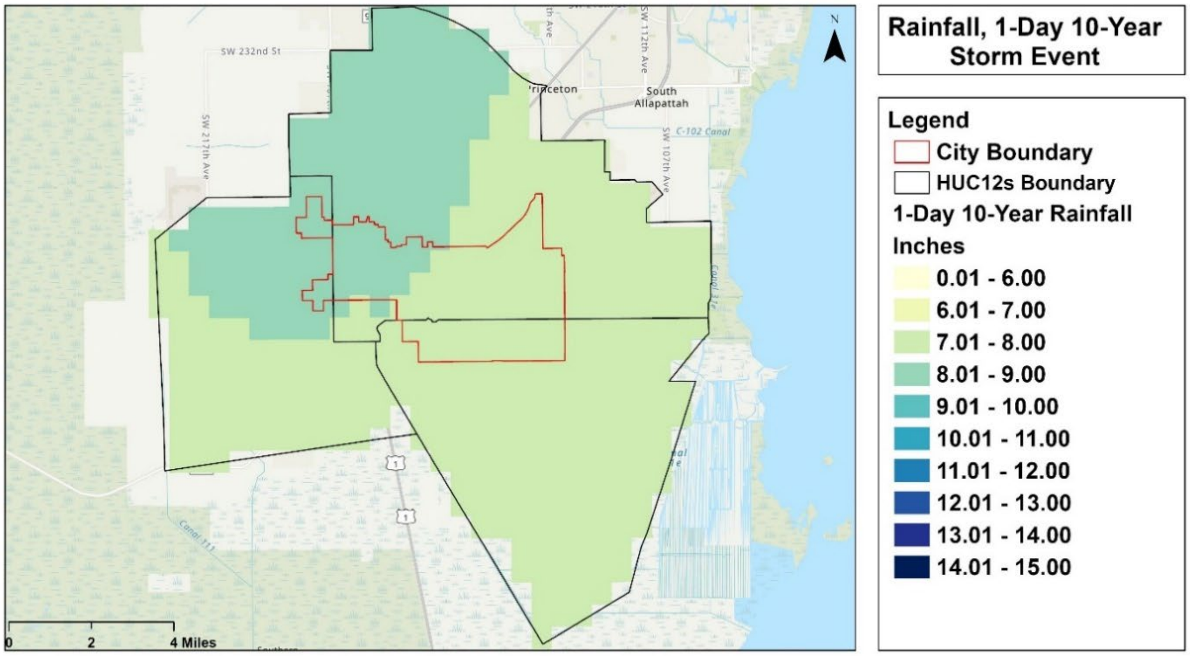


Figure 34. Rainfall distribution map for Homestead for 1-day 10-year storm, as generated by FAU CWR3

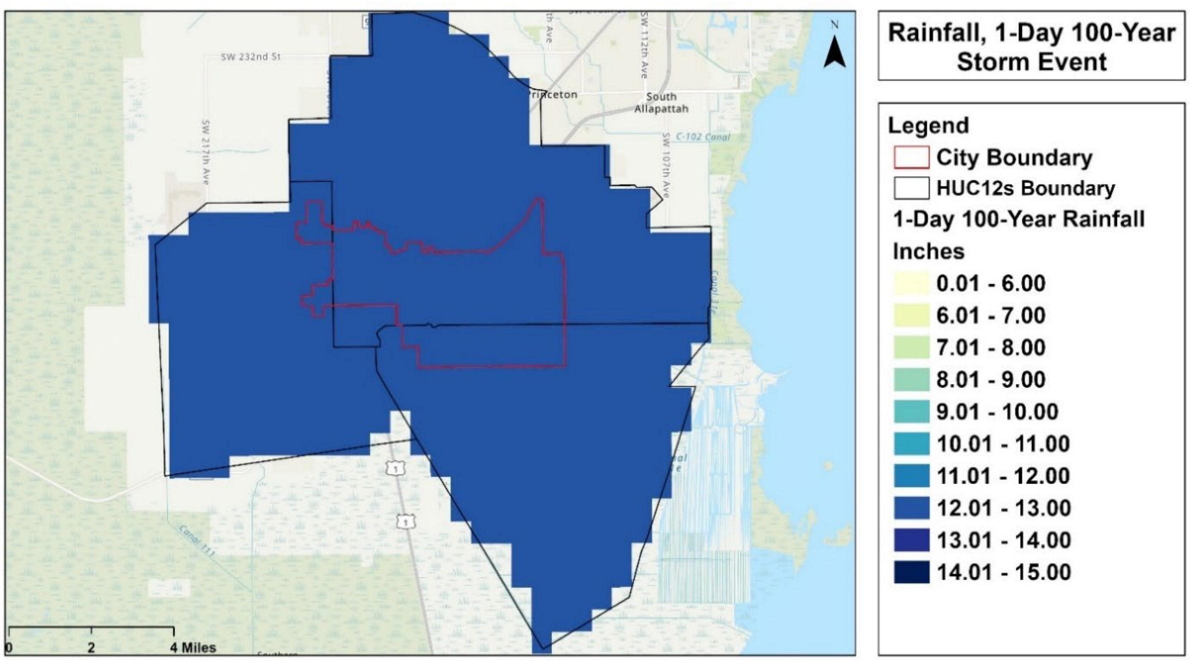


Figure 35. Rainfall distribution map for Homestead for 1-day 100-year storm, as generated by FAU CWR3

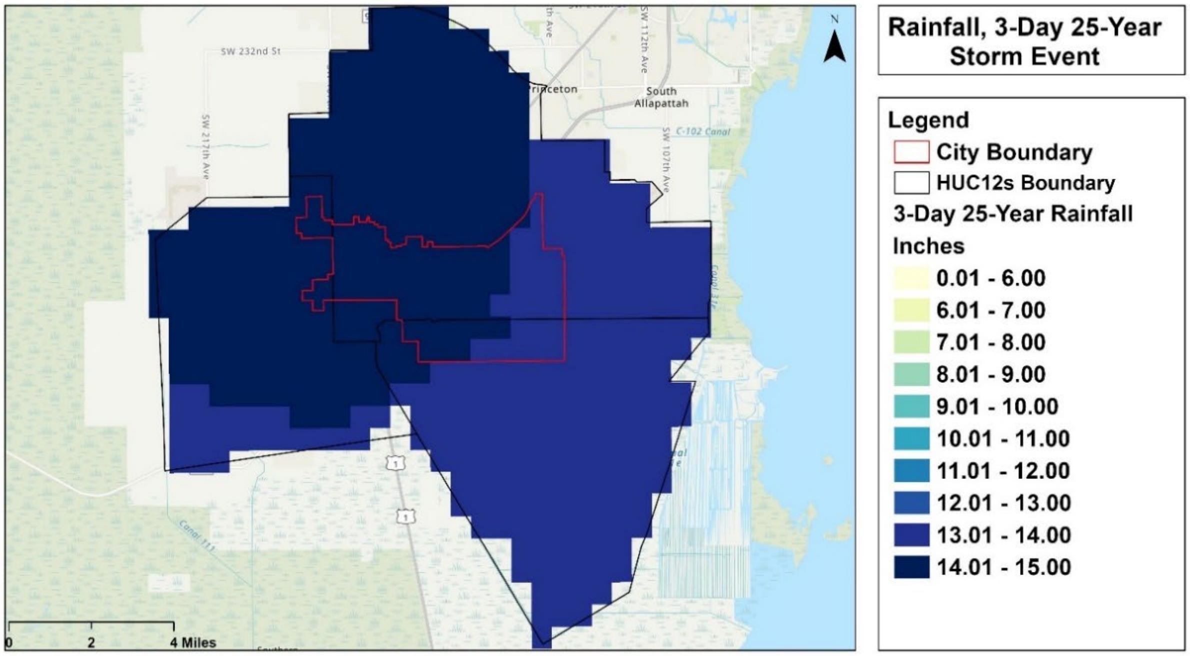


Figure 36. Rainfall distribution map for Homestead for 3-day 25-year storm, as generated by FAU CWR3

The historical average monthly rainfall for two local stations from 01/01/2010 to 03/21/2021 is shown in Figure 37. The actual locations for the stations are shown in Figure 38. Ongoing evapotranspiration is shown in Figure 39.

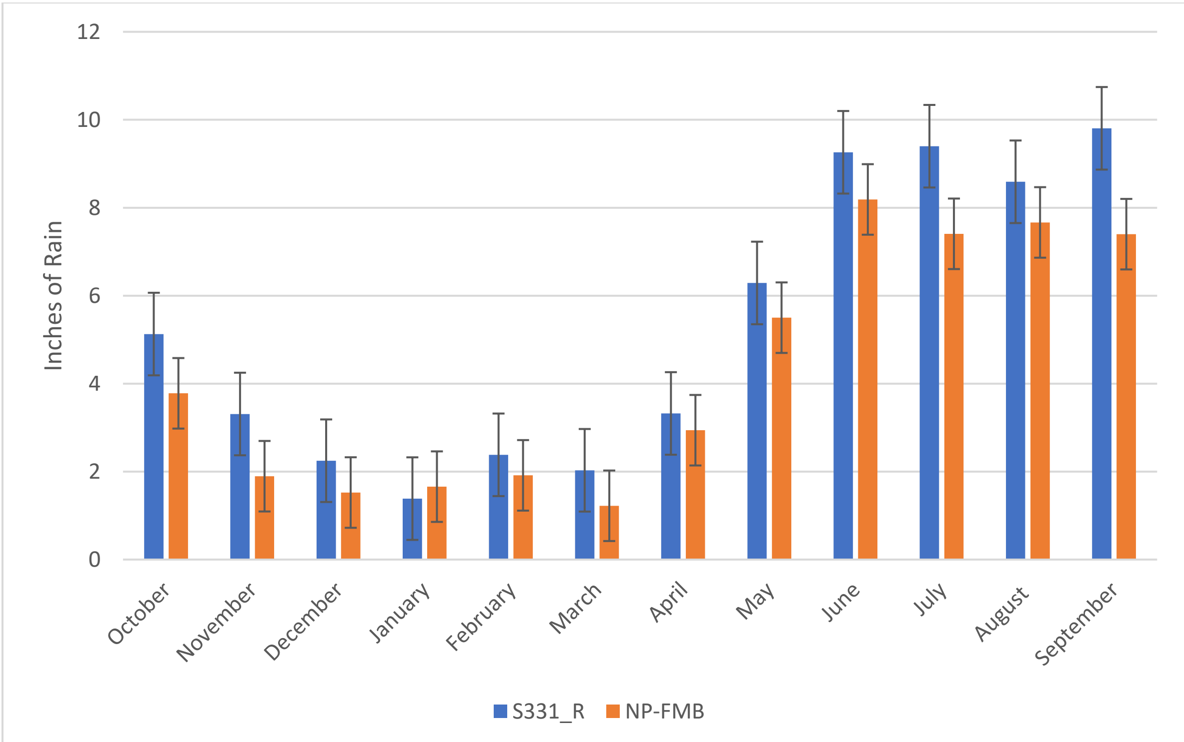


Figure 37. Historical monthly rainfall for Homestead from 2 local monitoring stations

Figure 38. Location of rainfall stations

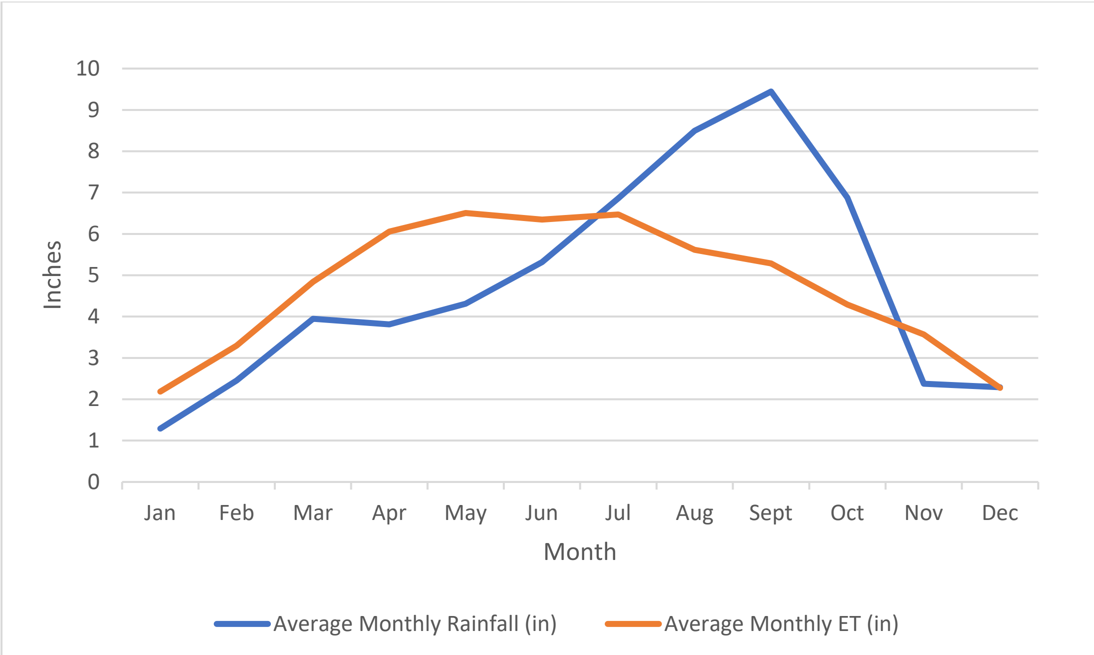


Figure 39. Comparison of rainfall and evapotranspiration for southeast Florida (Bloetscher, 1995)

2.8 Stormwater Infrastructure Inventory

Accumulated stormwater runoff from developed property must be managed in an organized and systematic manner to ensure the full use of the property and that public services are not disrupted. Stormwater facilities create choke points for water flow, so HUC12s need to be broken into smaller sub-elements. Stormwater facilities must be constructed and maintained to reduce the negative impacts of runoff. Local community stormwater systems consist of structures that channel stormwater to canals or directly into the ground to help resupply groundwater. These stormwater structures include catch basins, curb inlets, culverts, canals, swales, pump stations, ditches, manholes, levees, dams, locks, etc.

Scaling is relevant as discussed in Hindle et al. (2024). The screening tool model available using the databases described in Section 2.0 generally applies to large areas and smaller, localized neighborhoods. However, localized infrastructure improvements in small subwatersheds will have more impact on stormwater management than larger watersheds. Hence, there is some degree of economy of scale – larger infrastructure will have wider-ranging effects than a single catch basin. However, under-designed piping will be identified as failing to meet the level of service standard for the watershed. Table 9 shows an example of the hierarchy of infrastructure relevant to flood modeling.

Table 9. Hierarchy of infrastructure based on flood modeling scale

Scale of Modeling	**HUC/Area**	**Examples of Infrastructure of Concern**
TMDL Region/USGS Watershed	8-digit	Major canals, dams, large rivers, lakes, ocean
Subwatershed	12-digit (up to 50 square miles)	Primary and secondary canals, dams, large rivers, lakes, ocean, streams, smaller lakes, large bridge/culvert structures, drainage operations/staging
Community	Square miles	Rivers/streams/canals, interceptors/large ditches, neighborhood lakes/large retention/detention areas, major roadway conveyances
Neighborhood	Acres	Catch basins, swales, 15" piping, crowns of road, culverts under driveways, local retention/detention areas

The presence or absence of catch basins is most relevant on a neighborhood scale. However, itemizing catch basins and piping is likely of limited value at the subwatershed scale. Highly localized infrastructure (i.e. culverts, bioswales, etc.) is unlikely to be significant in a watershed-scale screening analysis. The modeling framework developed by FAU permits downward scaling from the 8-digit HUC level to neighborhood or parcel levels, albeit with each downscale requiring additional information regarding stormwater infrastructure and introducing more likelihood for data gaps or errors since, in many communities, the stormwater infrastructure asset inventory and condition is not well-defined. At the same time, subwatershed, community, and neighborhood infrastructure is more likely to be regulated as a part of an MS4 stormwater permit, which requires additional record-keeping, policy development, inspections, and maintenance associated with an asset management plan that requires an inventory of assets.

At the HUC8 level, the key stormwater infrastructure is primarily related to drainage canals, drainage structures, and pumping stations. At the HUC12 level, smaller pumps, weirs, salinity structures, and outfalls are important. In neither of these scales, do catch basins and small drainage pipes exert a substantial influence. At the local level, these pipes and catch basins do matter, but the condition is of more importance than the infrastructure itself. For example, FDOT requires no less than 15-inch reinforced concrete pipes for stormwater conveyance. For a dead-end pipe, the stormwater flow velocity will rarely be enough to carry the sand and silt downstream. As a result, the pipes and catch basins are routinely full of sand or covered with palm fronds/leaves/garbage or other debris. This cannot be modeled, and while MS4 permits attempt to create a regulatory framework requiring routine maintenance, the timing of a storm and catch basin/pipe cleaning is truly relevant.

Hindle et al. (2024) demonstrated the impact of changes to infrastructure on scaling. In this peer-reviewed paper, they outlined the infrastructure by basin and proceeded to model at 3 levels in the Caloosahatchee basin – HUC8, HUC12, and community-level. In the City of Clewiston, there is minimal drainage infrastructure. In fact, shallow swales are the only structures of note. There are very few street inlets, mostly along US-27/Sugarland Highway, and no culverts under roadways in most of the City. Hence, there is no master stormwater system in Clewiston. The small canals that traverse the City, including the Clewiston Drainage District (CDD) Canals 1 through 7 and Lopez Canal, which connects to the major C-21 Canal (north) and Industrial Canal (east), were included in the analysis. A recent program to seal the sewer system eliminated the inflow of rainwater to the sanitary sewer collection system, introducing additional "new" flooding to areas in the City. The modeling was conducted in accordance with Zhang et al. (2020) for each of the three levels. Three parallel analyses were conducted (Table 10). The flood risk modeling efforts and comparative analysis discussed herein were evaluated visually and statistically at three nested levels of scale, 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 (Table 11), which is the standard used by the South Florida Water Management District (SFWMD), and the 1-day 100-year storm (Table 12) used by FEMA and other water management districts. This statistical comparison is an objective method to quantitatively measure the following:

- How the predicted flood extent changes with modeling at different scales
- Which infrastructure explains 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	349,730	267,244	22,024	2,887
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
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

*Clewiston and the Ninemile Canal HUC 12 are located at the far east of the HUC8

The results were similar across all three scales.

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%

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%

A challenge with stormwater infrastructure is related to recordkeeping. It is not uncommon for stormwater data to be incomplete in most jurisdictions and completely lacking in others. Data quality differs from jurisdiction to jurisdiction; some are on GIS formats, while others are paper maps or as-builts that represent the infrastructure at a macroscale level. The condition of the assets may be lacking, and the maintenance history may not be available either. Stormwater assets may have been installed with no records, especially in rural areas, farm fields, and private property. An example of available information on stormwater infrastructure in Homestead, FL is shown in Figure 40.

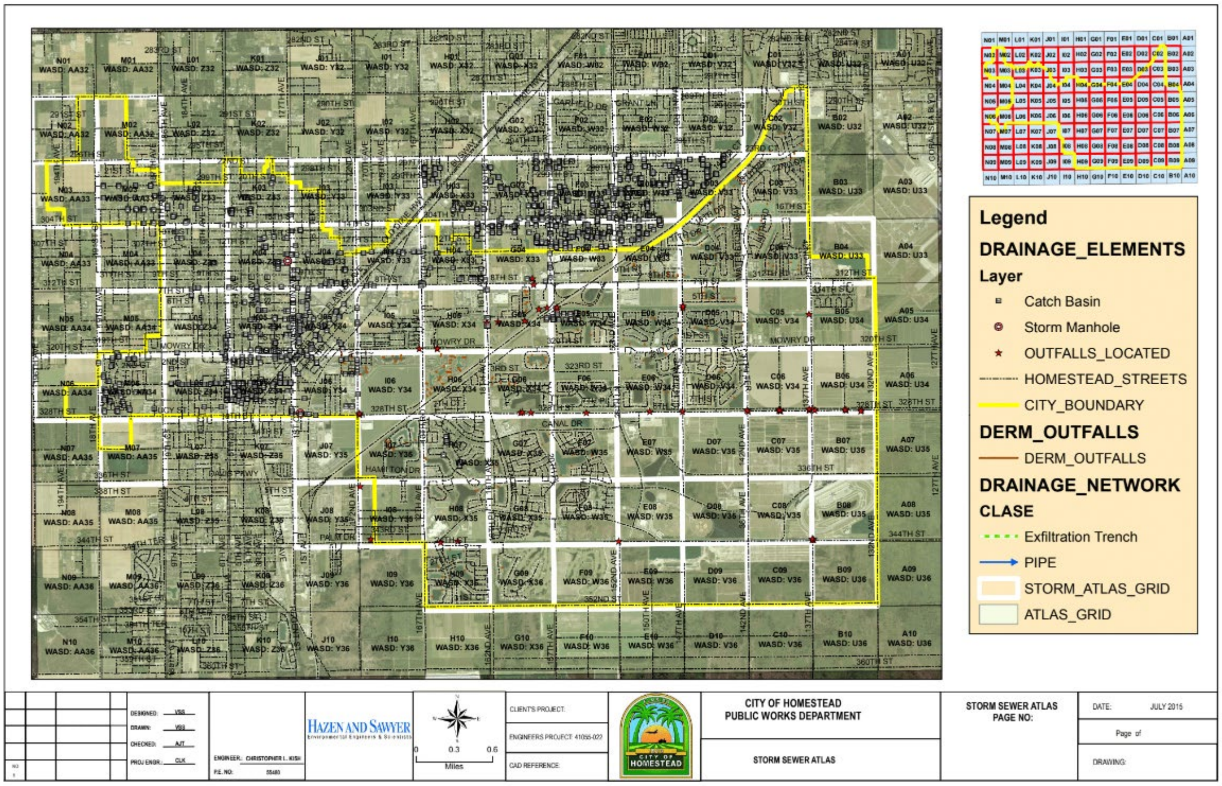


Figure 40. City of Homestead Stormwater infrastructure

As sea level rises, access to roads, bridges, rail, and transit could be at risk of flooding, causing the effects of sea level rise to spread indirectly throughout the entire transportation network, affecting the overall system performance. For example, the flooding of a critical road or facility access can cause a shifting of traffic flow, causing congestion in other arterial networks that are not actually flooded. Since the roadway network would be unable to carry the traffic demand, the system would experience operational failure and delays. Moreover, the inundation of a critical access road could cause transportation connectivity problems to essential infrastructure like ports or airports as well as issues with maintaining evacuation routes.

Transportation infrastructure relies on the effectiveness of flood control and stormwater drainage systems for the transportation corridors. Road integrity relies on adequate drainage. The increased risk of severe flooding in Florida's low-lying terrain can adversely affect transportation infrastructure along the coastline; roads can be inundated, and roadway beds will be damaged. Sea level rise will cause increased water table levels (FDOT, 2012), as regional groundwater tables cannot exist naturally below mean high tide (2 feet in Florida). Adding 3 feet of sea level rise on top of groundwater would compound the risk of flooding in low-lying areas. Road bases below 5 feet NVGD would become saturated under this scenario, likely causing premature base failure. As soil storage capacity is diminished due to rising groundwater elevations associated with sea level rise, the potential for more frequently flooded roadways would likely damage pavements (FDOT, 2012). Hence sea level rise must be accounted for in WMPs in coastal areas. To allow flexibility in the analysis due to the range of increases within the different time periods, an approach that uses incremental increases of 1 ft of sea level rise up to the medium-high estimate was suggested and utilized for modeling. The increments can work as threshold values for planning considerations in terms of allowing planners to know ahead of time where the next set of vulnerable areas will be, to allow for a proactive response approach that can be matched to the observed future rates. It also highlights the tipping points where sea level rise and flood protection will require a completely revised strategy. Sea level rise is a major concern since nearly half the US population lives within 50 miles of the coast, involving most major commercial, residential, and economic enterprises.

2.8.1 Roadway Drainage Design Standards

The United States Department of Transportation (USDOT) published a policy statement on climate adaptation that states the agency "shall integrate consideration of climate impacts and adaptation into the planning, operations, policies, and programs of USDOT in order to ensure that taxpayer resources are invested wisely, and that transportation infrastructure, services, and operations remain effective in current and future climate conditions." The Fixing America's Surface Transportation (FAST) Act, signed into law in December 2015, included several provisions addressing the resilience of the nation's transportation system. It requires agencies to consider resiliency during transportation planning processes. The FAST Act is administered by the Federal Highway Administration (FHWA) and expanded the scope of the planning process for state Departments of Transportation, Metropolitan Planning Organizations (MPOs), and the Federal Transit Administration (FTA) to include the following:

- Consideration for implementation of a new planning factor for states and MPOs: improving the resiliency and reliability of the transportation system (23 CFR 450.206(a)(9) and 23 CFR 450.306(b)(9)).
- During the course of development of a metropolitan transportation plan and the transportation improvement program, consult with agencies and officials responsible for natural disaster risk reduction (23 CFR 450.316(b)).
- Assess capital investment and other strategies as part of the transportation planning process to reduce the vulnerability of the existing transportation infrastructure to natural disasters (23 CFR 450.324(g)(7)).

At the State level, Florida passed the Community Planning Act (CPA) in the year 2011, which designated Adaptation Action Areas to address coastal hazards and potential impacts of sea level rise to prioritize funding for infrastructure improvements and adaptation planning eventually. In 2015, Florida Senate Bill 1094, "An Act relating to the peril of flood," also became law, which required planning considerations for potential coastal future flood risk due to sea level rise and storm surge as part of local area comprehensive plans. It also mandated several changes related to flood insurance and promoting strategies that mitigate risk. As part of the Florida Transportation Plan (FTP), FDOT's long-range goal envisions an "agile, resilient, and quality infrastructure," with continued preparation for "extreme weather events such as more frequent or severe tropical storms; flood risks in coastal areas resulting from high-tide events, storm surge, flash floods, stormwater runoff, and related impacts; changes in precipitation patterns and temperatures; and other environmental conditions that could impact transportation infrastructure." Chapter 334, F.S., known as the Florida Transportation Code, establishes the responsibilities of the State, counties, and municipalities for the planning and development of the transportation systems serving the people of Florida, with the objective of assuring development of an integrated, balanced statewide system. The Code's purpose is to protect the safety and general welfare of the people of the State and to preserve and improve all transportation facilities in Florida. Under Section 334.044, F.S., the Code sets forth the powers and duties of FDOT to develop and adopt uniform minimum standards and criteria for the design, construction, maintenance, and operation of public roads.

With respect to the design of roadways, design standards are not regulatory standards. Section 4.2 of the Drainage Manual "does not require any FDOT facility to not overtop for a 100-year storm, nor does it require a roadway to be elevated above a FEMA mapped floodplain," according to an email from Steve Olson, the FDOT district five communications manager. Instead of the FEMA maps, FDOT relies in part on anecdotal evidence of past flooding. Stormwater management facilities are to be designed to provide the necessary quantity, rate, and quality control based on the presumption that for the existing discharge all necessary quantity, rate, and quality control of stormwater from upper property has occurred prior to reaching the right-of-way (which is often not the case).

FDOT does have a series of guidelines for designing infrastructure, as summarized in Table 13. The standard design frequencies for culverts, bridge-culverts and bridges are as follows:

Table 13. Summary of FDOT infrastructure design frequencies

Facility	Design Frequency
Mainline interstate	50 years
High use or essential: Projected 20-year AADT* > 1500	50 years
Other: Projected 20-year AADT* < 1500	25 years
Roadside ditch culverts	10 years
Pedestrian and trail bridges	10 years
General design for ditches and pipes	3 years
General roadway construction	3 years
General design work that involves replacement of a roadside ditch with a pipe system by extending side drainpipes	10 years
General design on work to storm drains for Interstate facilities	10 years
Interstate facilities for sag vertical curves which have no outlet other than a storm drain system, and for the outlet of systems requiring pumping stations	50 years

*AADT= Annual average daily traffic, AADT is preferred but if not available, ADT may be utilized.
Note: flood frequencies used for scour analysis may differ. Site-specific factors may warrant the use of an atypical design frequency

Note that none of these standards is the 1-day, 100-year storm event. The FDOT drainage manual (FDOT, 2016) notes that the required number of storms to be evaluated varies depending on whether the site discharges to a watershed with a positive outlet. Watersheds in Florida with positive outlets drain to surface waters that ultimately drain to the Gulf of Mexico or the Atlantic Ocean. Watersheds without positive outlets are typically those that drain to sinks, closed lakes, or drainage wells. Occasionally, watersheds contain up to a certain event, such as a 10-year or 25-year event. The storms to be evaluated are shown in Table 14. Note that the 7-day and 10-day durations are required only for discharges to watersheds without positive outlets (closed basins).

Table 14. FDOT design storms required to be modeled for infrastructure evaluation (FDOT, 2016)

Duration	Frequency					
	3-year	5-year	10-year	25-year	50-year	100-year
1-hour	Required	Required	Required	Required	Required	Required
2-hour	Required	Required	Required	Required	Required	Required
4-hour	Required	Required	Required	Required	Required	Required
8-hour	Required	Required	Required	Required	Required	Required
1-day	Required	Required	Required	Required	Required	Required
3-day	Required	Required	Required	Required	Required	Required
7-day	Closed Basin	Closed Basin	Closed Basin	Closed Basin	Closed Basin	Closed Basin
10-day	Closed Basin	Closed Basin	Closed Basin	Closed Basin	Closed Basin	Closed Basin

There are generally two accepted sources for rainfall values: a) FDOT and b) other state agencies such as the water management districts or FDEP. The FDOT rainfall data consists of Intensity Duration-Frequency (IDF) curves and isopluvial maps of Florida. These are available from the FDOT website (www.fdot.gov). The other agencies also have isopluvial maps of their regions. For short duration storms of 1-hour through 8-hour duration, the FDOT's IDF curves are the only source.

There are 11 geographic zones within the state (Figure 41), with each zone having an associated IDF curve. Figure 42 shows an example of the IDF curves for Area 10 (the Southeast coast). The rainfall depths are obtained by multiplying the intensity by the duration. For example, in Zone 1, if the average intensity of a 5-year, 2-hour event is 1.8 inches per hour (IPH). Then, the rainfall depth of a 5-year, 2-hour event = 1.8 IPH × 2 hours = 3.6 inches, but this does not apply for storms with more than 8-hour duration, which must use FDOT's isopluvial maps.

Figure 41. FDOT rainfall regions (FDOT, 2016)

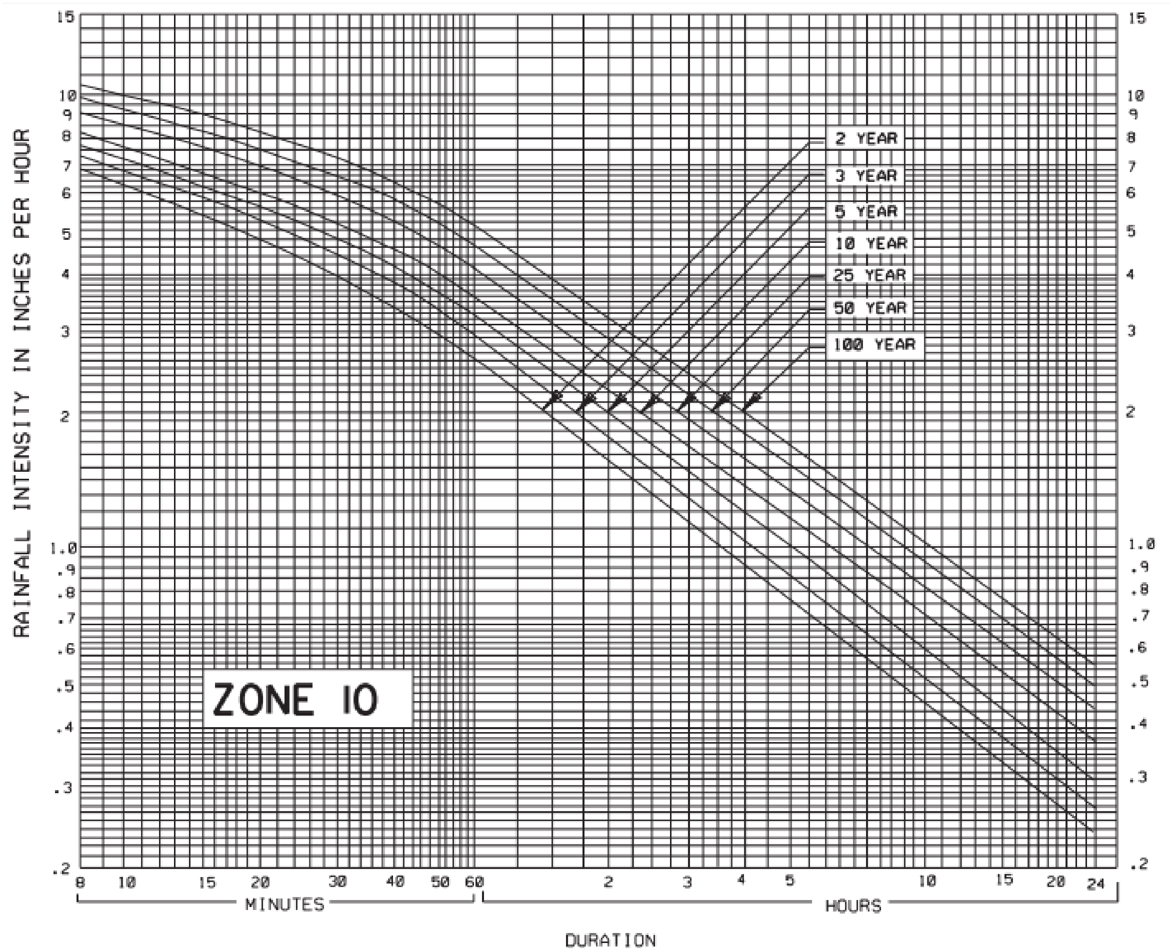


Figure 42. IDF curves for Zone 10 (southeast Florida) (FDOT, 2016)

FDOT permits the use of rainfall depths from other agencies if the depths are greater and the source of the rainfall data is identified. The Department does not have isopluvial maps for the 3-year frequency storms or the 3-day duration storms, although SFWMD does. Table 15 outlines the source of the data.

Table 15. Rainfall data source and calculation for FDOT permitting (FDOT, 2016)

Duration	**Frequency**						
	2-year (Note 4)	**3-year**		**5-year**		**10-year and greater**	
	Depth	**Intensity**	**Depth**	**Intensity**	**Depth**	**Intensity**	**Depth**
1-hour		IDF curve	Note 1	IDF curve	Note 1	IDF curve	Note 1
2-hour		IDF curve	Note 1	IDF curve	Note 1	IDF curve	Note 1
4-hour		IDF curve	Note 1	IDF curve	Note 1	IDF curve	Note 1
8-hour		IDF curve	Note 1	IDF curve	Note 1	IDF curve	Note 1
1-day	Isopluvial map		Note 3		Isopluvial map		Isopluvial map
2-day (Note 5)	Isopluvial map				Isopluvial map		Isopluvial map
3-day	Note 2		Note 3		Note 2		Note 2
4-day (Note 5)	Isopluvial map				Isopluvial map		Isopluvial map
7-day	Isopluvial map		Note 3		Isopluvial map		Isopluvial map
10-day	Isopluvial map		Note 3		Isopluvial map		Isopluvial map

Note 1 = intensity × duration

Note 2 = average of 2-day and 4-day depths of same frequency

Note 3 = average of 2-year and 5-year depths of same duration, unless 3-year data is available from another agency

Note 4 = 2-year depth is required only to obtain 3-year depths

Note 5 = 2-day and 4-day depths are required only to obtain the 3-day depths

2.8.2 Local Drainage Design Standards

For gray infrastructure, most local governments adopt FDOT standards including the frequency of storm events. For development they follow water management district standards. The SFWMD and US Army Corps of Engineers have standards for larger regional infrastructure, but these are rarely of interest to local governments. A typical standard is to design an infrastructure system that will provide flooding relief to a low-lying neighborhood for the 1-day, 10-year storm event (defined by FDOT), with no more than 6 hours of street flooding, none of which being more than 2 inches at the crown of the road.

2.9 Capital Improvement and Financing Plan

Once the vulnerability assessment and mitigation measures have been determined, the next step is to implement the plan to address these issues. In other words, it is often possible to add mitigation measures to existing capital improvement programs. Every infrastructure agency will allocate funds for operations, maintenance, debt, and capital. These factors are brought together in annual budget documents. In most cases, infrastructure agencies should be set up as an enterprise fund to allow the organization to pay its own way, making it easier to evaluate the operational aspects of an infrastructure system. Note WMP8 scores are only awarded is a separate source of funding via a stormwater assessment of utility fee is approved by ordinance.

Coordination between the financial, budget, and operating policies of a utility system allows managers to properly allocate costs to those benefiting from the service, develop pricing strategies that can be clearly explained to the public, and prevent challenges to allocation methodologies. Operations, capital programs, and long-term variability of the utility system operation require financial and facility planning. Multi-year economic forecasts and financial plans are standard tools in business and are worthy of consideration by watershed and flood protection agencies.

An example process that USEPA (2013) suggests for capital plans is as follows:

1. "Inventory existing management efforts in the watershed, considering local priorities and institutional drivers
2. Quantify the effectiveness of current management measures
3. Identify new management opportunities
4. Identify critical areas in the watershed where additional management efforts are needed
5. Identify possible management practices
6. Identify relative pollutant reduction efficiencies
7. Develop screening criteria to identify opportunities and constraints
8. Rank alternatives and develop candidate management opportunities"

A best practice is to develop a prioritized project list. The WMP purposes, WMP8 requires a stormwater utility fee or assessment fee.

2.10 Data Gaps

Data must be reviewed to determine its quality and identify any major gaps. A true data gap is when the information is missing or lacks sufficient resolution in space or time to identify or characterize a key component of the watershed properly. Data gaps include updates since 2016 for the Florida land use codes, future land use. Small waterbodies and impervious surfaces have not been well delineated in the NLCD 2016 dataset. Additionally, much local stormwater data, and many county roadway culvert data may be insufficient for localized modeling purposes.

Examples of other common data gaps include: 1) missing baseline data, 2) missing correlation data (i.e. flow rates that correspond to specific water quality sampling event timing or locations, 3) non-representative sampling, 4) insufficient data points, 5) dataset age, 6) lack of adequate resolution, 7) lack of upstream or downstream data points, 8) poor spatial coverage, 9) lack of accuracy and precision, 10) bias, and 11) variable detection/quantitation limits or collection procedure. Lack of inventory for the stormwater infrastructure is a common challenge.

There are some known issues. In some regions of Florida, the groundwater monitoring well density is not spatially uniform or extensive. Some important areas like the Keys and the Everglades have limited (if any) well coverage. Spatial interpolation using a stochastic variance-dependent interpolation (e.g., Ordinary Kriging) can be used to estimate groundwater levels at points of interest or to generate the surface. A subset of available data is used to create a validation dataset, and the rest of the data is used for calibration (i.e., estimation of parameters of the interpolation model). Where the coast is present, the coast is used as a constant head boundary (with sea level rise incorporated). For regions with spatially sparse or non-uniform groundwater well coverage, the groundwater levels are estimated using a multiple linear regression approach from auxiliary variables in addition to the limited groundwater well observations in a watershed.

Different levels of quality of LiDAR, or gaps in coverage are potential issues to address. Kriging and MLR are means to help address this, along with USGS maps and multiple LiDAR sourcing. Outliers (very high or low groundwater levels attributed to various reasons) are noted at several sites. Outliers and anomalous groundwater levels in the database are initially evaluated, identified, and, if found to be faulty, are replaced by region-specific mean values based on observations available from the nearest well. Missing data is also an issue at some monitoring wells. Missing date-specific data are estimated using simple temporal interpolation based on observations available in time. If a station (or monitoring well) data contains large amounts of missing data, it is not used to generate the groundwater surface.

The king tides in south Florida happen within the same period every year between September and November. This period coincides with the end of the wet season and the height of the hurricane season. The culmination of these phenomena means that groundwater-related flooding risks are greatest at this time, and it also allows the assumption that rainfall and tidal influences on groundwater are most correlated at this time and can be quantified indirectly through observable groundwater levels alone. However, since this is an observation-driven modeling effort with spatially explicit implications, discrete, observational values of groundwater, surface water, rain, tides, etc., are also required.

As discussed previously, scaling matters. Modeling at the watershed scale does not permit detailed analysis down to the level of a bridge culvert from the current data sets due to spatial extent. Data must be in the same datum (the datum used here is NAVD88) and length units (ft). Spatially explicit rainfall data (NeXRAD) and storm surge input are needed, but the records are lacking for some areas of the State.

If there are concerns about data gaps, the first step is to assess if the data are essential to the understanding of the problem. If the necessary datasets are available, it must be determined if the data quality is acceptable (sufficient resolution, long enough time series, recently updated, level of accuracy, etc.). The level of detail necessary will vary depending on the modeling goals and is usually found along a spectrum, as summarized in Table 16. Using low-quality data will complicate making the correct management decision and mounting a defensible allocation of resources to implement the action plan. Although data gaps can be identified during the data inventory process, more specific requirements are often discovered during modeling.

Table 16. Summary of level of detail for certain types of screening data (USEPA, 2008)

Data Type	**Low**	**Medium**	**High**
Flow	Summary statistics (range, average)	Spatial analysis of flow data in GIS	Spatial and temporal analysis of flow data in GIS often combined with modeling and supplemental monitoring
Land Use	General distribution using broad categories	Specific identification of detailed categories by sub-watershed	Statistical analysis of detailed categories in relation to average flow
Soils	General distribution of soil types	GIS analysis of locations and types of soil	Detailed analysis of soil distribution in relation to streams and erosion potential
Habitat	General distribution of habitats	Mapping of critical habitats and buffers	Landscape pattern measurement near critical habitat with GIS modeling

3.0 FLOOD MAPPING

Taking information from the Local Mitigation Strategies planning document with input from the stakeholder group is a best practice for describing the flood hazards likely to be experienced in the community. For instance, flooding may be primarily attributed to riverine/inland flooding, coastal/tidal/surge flooding, etc. Next it is important to determine the most vulnerable areas and to what extent the damage can be predicted. If an area is flood prone, then it is likely that it has flooded in the past, so it is important to create and maintain a log of historical occurrences, locations of repetitive loss, impacts, damage estimates, mitigation strategies, and lessons learned from previous flood events.

To complete a flood risk assessment, a diversified approach includes the development of surface water flow forecasting models, demand forecasting models, and an integrated surface water – groundwater hydrologic model, which all incorporate rainfall and temperature variables as driving forces. These models can take output of downscaled climate models that provide different rainfall and temperature time series and make assessments of the effects of changes in these parameters and how they affect the service area.

3.1 Modeling the Watershed

To evaluate a watershed's runoff response from design storms of various magnitudes and durations under current and predicted future conditions, modeling software is needed. The modeling of stormwater routing and flood risk can take a number of forms such as solutions for simple cases or numerical computer codes for more complex cases where a high degree of accuracy is needed. For small communities, it may be sufficient for relatively simple applications, but for more extensive modeling, significantly more data may be needed if surface interfaces and competing users are located in a given basin.

For the basin or watershed approach, data-driven models appear to be more appropriate than simple local modeling. There are numerous resources available that describe, in varying levels of detail, the processes, underlying equations, and numerical methods of groundwater modeling including, but not limited to, those listed in the reference pages. A flood risk model attempts to "approximate reality" while being transparent regarding its uncertainties and limitations over a potentially open-ended time frame. At the same time, it must be understood that models are mathematical approximations of typical or average conditions estimated for the basin parameters with limitations.

The simplest representation of floodplain flow is to treat the flow as one-dimensional along the center line of the river channel (DHI, 2003). Many hydraulic situations can assume 1-dimensional conditions, either because a more detailed solution is unnecessary (e.g. the purpose does not require knowledge in other dimensions) or because a 1-dimensional solution is sufficient to approximate real conditions, such as in a confined channel or in a pipe. One-dimensional models can be used for open surface floodplain flow too, in which case floodplain flow is part of the one-dimensional channel flow, which is assumed to be in one direction parallel to the main channel, and one cross-sectional averaged velocity is used to represent large variations in velocity across the floodplain.

Two-dimensional models represent floodplain flow as a two-dimensional field with the assumption that the third dimension (water depth) is shallow in comparison to the other two dimensions (DHI, 2012; Roberts et al., 2015). Two-dimensional flood models such as ISIS, MIKE 11, HEC-RAS, HEC-HMS and others represent the channel and floodplain as a series of cross-sections perpendicular to the flow direction and solve either the full or some approximation of the one-dimensional shallow water equations (Bates and De Roo, 2000). These models require less computer effort compared to hydrodynamic models. They are fast, robust, and most desirable for applications that do not require velocity output and have low demands on the representation and accuracy of flow dynamics in the vertical direction (i.e. flooding).

Most approaches solve the two-dimensional shallow water equations, which represent mass and momentum conservation in a plane and can be obtained by depth-averaging the Navier-Stokes equations. Two-dimensional numerical models for unsteady shallow flows and various computational techniques using finite difference, finite element, and finite volume schemes have been reported (Table 17). Two-dimensional flood models such as TUTFLOW, SOBEK and MIKE 21 solve the two-dimensional shallow water equations by means of appropriate numerical schemes (Mignot et al., 2006; Abderrezzak et al., 2009; Dottori and Todini, 2013; Song et al., 2015). Advances in remote sensing technology, particularly through high resolution and high accuracy input data such as airborne LiDAR and Synthetic Aperture Radar (SAR) data, and improved computing capacity seem to have increased the popularity of two-dimensional models. For many scales of floodplain flow, complex three-dimensional representation of flow dynamics may be regarded as unnecessary, as a two-dimensional shallow water approximation may be adequate, especially given the type and quality of data typically available for model construction and validation (Alcrudo, 2004). However, modeling of vertical turbulence, vortices, and spiral flow at bends is important during catastrophic floods, such as those occurring due to dam breaks, tsunamis, flash floods, or embankment and levee breaches.

Table 17. Available models and their strengths and weaknesses (from Teng et al., 2017)

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
HEC-RAS	USACE, 1995	1-D Hydraulic	Basically, the model solves the one-dimensional energy equation for steady flow. However, it can solve the full 1-D shallow water equation for unsteady flows.	One-dimensional energy equation to solve for friction and contraction	Implicit finite difference solution	Open source However, user assistance is limited to USACE users	Extensive documentation, suitable for a wide range of data quality, easily adaptable and easy to set up	Model instability and limitation in environments that require multi-dimensional modelling
HEC-HMS	USACE, 1992	Hydrologic	Primarily designed to simulate the precipitation run-off process of dendritic drainage basins Also capable of solving a range of hydrologic problems	Different statistical and mathematical concepts describing physical processes are used in modelling	Analytical solutions of underlying mathematical representation of hydrologic processes.	Open source However, user assistance is limited to USACE users	Extensive documentation, suitable for a wide range of hydrologic applications and amenable for integration with other software	Generally fails under dynamic flood simulation conditions
ISIS-2D	Halcrow (now CH2M HILL), 2009	2-D Hydraulic	Designed to work either standalone or within the ISIS suite	Full two-dimensional shallow water equations	Alternating Direction Implicit (ADI), FAST and Total Variation Diminishing (TVD)	Commercial	Suitable for hydrodynamic flood simulation	Slow simulation speed and requires a high-resolution topographic data

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
ISIS-1D	Halcrow (now CH2M HILL), 2008	1-D Hydraulic	Designed primarily for modeling water flows and levels in open channels and estuaries	Full one-dimensional shallow water equation	Muskingum-Cunge scheme for steady state and 4-point Preissmann scheme for unsteady state	Commercial	Suitable for steady, unsteady, subcritical, supercritical, and transitional flows	Assumes velocity is normal to cross section and not suitable for dynamic flood simulation
ISIS - FREE	Halcrow (now CH2M HILL), 2009	Coupled 1-D/2-D Hydraulic	Provides an advanced one-dimensional (1D) and two-dimensional (2D) simulation engine, analysis, and visualization tools	One-dimensional and two-dimensional shallow water equations	Alternating Direction Implicit (ADI), FAST and Total Variation Diminishing (TVD)	Open source	Suitable for wide range of applications including urban areas, coastal and river channels	Limited to 250 1D nodes and 2500 2D cells
ISIS-FAST	Halcrow (now CH2M HILL), 2011	Simplified 1-D / Simplified 2-D	Quick simulation of flooding using simplified hydraulics	Simplified shallow water equations	FAST solvers	Commercial	Simulation speeds are up to 1000 times quicker when compared to traditional 2-D flood models	Requires high resolution data and is commercial software
LISFLOOD-FP	Bates and De Roo, 2000	Simplified 2-D	A raster-based hydraulic model that is assumed to possess the simplest hydrologic process representation	One-dimensional, kinematic, and two-dimensional diffusive wave equations	Explicit finite difference solution	Research	Extensive documentation, easily adaptable and simple to set up	Requires a high-resolution topographic data for simulation.

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
LISFLOOD	De Roo, Wesseling, and Van Deursen, 2000	GIS-based distributed hydrologic model	LISFLOOD is a GIS-based hydrological rainfall-runoff-routing model	One-dimensional, kinematic wave equation	4-point implicit finite difference solution and analytical solutions of other hydrological components	Research	Wide range of applications including simulation of interception of rainfall by vegetation, evaporation of intercepted water and Leaf drainage.	Not a stand-alone code, it requires a base platform of PCRaster modelling environment
Newer MIKE 11	DHI, 1997	1-D	Full one-dimensional Saint Venant equations, diffusive and kinematic wave approximation	Muskingum method and Muskingum-Cunge method for simplified channel routing	Complemented by a wide range of additional modules and extensions covering almost all conceivable aspects of river modelling	Commercial	Limited to rivers and fluvial-related flood events. Model can be unstable under two-dimensional flood conditions	
MIKE 21	DHI, 2003	2-D	Developed to simulate flows, waves, sediments and ecology in rivers, lakes, estuaries, bays, coastal areas, and seas in two dimensions	Full two-dimensional shallow water equations	Implicit finite difference techniques with the variables defined on a space-staggered rectangular grid	Commercial	Suitable for hydrodynamic flood simulation. Simulates bulk flow characteristics, flow velocity in various directions of flow	Simulations time steps and model stability are affected by C-F-L condition. Needs to be calibrated

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
MIKE-FLOOD	DHI, 2003	Coupled	Developed to enhance the independent functionalities of MIKE 11 and MIKE 21	One-dimensional and two-dimensional shallow water equations	Coupled solution of 1-D/2-D shallow water equations	Commercial	Satisfactory real-time simulation of flood inundation in river, coastal and urban areas	Not well adapted in terms of application to many geographic locations, and models require calibration
TUFLOW – 1D	BMT-WBM, 1990	2-D	Simulation of complex hydrodynamics of flood using full 1-D St. Venant equations	Full one-dimensional shallow water equation	Second order Runge–Kutta finite-difference solution	Commercial	Dynamic linking capability between domains. Fast from computational point of view	There are uncertainties in solution and are poor at process representation
TUFLOW – 2D	BMT-WBM, 1997	Simplified 2-D	Simulation of complex hydrodynamics of flood using full 2-D free surface shallow water equations	Full two-dimensional free surface shallow water equations	Stelling Finite Difference and ADI	Commercial	Dynamic linking capability between domains with satisfactory representation of process	Slow, but dynamically captures bulk flow characteristics
JFLOW	JBA Consulting, 1998	2-D	It is basically a simplified physics flood model	Diffusion wave equation	Explicit finite difference scheme	Commercial	More accurate flood simulation and simple to set up and useful at coarse resolution	Conditional stability through the C-F-L condition Unable to account for effects of small-scale features during flood simulation

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
DIVAST (depth-integrated velocities and solute transport)	Liang, Falconer and Lin, 2007	2-D	Solution that includes the effects of local and advective accelerations, the earth's rotation, free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model	Full 2-dimensional shallow water equations	Implicit finite difference technique and the ADI formulation	Commercial	Unconditionally stable. Constant time steps	Lacks the ability to capture shock resulting from simulation
DIVAST- TVD	Falconer and Xia, 2013	2-D	To address some limitations inherent in the original DIVAST model	Full 2-dimensional shallow water equations	TVD-McCormack explicit finite difference scheme	Commercial	Ability to capture shock	Conditional stability
SOBEK	Deltares, 2019	Scheme. By means of a rectangular grid	Specially designed for overland flow	Two-dimensional Saint-Venant equations	Finite difference	Commercial	Capable of handling wetting and drying, spatially varying surface, roughness, and wind friction	Conditional stability
SOBEK	Deltares / Delft Hydraulics, 2020	1- D	Specially designed for rural, urban and river flows	One-dimensional Saint-Venant equations	Finite difference	Commercial	Breaches can be modelled by means of a complex “river weir” with time dependent properties	Conditional stability

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
TELEMAC 2-D	Électricité de France (EDF), 2010	2-D	Designed to address the challenges of process representation and limitations in channel and floodplain flood modelling	solves the full two-dimensional shallow water equations	finite-element or finite-volume method and a computation mesh of triangular elements	Open source	It can perform simulations in transient and permanent conditions	Conditional stability
TELEMAC 3-D	Électricité de France (EDF), 2010	3-D	To address some limitations inherent in the 2-D version of the model	Navier-Stokes equations, whether in hydrostatic or non-hydrostatic	finite-element or finite-volume method and a computation mesh of triangular elements	Open source	Ability to capture 3-D hydrodynamic features of an area. Suitable for all flood sources	Conditional stability
TRENT 2000	Nottingham University, 2000	Full 2-D	A flood model that can capture full hydrodynamic properties	Shallow water equations	Explicit Finite difference scheme	Commercial	Shock capturing ability	Stable at CFL condition, using adaptive time stepping
MOD_freeSURF 2D	Martin and Gorelick, 2005	2-D	To obtain a more efficient flood simulation through a more robust numerical scheme	Unsteady state Shallow water equations	Semi-implicit, semi-Lagrangian numerical scheme	Open source	Modularity, computational efficiency, and minimum data requirement	Lacks extensive validation
CADDIES	Ghimire et al., 2013	2-D	A model that performs optimally at simulating flooding in urban areas	Rules that govern movement of water in-between cells	Cellular automata	Open source	Fast simulation of flooding	Lacks extensive validation

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
FLO-2D v. 2007.06 and 2009.06	O'Brien, 2007	Simple 2-D	Hydrodynamic model for the solution of the fully dynamic equations of motion for one-dimensional flow in open channels and two-dimensional flow in the floodplain	Full 1-D and 2-D shallow water equations.	Finite difference solutions	Commercial	A combined hydrologic and hydraulic modelling for urban and river flooding	Bridge or culvert computations must be accomplished external to FLO-2D using methodologies or models accepted for NFIP usage
GUFIN	Chen et al., 2009	Simplified model	A model that simplifies the use of distributed models for urban environment	GIS- based	GIS and infiltration functions	Research	Integrates GIS, suitable for urban flooding, results compare well with numerical codes	Lacks extensive validation
MIKE URBAN 2010	DHI Water and Environment, 2010	Coupled 1D and 2D	Has the capability to analyze storm sewer networks. Flow conditions associated with weirs, orifices, manholes, detention basins, pumps, and flow regulators can be reflected	1-D unsteady flow	Implicit, finite difference numerical scheme.	Commercial	Suitable for flow in urban areas and integrates GIS capabilities	Lacks the ability to capture some hydrodynamic phenomenon such as shock and supercritical flows

Model Name	Author(s), Date	Model Type & Dimensionality	Key Assumptions	Mathematical Framework	Numerical Solutions	Access	Strengths	Limitations
USEPA (1971–2005)	SWMM, new versions through 2017	Generic	Designed to represented six major environmental components: external forcing, surface runoff, groundwater, conveyance system, contaminant built-up and (LID) controls	Kinematic wave model Full dynamic wave system.	Generally, the finite difference scheme	Open source	Extensive documentation, several upgrades, and adaptive to a range of hydrological and hydraulic operations - urban flooding, drainage, etc.	The model requires many add-ons, and a user needs to understand the detailed guidelines

Table 18 outlines three ways the models, regardless of the dimensionality, calculate results. Empirical models are relatively easy to implement because they are based on observations and can be extrapolated to serve as validation for data assimilation models. They are limited by spatial grids and weather. Simplified conceptual models are computationally efficient for computers and can mimic or predict impacts to the floodplain, but dynamic flooding is not possible. Hydrodynamic models can overcome the limitations of the empirical and simplified models, but they are computationally difficult and require extensive memory and time to develop. Since they require significant amounts of information to generate results, they are more useful when drilling down to the parcel level.

Table 18. Summary of flood screening model options (from Teng et al., 2017)

Method	**Strengths**	**Limitations**	**Suitable Applications**
Empirical methods	• Relatively easy to implement • Based on observation data • Derived inundation estimate is independent • Technology is rapidly improving	• Non-predictive • No/indirect linkage to hydrology (difficult to use in scenario modelling) • Coarse spatial and temporal resolution (although improving) • Engineering limitations (sensors, carriers, transmission devices) • Environmental limitations (clouds, wind, damaging weather conditions, other natural constrains) • Processing limitations (algorithm, artificial errors)	• Flood monitoring • Flood damage assessment • Serve as observations to support calibration, validation, and data assimilation for other methods
Simplified conceptual models	• Computationally efficient	• No inertia terms (not suitable for rapid varying flow) • No/little flow dynamics representation	• Flood risk assessment • Water resources planning • Floodplain ecology • River system hydrology • Catchment hydrology • Scenario modelling

Method	Strengths	Limitations	Suitable Applications
Hydrodynamic models	• Direct linkage to hydrology • Detailed flood risk mapping • Can account for hydraulic features/structures • Quantify timing and duration of inundation with high accuracy	• High data requirements • Computationally intensive • Input errors can propagate in time	• Flood risk assessment • Flood damage assessment • Real-time flood forecasting • Flood related engineering • Water resources planning • Riverbank erosion • Floodplain sediment transport • Contaminant transport • Floodplain ecology • River system hydrology • Catchment hydrology

From the perspective of screening for sizable areas within a watershed, large amounts of data, integration with GIS, and ease of calculation are important. Highly specific details are not appropriate for a screening tool set at the subwatershed level or higher. Hence a simplified model that has capability to drilldown to local levels with the same data sets, but adding more localized specifics, is useful.

3.1.1 CASCADE 2001

After careful consideration, the FAU team chose to use CASCADE 2001, which is a macroscale, GIS-based, multi-basin, spatial hydrologic/hydraulic routing model developed by the South Florida Water Management District (SFWMD), which appears to be more widely applicable across many portions of the State of Florida. The basis for Cascade 2001 is a Fortran version of HEC-HMS, circa late 1990s (See Table 16. HEC-HMS is a product of the Hydrologic Engineering Center within the U.S. Army Corps of Engineers. The program was developed beginning in 1992 as a replacement for HEC-1 which has long been considered a standard for hydrologic simulation. The new HEC-HMS provides almost all of the same simulation capabilities, but has modernized them with advances in numerical analysis that take advantage of the significantly faster desktop computers available today. It also includes a number of features that were not included in HEC-1, such as continuous simulation and grid cell surface hydrology. It also provides a graphical user interface to make it easier to use the software. The program is now widely used and accepted for many official purposes, such as floodway determinations for the Federal Emergency Management Agency in the United States.

The program is a generalized modeling system capable of representing many different watersheds. A model of the watershed is constructed by separating the water cycle into manageable pieces and constructing boundaries around the watershed of interest. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems including flood hydrology, and small urban or natural watershed runoff. The Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact and flood damage reduction, among others.

HEC-HMS is designed to simulate the precipitation-runoff processes of drainage basins. Any mass or energy flux in the cycle can then be represented with a mathematical model. Each mathematical model included in the program is suitable in different environments and under different conditions. The physical representation of a watershed is accomplished with a basin model. Hydrologic elements are connected in a dendritic network to simulate runoff processes. Available elements include subbasins, reaches, junctions, reservoirs, diversions, sources, and sinks. Computation proceeds from upstream elements in a downstream direction. An assortment of different methods are available to simulate infiltration losses. There are many options to choose from for soils, runoff, infiltration and runoff. Multiple precipitation to runoff conversion can be used. An implementation of the kinematic wave method with multiple planes and channels is also included. All of the previously-mentioned transform methods can be used with basin-average and/or gridded meteorologic data.

Water impoundments can also be represented. Lakes and/or reservoirs can be described user-entered elevation-storage-discharge relationships. Alternatively, outflow and storage within a lake or reservoir can be simulated by describing the physical spillway and/or outlet structures. Pumps can also be included as necessary to simulate an interior flood area. Control of the pumps can be linked to water depth in the collection pond and, optionally, the stage in the main channel. Diversion structures can also be represented. One major concern when the South Flroida water Management District created Cascade 2001 was that the HEC-HMS models did not account for groundwater elevations, certain soil infiltration characteristics, storm events and the tidal/water body issues relevant to southeast Florida. Hence the district used HEC-HMS as the basis to develop Cascade2001. Among the storm issues is short-term tropical events which are not common elsewhere. As a result, the District modified the four different methods for analyzing historical precipitation to permit user-specified hyetograph method is for precipitation data analyzed outside the program. The frequency storm method uses statistical data to produce balanced storms with a specific exceedance probability based on NOAA and District observation stations. Sources of supporting statistical data include the National Weather Service (NWS) Technical Paper 40 (May 1961). The hypothetical storm method implements the primary precipitation distributions for design analysis using Natural Resources Conservation Service (NRCS) criteria Technical Release 55 (June 1986). Cascade can be used for computing the probable maximum precipitation using NOAA criteria.

The time span of a simulation is controlled by control specifications. A simulation run is created by combining a basin model, meteorologic model, and control specifications based on a precipitation event or boundary condition (sea level rise). The model includes features designed to increase the efficiency of producing forecasts of future conditions. Zones can be created that group subbasins together on the basis of similar hydrologic conditions or regional characteristics, but this is not the preferred solution – separate sub-basin models are preferred to provide downstream impacts.

Watersheds exhibit a great deal of variability. The land surface elevation can vary dramatically from headwaters to outlet. Soil properties change from one place to another place. Land use also changes with location but also changes over time. Each of the hydrologic processes can be modeled at varying levels of detail. There is a lack of perfect knowledge of the atmospheric conditions over the watershed. All of these issues jointly produce uncertainty in the simulated watershed response. The uncertainty analysis allows parameters to be represented with a probability distribution function (PDF) and then performs a Monte Carlo simulation to describe the uncertainty in output variables such as peak flow, volume, and reservoir pool elevation. Cascade2001 develops results and FAU developed Z-score and probabilities related to the Cascade2001 results. The current models include integrated GIS tools allow the user to create a basin model from a digital elevation model.

Cascade 2001 accomplishes the goal of delineating flood-prone areas by predicting how areas with low elevations may be affected by a selected rainfall event (e.g. 3-day, 25-year event), inundation from the ocean directly, from rising groundwater levels, and inundation from the inability of inland areas to drain. The model permits the investigator to run different storm events to determine flooding scenarios. The boundaries are critical for basin studies and must be chosen carefully.

CASCADE 2001 includes the following features:

- Data entry by random access
- Designed to be run on a personal computer
- Santa Barbara Hydrograph model

- Storm frequencies: 3-, 5-, 10-, 25-, and 100-year
- Storm durations: 1- and 3-day
- Gravity, pump, or (n) gated spillway discharges
- Accounts for off-site receiving body tailwater impacts
- Control devices (”bleeders”): V-notch, circle, rectangle, rectangular notch, inverted triangle
- Weir devices: broad-crested, sharp-crested, drop inlet
- Methodologies based on those in the District's Environmental Resource Permit Information Manual
- Rainfall distributions: South Florida Water Management District; and Orange County, FL
- Link to DSS (Data Storage System), a data storage format developed by the U.S. Army Corps of Engineers
- Duration of rainfall event may be established by use of calendar dates and clock times
- Can manage multiple off-site receiving bodies
- Computes stage-storage relationship from site information
- Allows selection of coefficients of flow for most weirs and orifices
- Includes flap gates on outfall pipes as an option and includes tailwater elevation control as an option for pump outfalls
- Allows user to specify stage at which modeling begins for each basin
- Allows user-defined rainfall distributions”

The program creates a situation where the hydrograph for runoff causes water to a certain level and then decreases as the hydrograph decreases. The highest level is normally used to show maximum flooding even though it may be very short-term. Where there are many sub-basins or structures, each must be modeled separately, with the upstream data used as inputs downstream. That specified level can be used to develop flooding maps for the area. Running the simulation requires defining the basin (HUC or sub-HUC) and input of the following data:

- Study area
- Portion of area above a given elevation
- Initial ground water stage
- Longest travel time for the runoff to reach the most distance point of discharge
- Ground storage as estimated from the USDA gridded National Soil Survey Geographic Database (gNATSGO)

- Available water storage (AWS) for a soil layer of 0-150 cm
- Average amount of precipitation that can be stored in the soil layer as given by:

$$\text{Ground storage} \approx (\text{Water holding capacity}) \times (\text{Surface elevation} - \text{GW elevation})$$

$$= 2 \times (\text{AWS for a soil layer of 0-150 cm}) / 150\text{ cm} \times (\text{Surface elevation} - \text{GW elevation})$$

The rainfall is based on the SFWMD 3-day, 25-year storm, but can be modified for any rainfall event using the accumulated rainfall table obtained from NOAA Atlas 14 Point Precipitation Frequency Estimates (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html).

The screening tool starts with a flood response model (CASCADE2001) whose output is used to develop flood risk/hazard maps at 3 m resolution to identify areas of concern. Next, groundwater table elevations and surface water gauges downloaded from the applicable water management district, tidal information for coastal areas from the NOAA Tides & Currents website (https://tidesandcurrents.noaa.gov), soil maps from USDA, and topographic data obtained from various sources. Figure 43 shows how the GIS layers conceptually interface in the tool and how they are combined for the spatial analysis. The general database sources used for this analysis are summarized in Table 19 (note these have continuously been updated with more recent data).

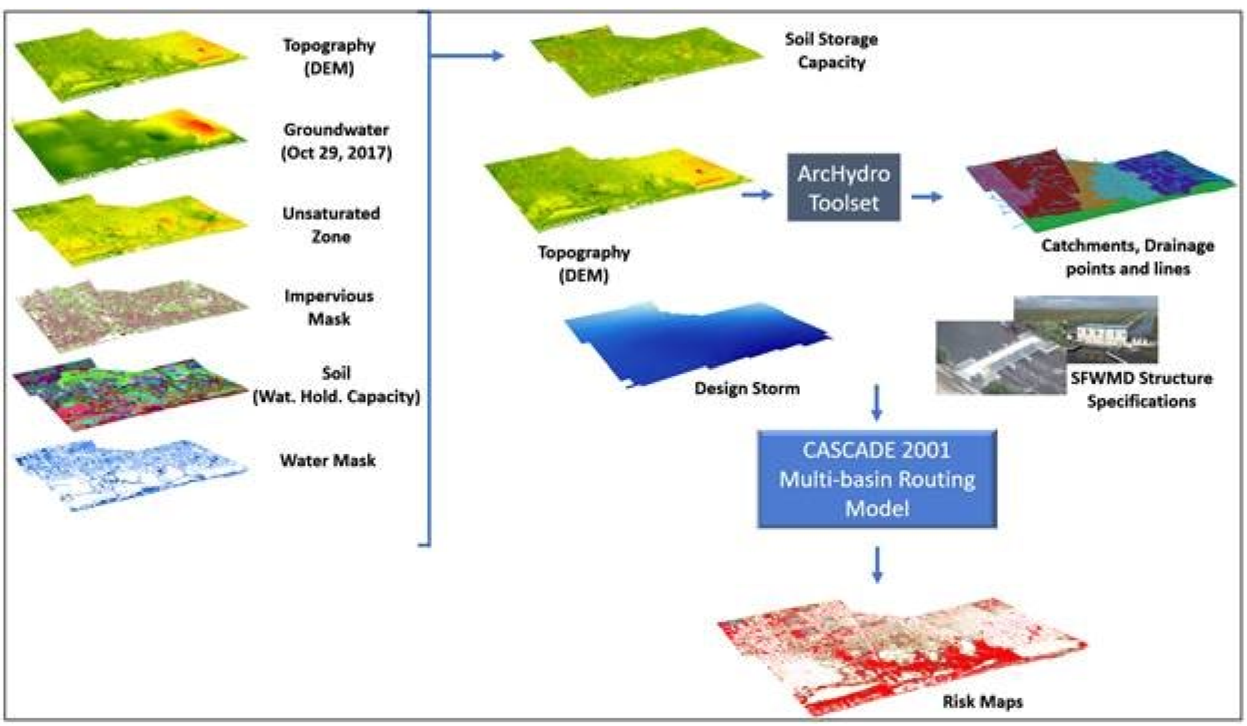


Figure 43. Process for the utilization of data layers to develop a screening tool, using flood modeling software (in this case CASCADE 2001).

The model integrates with GIS. The stage elevations were determined from the topographic LiDAR maps. The output dataset defines the flood level elevation for the basin. All values under the ground surface elevation were colored blue, where inundation/flooding were likely to be present. In areas that flooded, the same procedure was undertaken to re-run the model at smaller scale to better resolve problematic areas.

Running the simulation requires defining the basin (HUC or sub-HUC) and input of the following data:

- Study area
- Portion of area above a given elevation
- Initial ground water stage
- Longest travel time for the runoff to reach the most distance point of discharge
- Ground storage as estimated from the USDA gridded National Soil Survey Geographic Database (gNATSGO)
- Available water storage (AWS) for a soil layer of 0-150 cm
- Average amount of precipitation that can be stored in the soil layer as given by:

Ground storage ≈ (Water holding capacity) × (Surface elevation – GW elevation)
= 2 × (AWS for a soil layer of 0-150 cm) / 150 cm × (Surface elevation – GW elevation)
The rainfall is based on the SFWMD 3-day, 25-year storm, but can be modified for any rainfall event using the accumulated rainfall table obtained from NOAA Atlas 14 Point Precipitation Frequency Estimates: **https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html**.

Table 19. Summary of database sources for key information needed for modeling used in development of this document

Name	Sources	Date Created or Date Range	Source Data Format
Rainfall	NOAA Atlas 14 Precipitation Frequency Estimates https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html	1840-2013	Raster image format (downloaded and processed)
Soil	USDA Soil SSURGO gSSURGO Database: https://sdmdataaccess.nrcs.usda.gov/	Released in 2019	Raster image format (downloaded and processed)
Landcover	USGS 30m resolution, derived from Landsat satellites https://www.mrlc.gov/data/nlcd-2016-land-cover-conus	Created for 2016	Raster image format (downloaded and processed)
Waterbodies	NHD24Area_dec07, and nhd24waterbody_dec17, both from National Hydrography Dataset created originally by USGS https://www.usgs.gov/core-science-systems/ngp/national-hydrography/national-hydrography-dataset	Created in 2007	Converted to binary raster image format (downloaded and processed)
Impervious Surface	USGS 30m resolution, derived from Landsat satellites https://www.mrlc.gov/data/nlcd-2016-land-cover-conus	Created for 2016	Converted to binary raster image format (downloaded and processed)
LiDAR Elevations	From USGS, NOAA, Counties and Cities of FL https://viewer.nationalmap.gov/basic/	2000-2019	Raster image format (downloaded and processed)

3.1.2 Design Storm Events

Successful watershed master plans evaluate design storms of various magnitudes and durations under current and predicted future conditions (Association of State Floodplain Managers, 2020). This means the most appropriate design storm(s) must be included. Several design storms are expected to be evaluated in the WMP. Per the FEMA NFIP CRS Coordinator's Manual (2017), full credit (150 points) can be obtained in the following situations:

- If developers account for the runoff from three storms: the 100-year storm, another storm larger than the 10-year, and the 10-year storm;
- If the design storms include all storms up to and including the 100-year storm event;
- If 100-year retention is required. For CRS purposes, retention (as opposed to detention) means that a basin has no outlet, and stored runoff must be infiltrated into the soil, pumped out for irrigation, or otherwise disposed of on site; or
- If 100-year detention is required with a release rate based on the pre-development 10-year runoff.

If the applicable regulations are based on inches of rainfall, the value must be converted to a storm recurrence interval. To do this, we use the Rainfall Frequency Atlas of the United States (the National Weather Service's Technical Paper 40; accessible at http://www.ncdc.noaa.gov/oa/documentlibrary/rainfall.html). Table 20 explains how credits are assigned for the design storm (DS).

Table 20. Summary of requirements for design storms (DS) credits in CRS

Design Storms Used	DS Credits
2-year, 5-year, and 10-year	14
25-year	36
10-year and 25-year	50
100-year	100
25-year and 100-year	136
10-year, 25-year, and 100-year	150

Design Storms (DS) credit is provided based on the design sizing of the runoff control facilities. For DS credit, the community's regulations generally must require pre- and post-development hydrology calculations and post-development runoff must be limited to pre-development levels. The standard used may be peak flow, volume, or a combination. Although the 100-year storm event is the basis for floodplain management, communities are also encouraged to evaluate the effects of stormwater management on smaller, more frequent storms. A design that maintains or reduces the peak flow from only the 100-year storm may increase peaks from smaller storms, increasing flood damage, with the CRS protocol gaining credits for evaluating impacts from each of these storms:

- 1-day/10-year event
- 3-day/25-year event (SFWMD, storm capture and long-term event)
- 1-day/100-year event (NFIP requirement)

During the year, typically, sea breezes from both coasts over the hot land surface cause the formation of intense storms inland. In addition, some of the high rainfall events occur from the hurricanes and tropical storms that strike Florida. Hurricanes and tropical storms generally produce tremendous amounts of rainfall, and coastal regions are more likely to experience these rainfall events. Based on the temporal rainfall patterns in this region, the period from November through April is considered the dry season, and June through September is considered the wet season. However, May and October are transitional months, having rainfall from both wet and dry season regimes. Long-term averages indicate that two-thirds of the annual rainfall occurs during the wet season. However, some of the heaviest rainfalls in Central and South Florida are generated by convective systems with the cooler season having an extra-tropical nature and the warm season having a tropical origin (Pathak, 2001), although like the tropical events, they rarely last more than 24 hours.

The rainfall characteristics over Lake Okeechobee and the surrounding ocean are different from that of overland mass. Based on monthly, seasonal and annual rainfall data, the spatial variations in the rainfall amounts are unique within the area of the District. Spatial variations reduce as rainfall duration increases. The Palm Beach County area has the highest annual rainfall whereas the lower Kissimmee River and Lake Okeechobee areas have the lowest annual rainfall. The Southwest Coast area has unique characteristics with the highest and lowest average rainfall for wet and dry seasons respectively. The dry season rainfall varies with the lowest in the Southwest Coast and highest in Palm Beach County. Generally, spatial variation in rainfall amounts for shorter durations, such as one-, three-, and five- day, is significantly greater than month, season and annual rainfall (Pathak, 2001).

As a coastal state with little land more than 50 miles from the coast, much of the rainfall will drain to tide in a very short time. FAU used the SFWMD's 3-day 25-year storm event for the long term rainfall event as opposed to a 5 day event. Figure 44 shows the average annual precipitation across the US. Florida is among the higher volumes of rainfall per year. Figure 45 drills down into Florida. Note that much of Florida's rainfall occurs as convective summer storms (about 70%) or episodic tropical events. Figure 46 shows the rainfall intensity maps in one hour. Across Florida this value exceeds 4 inches in one hour, among the highest in the nation, while Figure 47 shows that the 1-day 24-year event varies from 8 to 12 inches in 24 hours across the state – also higher than much of the nation.

Figure 44. Average annual precipitation

(https://en.wikipedia.org/wiki/United_States_rainfall_climatology)

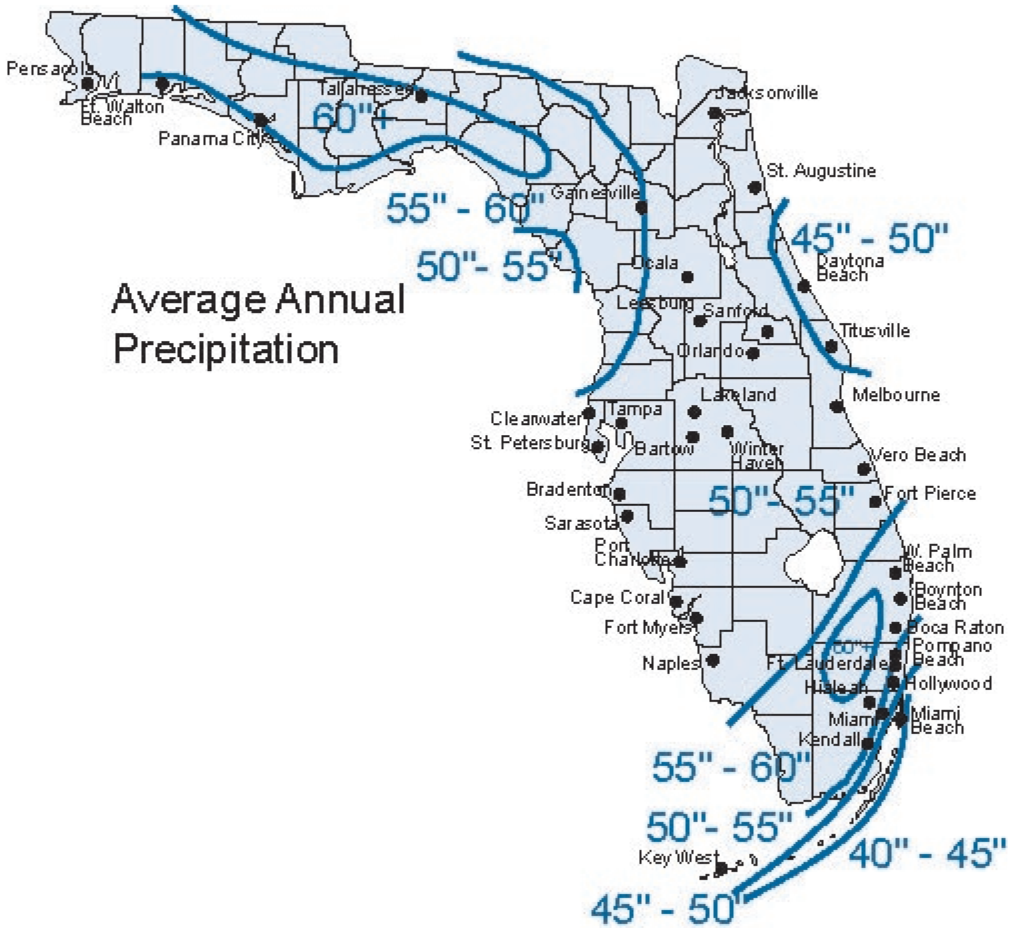


Figure 45. Florida average annual rainfall. https://climatecenter.fsu.edu/products-services/data/weather-planner-maps/average-annual-precipitation

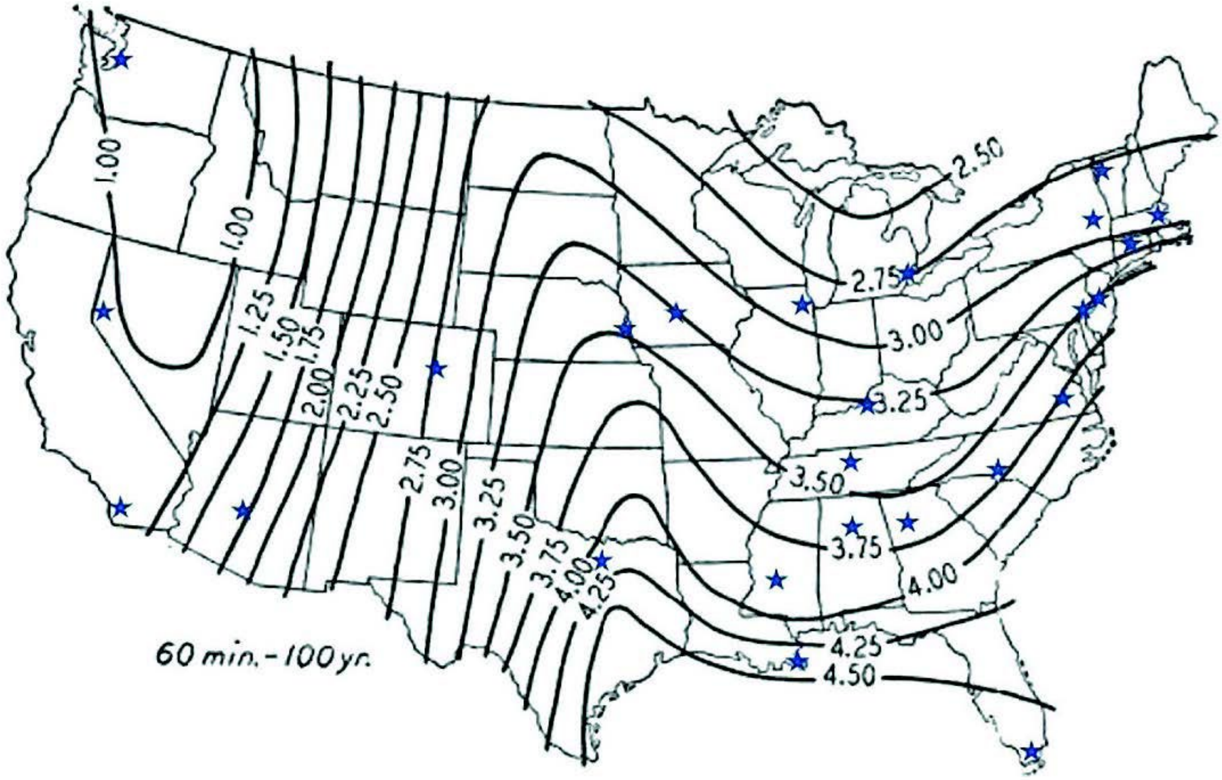


Figure 46. Hourly rainfall intensity https://iibec.org/rainfall-intensity-changes-over-time-have-the-codes-kept-pace/

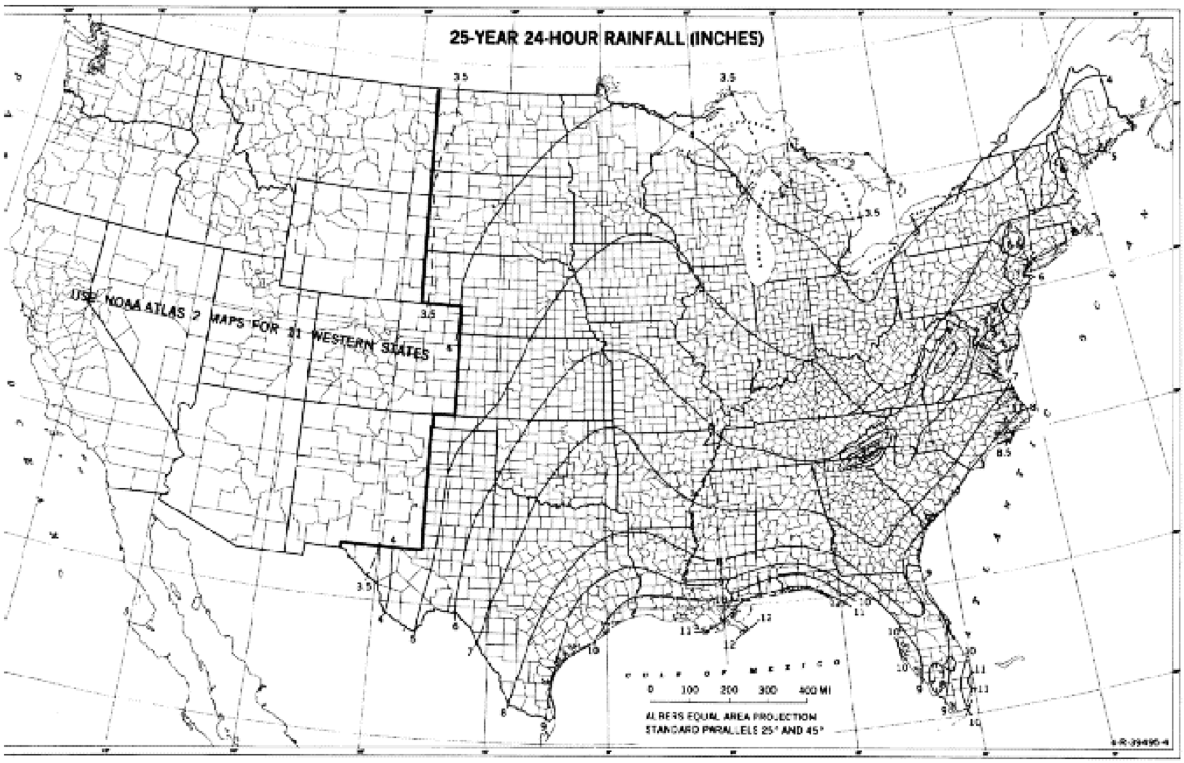


Figure 47. 1 day rainfall intensity
https://www.lmnoeng.com/RainfallMaps/RainfallMaps.htm#25yr,%2024-hr

Pathak (2001) used DBHYDRO records to note the following on 24 hour storms:

1. "The eastern region has recorded maximum rainfall of 18.0 inches. Five locations showed the highest rainfall of 18.0, 17.4, 17.0, 16.4, and 16.0 inches. This region has lower variability in maximum rainfall amounts. More than 20 locations recorded between 10 and 15 inches.
2. The western region has recorded maximum rainfall of 20.0 inches. Four locations showed the highest rainfall of 20.0, 19.0, 17.0 and 14.5, inches. This region shows moderate variability in

maximum rainfall amounts. Six locations recorded rainfall between 10 and 12 inches. More than 20 locations recorded between 9 and 10 inches of rainfall.

3. The northern region has a recorded maximum rainfall of 21.4 inches. Five locations showed the highest rainfall of 21.4, 17.0, 11.0, 10.0 and 10.0 inches. This shows that variability in maximum rainfall is high in this region. However, there were more than 10 locations that recorded between 9 and 10 inches of rainfall."

Pathak (2001) used DBHYDRO records to note the following on 24 hour storms:

1. "The eastern region has recorded maximum rainfall of 32.1 inches. Seven locations showed the highest rainfall of 32.1, 32.0, 26.8, 20.2, 19.6, 19.4, and 19.4 inches. This region has the moderate variability in maximum rainfall amounts. Thirteen locations recorded between 16 and 19 inches of rainfall.
2. The western region has recorded maximum rainfall of 29.0 inches. The highest four locations showed the highest rainfall of 29.0, 28.0, 21.7, and 16.2 inches. This region showed the highest variability in maximum rainfall amounts. Five locations recorded rainfall between 14 and 16 inches, while, 17 locations recorded between 12 and 14 inches.
3. The northern region has a recorded maximum rainfall of 13.8 inches. Six locations showed the highest rainfall of 13.8, 13.7, 13.7, 13.5, 13.1 and 13.1 inches. This showed that variability in maximum rainfall is low in this region. Eighteen locations recorded between 11 and 13 inches of rainfall."

Pathak (2001) used DBHYDRO records to note the following on 24 hour storms:

1. "The eastern region has recorded maximum rainfall of 36.6 inches. Five locations showed the highest rainfall of 36.6, 22.0, 21.4, 21.3 and 21.1 inches. This region has the moderate variability in maximum rainfall amounts. Six locations recorded between 19 and 21 inches of rainfall.
2. The western region has recorded maximum rainfall of 32.3 inches. The highest four locations showed the rainfall of 32.3, 21.9, 18.5 and 18.2 inches. This region showed high variability in maximum rainfall amounts. Five locations recorded rainfall between 15 and 17 inches. While, 14 locations recorded between 13 and 15 inches.
3. The northern region has a recorded maximum rainfall of 16.5 inches. Six locations showed the highest rainfall of 16.5, 15.5, 15.2, 14.8, 14.7 and 14.6 inches. This showed that variability in

maximum rainfall is low in this region. Ten locations recorded between 12 and 14 inches of rainfall."

Note all of these are extremes – the maximum storms, which are well beyond the 5 day events under any timescale. However, in all cases the 5 day maximum experienced rainfall was within 4" of the 3 day event, and in central Florida within 1.5 inches.

Pathak (2001) developed the following, which outlines the estimated average and maximum rainfall for the return periods of 1, 3 and 5 days:

Rainfall Estimates (inches) for Various Return Periods and Three Durations

Duration	One-Day		Three-Day		Five-Day	
Return	Rainfall (inches)		Rainfall (inches)		Rainfall (inches)	
Period	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2-year	2.6	5.0	3.4	6.6	3.7	6.9
5-year	3.7	8.8	4.9	8.9	5.7	10.0
10-year	4.5	11.4	6.2	11.5	7.1	12.4
25-year	5.3	15.1	7.2	15.4	8.9	16.6
50-year	5.7	17.8	8.1	18.9	10.1	21.2
100-year	6.0	21.0	8.9	22.8	11.0	26.6

Note that the 5-day 25-year event is less than 1.5" above the 3-day 25 year event, while as noted above the 100 year event is only 4" greater for the 3 day and 5 day events. Note the 5 day event recurrence frequency is not defined for watershed plans. However, FAU has consistently modeled the NOAA maximum which most areas of central and south Flroida are typically 13-18". Outside the regulatory status, FAU used the 3-day 25-year event because Pathak (2001) noted that "The DBHYDRO was queried for highest rainfall data that occurred during the recorded dates ***were hurricanes and tropical storms***." Tropical events bring heavy rain, high winds, storm surge, and other severe weather, impacting daily life for several days, but the most intense effects concentrated within a shorter "core" period. The period of heaviest rainfall is usually within 12 hours of landfall. For tropical cyclones moving faster than 6 knots, the average rainfall is usually 5–10 inches in 24 hours. Slower moving storms typically produce more than 15 inches of rain in 24 hours. The average storm total rainfall for a tropical cyclone impacting the contiguous United States from the Atlantic basin is about 16 inches, with 70 to 75 percent of the storm total falling within a 24-hour period. The heaviest rainfall usually occurs along or near the coast, and slightly to the right of the storm's track. In the Gulf of Mexico, heavy rainfall often occurs east of the storm's center. Depending on the storm's path, multiple regions could experience significant impacts over a few days, but typically rainfall is less than 24 hours. Therefore, what the data indicates is that Florida has very intense storms which are generally associated with summer storms or tropical weather events as opposed to frontal events that stagnate and linger for long periods of time as they can over the mainland.

The 3- day 25-year storm event refers to a weather system, like a hurricane or major storm complex, that is expected to produce significant impacts over a period spanning at least 3 days. This better mimics the actual conditions for the state and expanding the time only adds less that 10% to the total precipitation. Compounding the challenge is that as Table 1 shows, the 5 day storm frequency events is not shown in the NOAA files, making the ability to model it across the state difficult. The 3 and 4 day events are shown along with the 7 day events in Table 2. FAU estimated the 5 day event to be less than 0.8 inches different than the 3 day event, while the difference between the 1 day and 3 day event is 50 percent. Given the data noted by for the maximum rainfall differences noted above by Pathak (2001), the SFWMD decided to regulate based on the 3-day 25-year storm event as opposed to a 5-day event.

As a result, FAU used the SFWMD's 3-day 25-year storm event for the long term rainfall event as opposed to a 5 day event due to the rainfall intensity provided by hurricanes and requests that ISO consider the differences n the type of rainfall patterns experienced in Flroida, and use the 3-day 25 year event in lieu of the 5 day event given the higher intensity create more flooding.

Table 21. Rainfall Table – total rainfall – NOAA

https://hdsc.nws.noaa.gov/pfds/pfds_map_cont.html?bkmrk=fl

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	**0.525** (0.433-0.644)	**0.597** (0.491-0.732)	**0.713** (0.584-0.878)	**0.809** (0.659-1.00)	**0.942** (0.736-1.21)	**1.04** (0.795-1.36)	**1.15** (0.838-1.54)	**1.25** (0.870-1.74)	**1.39** (0.922-1.99)	**1.49** (0.962-2.19)
10-min	**0.769** (0.634-0.943)	**0.874** (0.719-1.07)	**1.04** (0.856-1.28)	**1.18** (0.965-1.47)	**1.38** (1.08-1.77)	**1.53** (1.16-2.00)	**1.68** (1.23-2.26)	**1.83** (1.27-2.54)	**2.03** (1.35-2.92)	**2.18** (1.41-3.20)
15-min	**0.938** (0.773-1.15)	**1.06** (0.877-1.31)	**1.27** (1.04-1.57)	**1.44** (1.18-1.79)	**1.68** (1.32-2.16)	**1.86** (1.42-2.43)	**2.05** (1.50-2.75)	**2.23** (1.55-3.10)	**2.48** (1.65-3.56)	**2.66** (1.72-3.90)
30-min	**1.41** (1.16-1.72)	**1.60** (1.31-1.96)	**1.91** (1.56-2.35)	**2.17** (1.77-2.68)	**2.53** (1.98-3.24)	**2.80** (2.14-3.66)	**3.08** (2.25-4.14)	**3.36** (2.34-4.68)	**3.74** (2.49-5.37)	**4.02** (2.60-5.90)
60-min	**1.83** (1.51-2.24)	**2.08** (1.71-2.55)	**2.49** (2.04-3.07)	**2.83** (2.31-3.50)	**3.30** (2.58-4.24)	**3.67** (2.80-4.79)	**4.04** (2.95-5.43)	**4.41** (3.07-6.14)	**4.91** (3.27-7.06)	**5.29** (3.41-7.76)
2-hr	**2.25** (1.87-2.74)	**2.56** (2.12-3.11)	**3.07** (2.54-3.74)	**3.50** (2.87-4.29)	**4.08** (3.22-5.19)	**4.54** (3.48-5.88)	**4.99** (3.68-6.67)	**5.46** (3.83-7.54)	**6.08** (4.08-8.68)	**6.55** (4.27-9.55)
3-hr	**2.47** (2.06-2.98)	**2.81** (2.34-3.39)	**3.37** (2.80-4.09)	**3.85** (3.18-4.70)	**4.52** (3.59-5.73)	**5.05** (3.90-6.52)	**5.59** (4.14-7.44)	**6.14** (4.34-8.46)	**6.89** (4.65-9.81)	**7.47** (4.89-10.8)
6-hr	**2.86** (2.41-3.42)	**3.25** (2.73-3.89)	**3.92** (3.28-4.70)	**4.51** (3.75-5.45)	**5.39** (4.34-6.84)	**6.12** (4.78-7.89)	**6.88** (5.17-9.15)	**7.70** (5.50-10.6)	**8.85** (6.04-12.6)	**9.77** (6.45-14.1)
12-hr	**3.31** (2.81-3.92)	**3.74** (3.17-4.43)	**4.54** (3.84-5.40)	**5.30** (4.45-6.35)	**6.50** (5.32-8.27)	**7.54** (5.97-9.72)	**8.68** (6.59-11.5)	**9.94** (7.19-13.7)	**11.8** (8.12-16.7)	**13.3** (8.83-19.0)
24-hr	**3.80** (3.26-4.46)	**4.30** (3.68-5.05)	**5.28** (4.50-6.22)	**6.26** (5.30-7.42)	**7.85** (6.51-9.99)	**9.27** (7.43-11.9)	**10.9** (8.34-14.4)	**12.6** (9.24-17.3)	**15.2** (10.6-21.6)	**17.4** (11.7-24.8)
2-day	**4.36** (3.76-5.06)	**4.96** (4.28-5.77)	**6.17** (5.30-7.20)	**7.39** (6.31-8.68)	**9.39** (7.87-11.9)	**11.2** (9.04-14.3)	**13.2** (10.2-17.4)	**15.5** (11.4-21.1)	**18.8** (13.2-26.4)	**21.6** (14.6-30.5)
3-day	**4.78** (4.15-5.52)	**5.44** (4.71-6.28)	**6.76** (5.84-7.84)	**8.09** (6.94-9.44)	**10.3** (8.66-12.9)	**12.2** (9.96-15.6)	**14.5** (11.3-19.0)	**16.9** (12.6-23.0)	**20.6** (14.6-28.9)	**23.7** (16.1-33.4)
4-day	**5.18** (4.52-5.96)	**5.84** (5.08-6.72)	**7.18** (6.22-8.29)	**8.55** (7.36-9.94)	**10.8** (9.15-13.6)	**12.9** (10.5-16.3)	**15.2** (11.9-19.9)	**17.8** (13.3-24.1)	**21.7** (15.4-30.3)	**24.9** (17.0-35.0)
7-day	**6.30** (5.53-7.18)	**6.87** (6.03-7.85)	**8.12** (7.09-9.30)	**9.44** (8.19-10.9)	**11.7** (9.98-14.6)	**13.8** (11.3-17.3)	**16.1** (12.7-21.0)	**18.8** (14.2-25.4)	**22.9** (16.4-31.8)	**26.3** (18.1-36.7)
10-day	**7.26** (6.40-8.23)	**7.82** (6.89-8.88)	**9.04** (7.93-10.3)	**10.3** (9.00-11.8)	**12.5** (10.7-15.5)	**14.5** (12.0-18.2)	**16.8** (13.4-21.8)	**19.5** (14.7-26.1)	**23.4** (16.8-32.4)	**26.7** (18.5-37.2)
20-day	**9.88** (8.79-11.1)	**10.7** (9.52-12.0)	**12.3** (10.8-13.8)	**13.7** (12.0-15.5)	**15.9** (13.5-19.0)	**17.7** (14.7-21.7)	**19.7** (15.7-25.0)	**22.0** (16.6-28.8)	**25.1** (18.2-34.2)	**27.7** (19.3-38.3)
30-day	**12.1** (10.9-13.5)	**13.3** (11.9-14.9)	**15.3** (13.6-17.1)	**16.9** (15.0-19.1)	**19.3** (16.4-22.7)	**21.1** (17.5-25.4)	**23.0** (18.3-28.7)	**25.0** (18.9-32.4)	**27.6** (20.0-37.2)	**29.7** (20.8-40.9)
45-day	**15.2** (13.7-16.8)	**16.8** (15.1-18.6)	**19.3** (17.3-21.6)	**21.4** (19.0-24.0)	**24.1** (20.5-28.0)	**26.1** (21.7-31.0)	**28.0** (22.3-34.5)	**29.8** (22.7-38.2)	**32.2** (23.3-42.9)	**33.8** (23.9-46.4)
60-day	**17.9** (16.2-19.8)	**19.9** (17.9-22.0)	**23.0** (20.6-25.5)	**25.4** (22.6-28.3)	**28.4** (24.3-32.8)	**30.6** (25.5-36.2)	**32.7** (26.2-40.0)	**34.6** (26.4-44.1)	**36.9** (26.9-49.0)	**38.5** (27.3-52.7)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

3.2 Cascade Watershed Modeling

3.2.1. Topography

High-resolution light detection and ranging (LiDAR) data was downloaded from the National Oceanographic and Atmospheric Administration (NOAA), the US Geologic Survey (USGS), and local agencies. Data was stitched together as necessary to create a smooth surface and smooth boundaries. The

LiDAR data sets were incorporated into ArcGIS to generate a topographic surface. High-resolution data was obtained with vertical accuracy = 1.0-4.5 inches. Kriging functions in ArcGIS are used to resolve any data gaps. The following steps were used for merging DEM datasets with 3 m and 10 m resolutions:

1. Create a new folder to store the merged (mosaic) datasets.
2. Start ArcMap
3. Add the DEM tiles to merge.
4. Open **ArcToolbox** >> **Data Management Tools** >> **Raster** >> **Raster Dataset (**Figure 48**)**

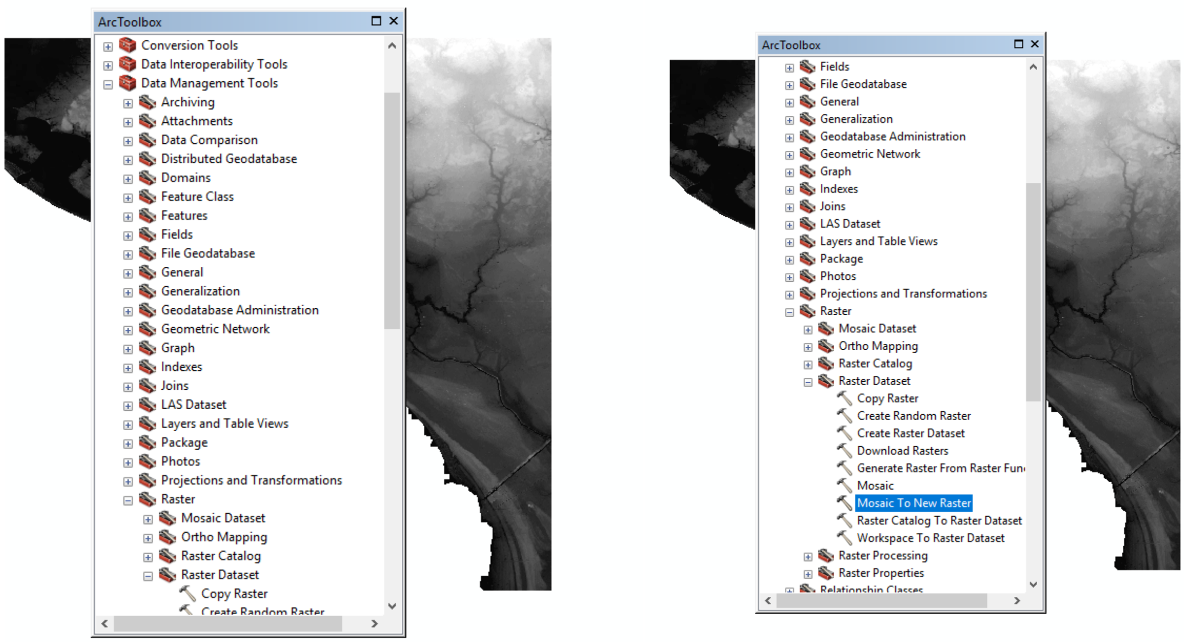


Figure 48. Arc tool databox for topography layer

5. Under **Raster Dataset**, click **Mosaic to New Raster**
6. A dialog window will open. (Figure 49)

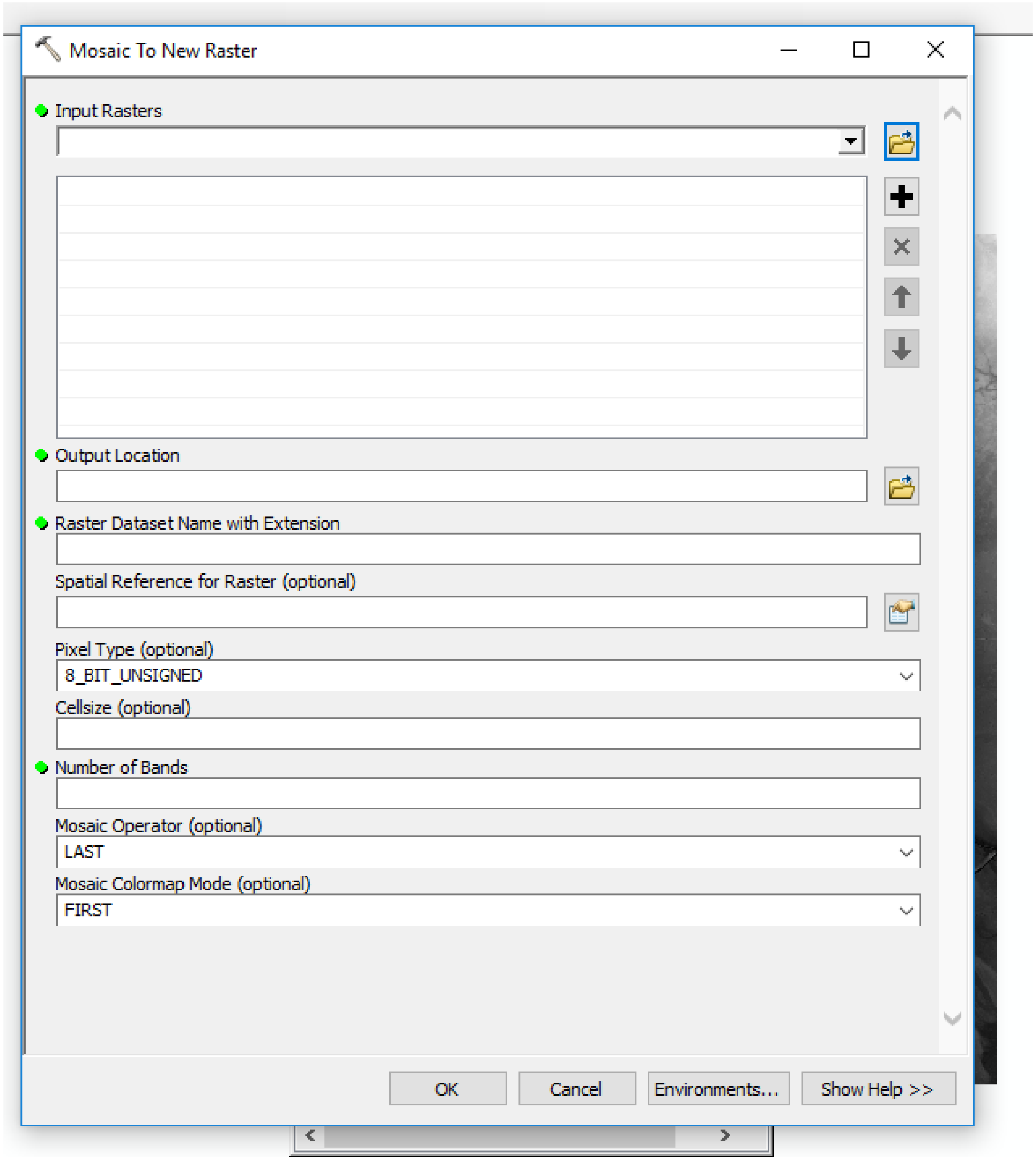


Figure 49. Raster Window

7. Under Input Rasters, click the drop-down arrow to start adding the raster datasets.
8. Add the 3 m DEM FIRST, then add the 10 m DEM. Under Output Location, click on the name of the folder created to store the merged datasets. Click Add. (see Figure 50)
9. Under Raster Dataset Name with Extension, type in the name of the new raster to create (this will be the name of the output raster).

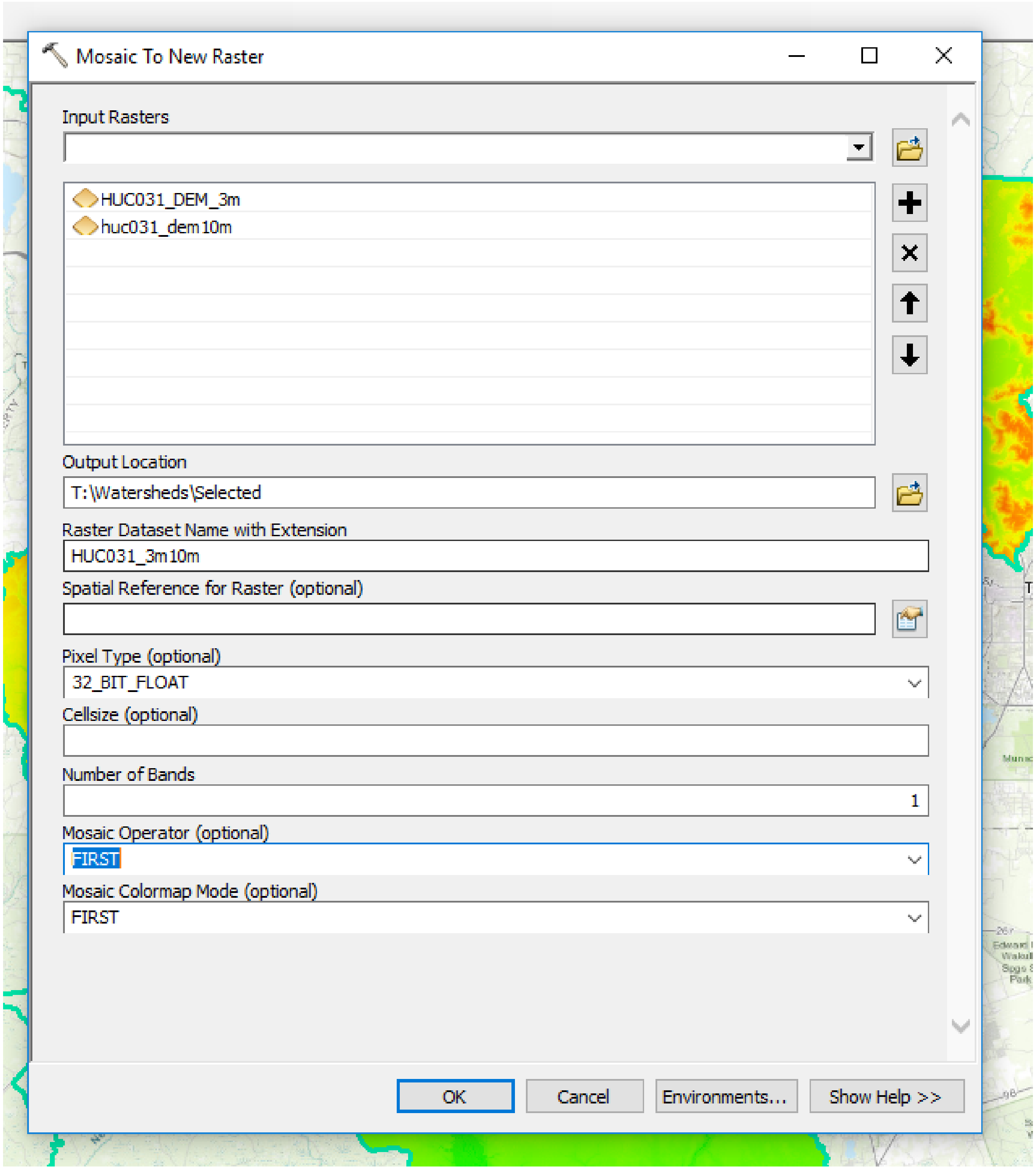


Figure 50. Revised HUC-TMDL map so TMDL regions match HUC boundaries.

10. Note: Signed Integer vs Unsigned RasterFormats

When merging images in ArcGIS (Data Management Tools > Raster > Raster Dataset >Mosaic to New Raster, specify the pixel depth and file type. Make note of the formats that support it.

IMG, TIFF (GeoTIFF), GRID, JPEG, JP2, BMP, GIF, PNG, BIL/BIP/BSQ, and DAT raster formats can store negative values.

IMG, TIFF and GRID are the most versatile formats. These formats accept 8-bit unsigned, 8-bit signed, 16-bit unsigned, 16-bit signed, 32-bit signed and 32-bit floating.

11. The files have the extension .TIFF / We will be using 32-BIT-FLOAT file format.
12. Leave Spatial Reference for Raster (optional) blank.
13. Under Pixel Type (optional), select 32_BIT_FLOAT.
14. Leave Cell Size blank.
15. Under Number of bands, enter 1
16. Under Mosaic Operator (optional) select FIRST. (Remember that you added the 3m DEM first, this means that the Mosaic Operator will resample the final output to the resolution of the first raster).
17. Leave Mosaic Colormap Mode (optional) also FIRST.
18. Click OK. The progress bar will display the status of the running tool.

For this project, the topography in coastal areas will be defined in 1 ft layers, starting with a 0 ft NAVD88 and ending with >15 ft. The latter resolves issues with large buildings and landfills (which approach 150 ft). The color palette should use blue to green to yellow to brown. Blues should only be used below 5 ft NAVD88 as these areas are most likely to flood.

3.2.2 Groundwater

Adequate well/station-based groundwater data is needed to create a groundwater surface in GIS. Well density varies considerably, and interpretation of data is required. The groundwater dataset was developed by analyzing recorded groundwater table elevations from 2005 to 2018 obtained from the water management districts, Florida Department of Environmental Protection (FDEP), and other state and local partners. To find the 99th percentile date, the data sets were trimmed and then tabulated in ascending order and reviewed to determine common dates within the 98-100th percentile of highest elevations as described in Section 2.2. Once a common date was found, the water levels in all wells were used to create the groundwater surface. Prior work indicates that while various interpolation methods can be used, ordinary kriging methods work well. For groundwater data, we identified the daily maximum record for each well. An example of the groundwater Excel sheet with five columns (Dbkey, Year, Month, Day, and Value) and processing steps using the tool are provided as follows.

1. To get the date in a specific basin, an Excel sheet is prepared to list all relevant well station IDs, as follows:

STATION
PB-99 2
PB-732
PB-445
PB-683
PB-809

2. The tool consists of two parts: 'GetStudyAreaWells'(part1) is for extracting the sheets from multiple Excel raw files and mergig them together as a data collection of the study area. 'RecordStats'(part2) is for analyzing the data collection and filtering the dates by the number and ranking of the water-depth records.
3. If the user has installed MATLAB, the apps with the extension of '.mlapp' are ready to use. Otherwise, the user needs to install the executable files. In this tutorial, we will take the '.mlapp' apps for example. Steps 5, 6 and 7 introduce how to install the executable files. If you are a MATLAB user, you could skip to step 8.
4. Each part of the tool includes a folder named 'for_redistribution' and a folder named 'for_redistribution_files_only'.

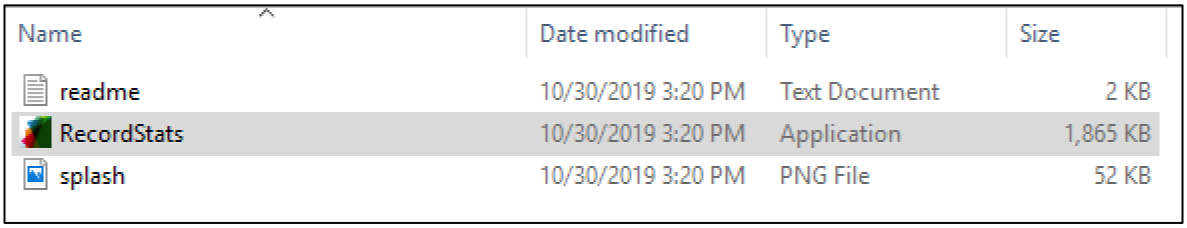
Name	Date modified	Type	Size
for_redistribution	10/30/2019 3:20 PM	File folder	
for_redistribution_files_only	10/30/2019 3:20 PM	File folder	
for_testing	10/30/2019 3:20 PM	File folder	
PackagingLog	10/30/2019 3:20 PM	HTML File	1 KB

5. The user should go to the folder of 'for_redistribution' to install 'MyAppInstaller_web.exe'.

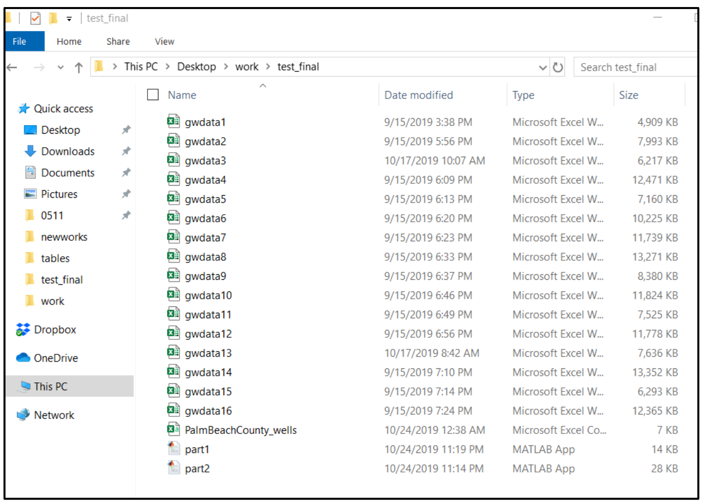
MyAppInstaller_web	10/30/2019 3:20 PM	Application	2,480 KB

6. Then, the executable file in the folder of 'for_redistribution_files_only' will be ready for use. If you get the security warning, click 'More info' and click 'Run anyway'. Note that each part has its

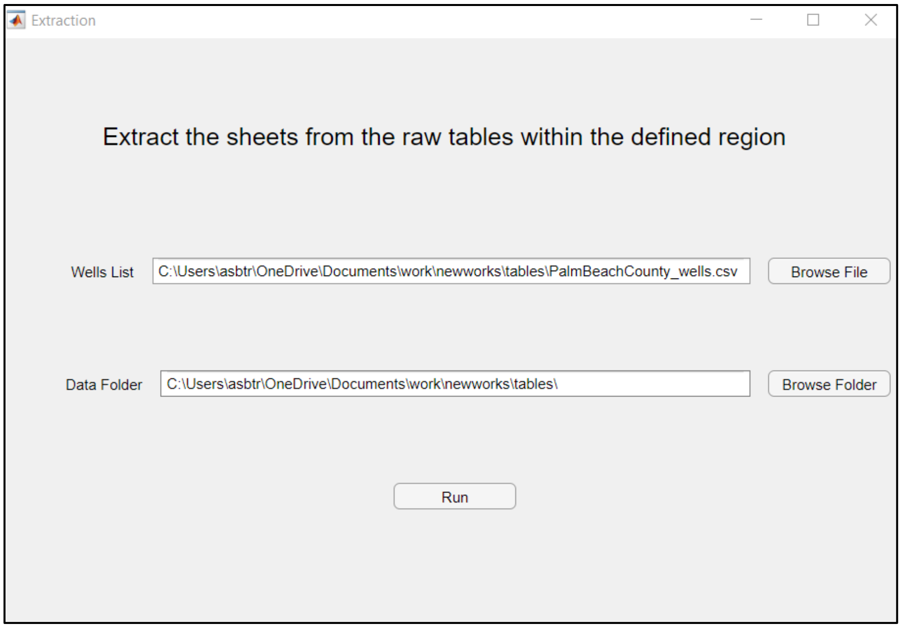
own installer. Since there are two parts, the user should install twice. The executable files in the folder of ‘for_redistribution_files_only’ will be regarded as the mlapp files in the following steps. (‘GetStudyAreaWells.exe’ corresponds to ‘part1.mlapp’, ‘RecordStats.exe’ corresponds to ‘part2.mlapp’):



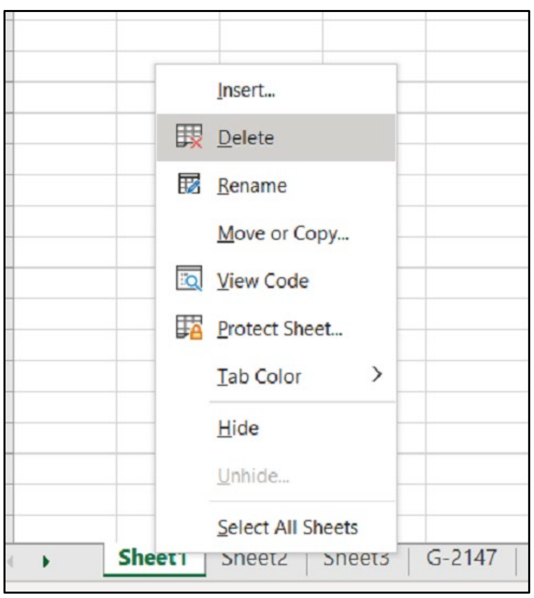
7. The user needs to store ‘part1.mlapp’ together with the raw data files and the study area’s wells list in the same folder:



8. Open ‘part1.mlapp’, the user will see the following interface. For the first blank, browse to the CSV table which stores the wells information of the study area. For the second blank, browse to the folder which stores the original Excel worksheets. By clicking and selecting any one of the Excel files in the folder, the whole folder will be selected. (Note: any Excel file other than the original worksheets should not be stored in this folder).



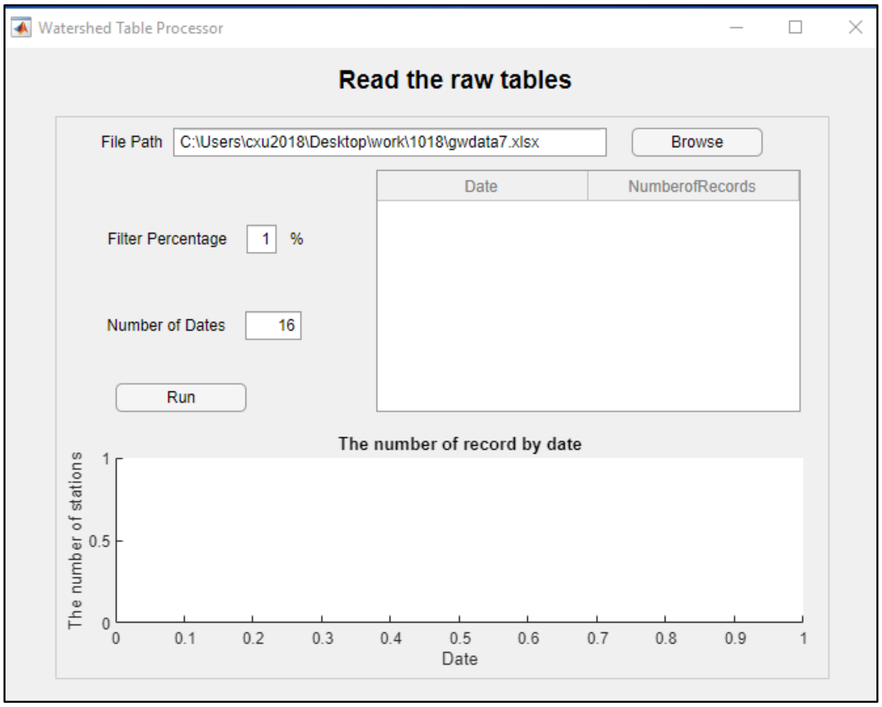
9. Click ‘Run’ and wait. As this task finishes, the user will see a ‘output.xlsx’ file in the work folder. This is the collection of the wells in the study area, each sheet corresponds to one well and its historical data.
10. This table has some blank sheets in the front, the user needs to delete them manually, then the collection is ready for use with the ‘part2’ tool.



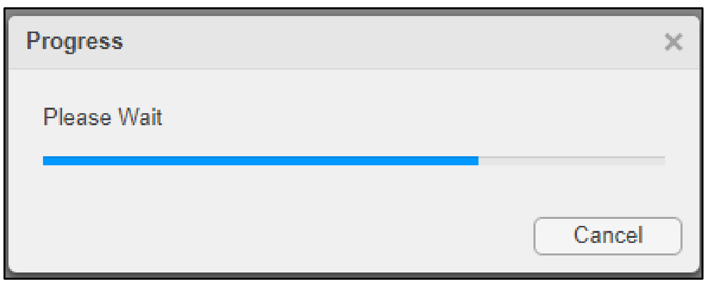
11. Open the ‘part2’ tool, to view the user interface. In order to run the program, you need to specify the following parameters: File Path (the directory of the groundwater Excel), Filter Percentage (you

can set such as 1%, 2%, 3%...), Number of Dates (the number of dates you want to get). After setting these parameters, click the Run button:

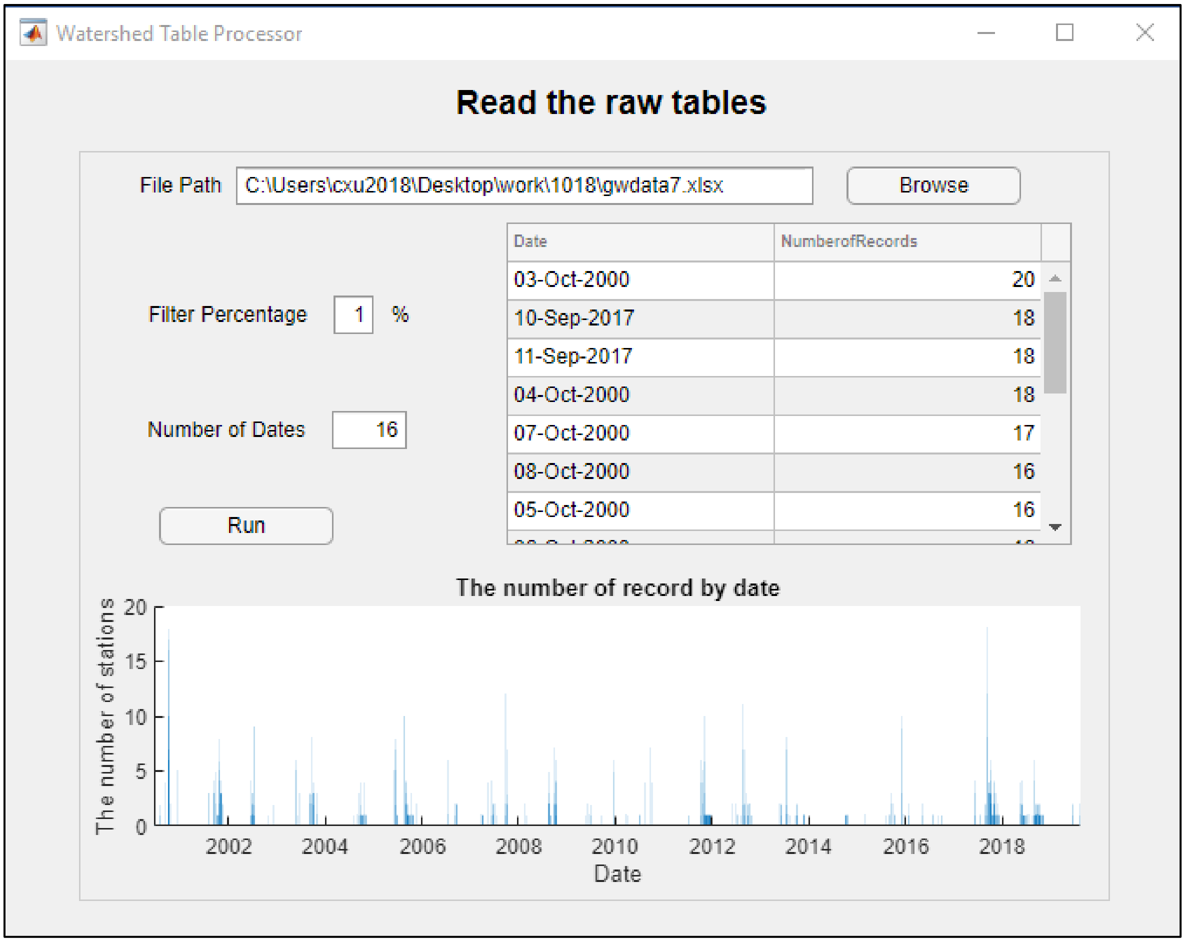
12.



13. While the program is running, you can see the progress bar.



14. When the program is finished running, the dates will be listed based on the number of wells entered into the filter percentage.

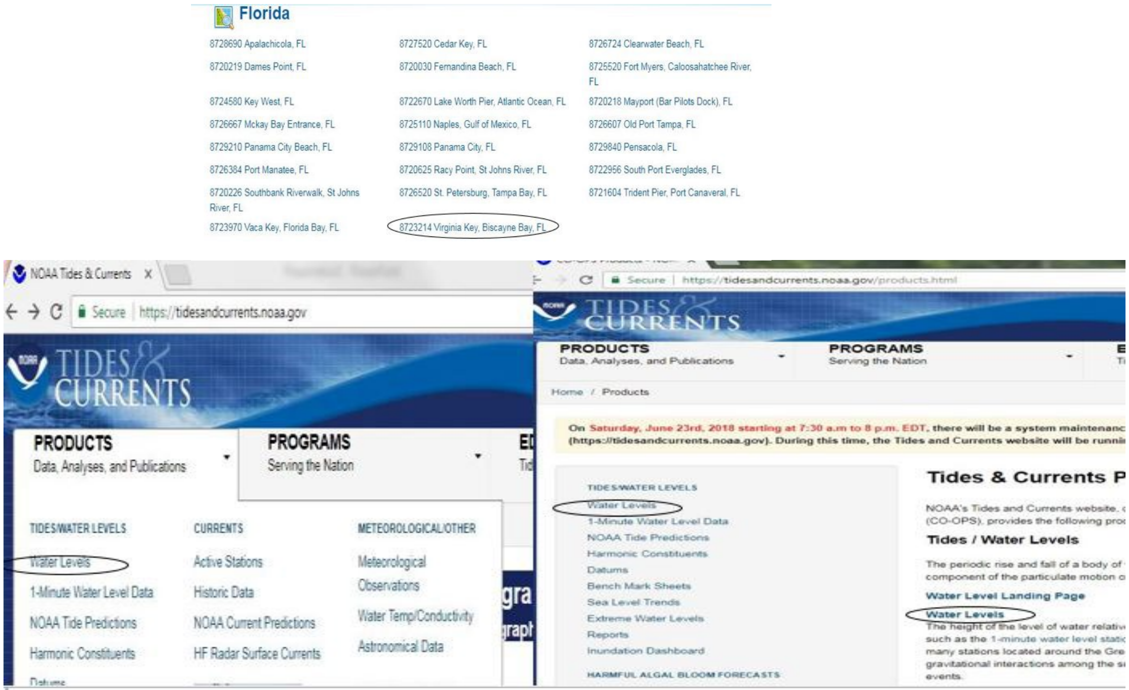


3.2.3 Surface Waters/Tides

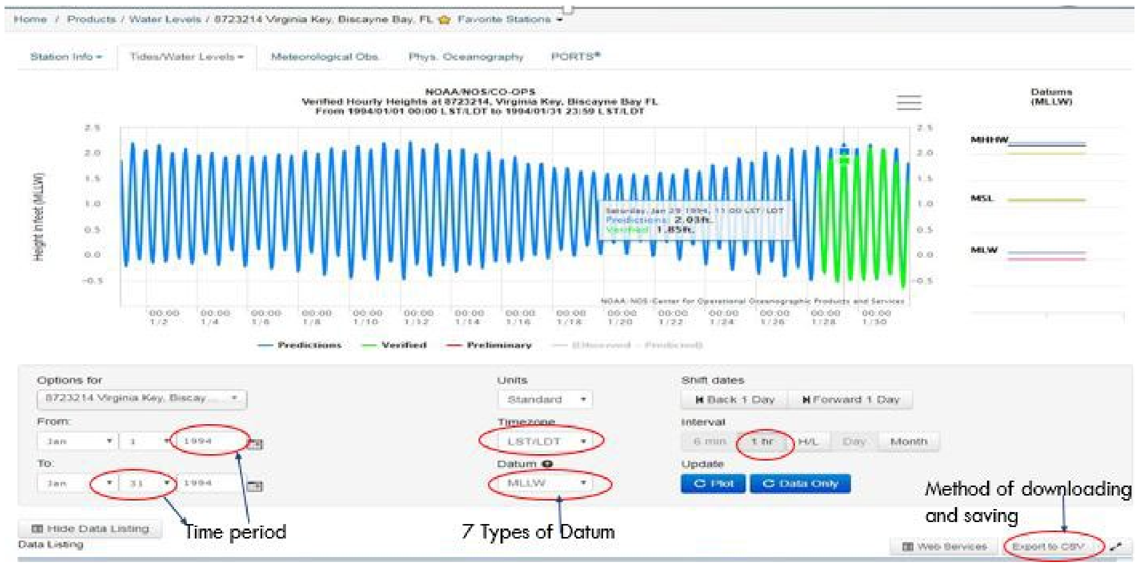
Because the water table is so shallow, surface waters affect groundwater. Therefore, once a common time period is found across the majority of wells, canal data can be gathered for that same common date (and two days prior in the event the canals were deliberately lowered). The canals form boundary conditions for the screening tool on the edges of the basin and affect localized groundwater. Using the water levels in the groundwater and canals, the only remaining boundary was the ocean. Hence, the tidal data was also obtained.

For the date in question:

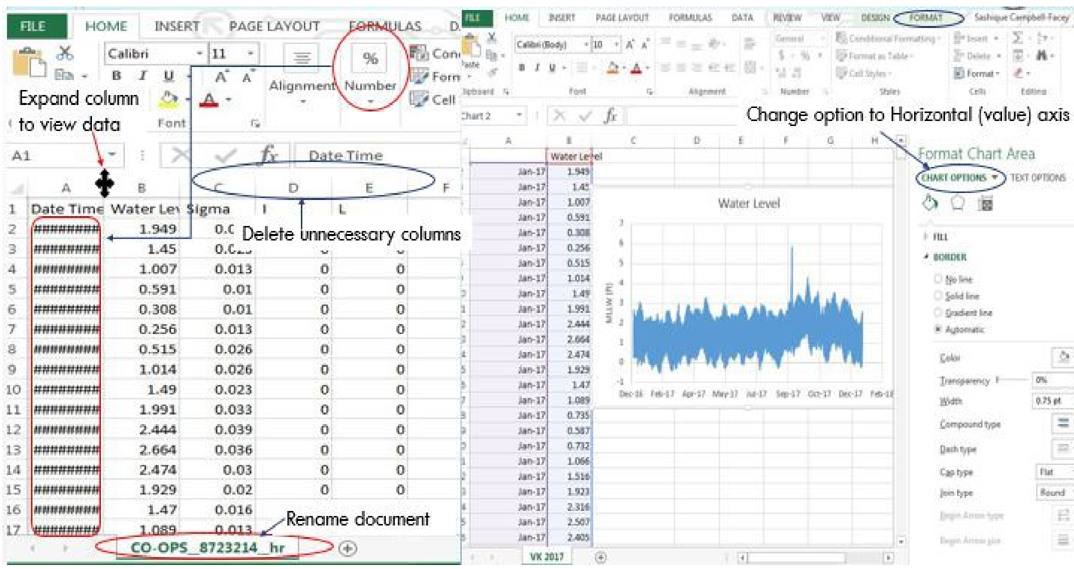
1. Go to the NOAA's Department of Tides and Currents at https://tidesandcurrents.noaa.gov/ then select the left tab labeled "Products."



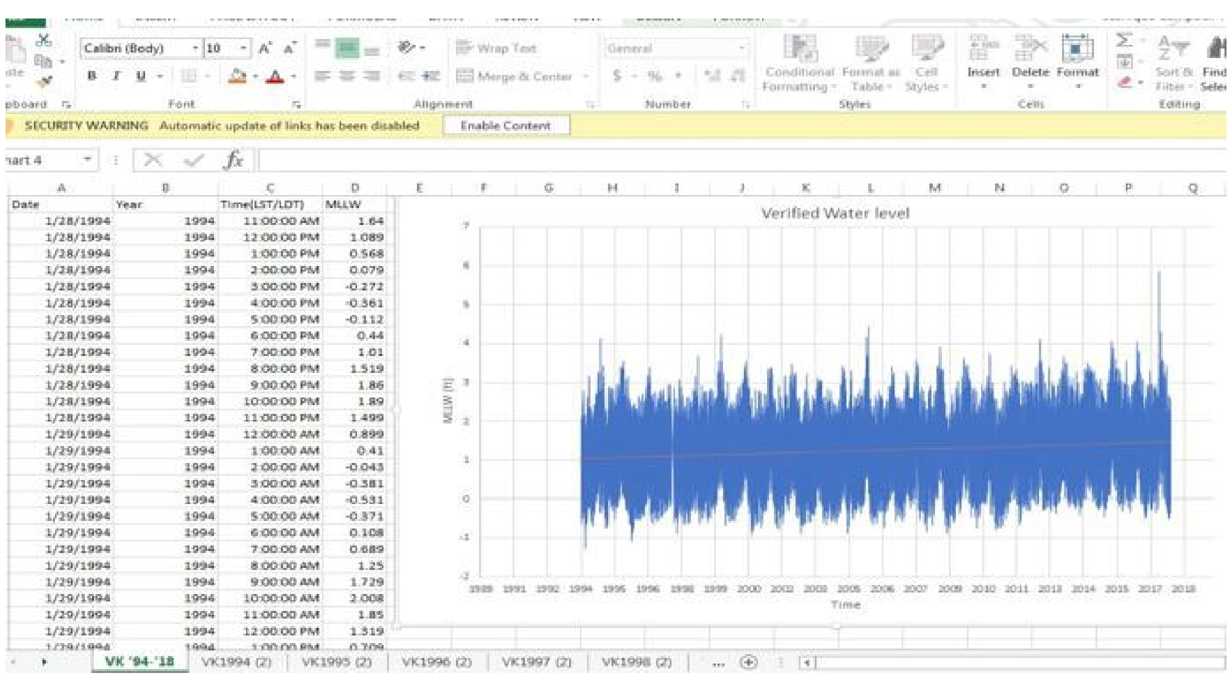
2. Select "Water Levels," then select "8723214 Virginia Key, Biscayne Bay, FL" under the list of active stations in Florida, or select the most appropriate station.
3. When the page opens, scroll down to the user-friendly retrieval tool and change the time zone from "GMT" to "LST/LDT".
4. Next change the datum type from "MLLW" to "NAVD", if data will be further processed or keep the datum type in "MLLW" if only assessing sea-level rise.



5. Change the time frame from the current date to "January 1, 1994 – December 31, 1994", then change the interval from "6 minute" to "hourly" and click "plot".
6. Click the button "Show Data Listing" for the option to download the data being displayed with the button "Export to CSV".
7. Once downloaded, further organizing is performed after saving the file as an Excel Worksheet rather than a CSV file, naming it according to station and year of data set.
8. Organizing includes expanding the "A" column, which gives visibility to the dates and time of the data. Then copy the values of column "A" into the new empty column "B".
9. Once the data has been copied into column "B," use the number option to change the custom appearance from "m/d/yyyy h:mm" to "dd-mmm", to allow for proper axis labeling when graphing.



10. Select all of column "B" and "C" (water level), then go to the insert tab and place the data in a "scatter line" type of chart.
11. Lastly, delete the last three columns, which only contain values displaying zero.
12. When the data is organized, selecting all columns allows for the chart to be created from tools in the "insert" tab.
13. Further presentation may include adding axis labels and chart title from the formatting section.



14. Repeat this process, but be sure to change the time period to the next year

3.2.3.1 Surface Waters – Not Tidal

As discussed in Chapter 2, current kriging spatial interpolation techniques cannot solve regions with sparse or no well observations, and an ideal groundwater table map/raster layer could not be produced for Tampa Bay Basin, as shown in Figure 51. All elevations are in feet with NAVD 88 datum.

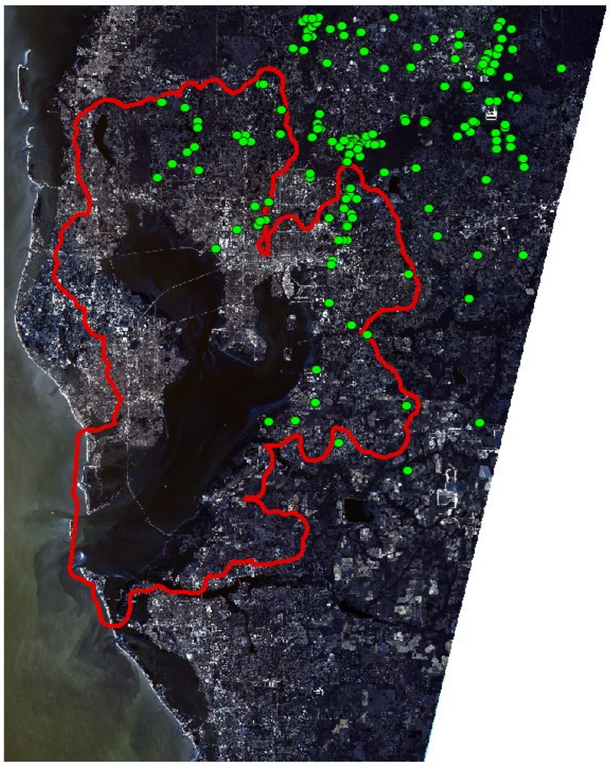


Figure 51. Groundwater well observations on a Landsat image showing the locations of wells within a 1-mile buffer of Tampa Bay Basin. (A total of 317 wells have data since 2000, among which 79 are within the 1-mile buffer zone). Note that no data on the west side and south part. In this situation, any spatial interpolation techniques cannot solve the issue, thus spatial extrapolation should be considered.

The multiple linear regression (MLR) approach has been well established for groundwater elevation estimation (e.g., Sepúlveda, 2003; Chung and Rogers, 2012). It assumes that the exposed water surface such as lakes, streams, rivers, and canals have the elevation of a local minimum water table referred to as MINWTE in literature. Groundwater table is closely related to MINWTE, and the depth-to-MINWTE which can be derived by subtracting MINWTE from DEM. Water table elevation (WTE) is estimated via a multiple linear regression model as below:

WTE = β1(MINWTE) + β2(Depth to MINWTE) + ε

where WTE = estimated water table elevation, and ε =statistical error.

MINWTE is created from surface water elevation. Therefore, if MINWTE is created based on surface water station data, tidal data, and elevation along streams/rivers/canals, and boundaries of water bodies, then WTE can be estimated from DEM and groundwater well data.

The following steps are used:

1. Get surface elevation observation data for the selected date. Note only limited stations have data for the specific date, thus, for surface stations which do not have data for that specific date, an average of maximum 5% top elevation is used. This is similar to the groundwater well observation processing. Surface water stations are displayed in Figure 52.

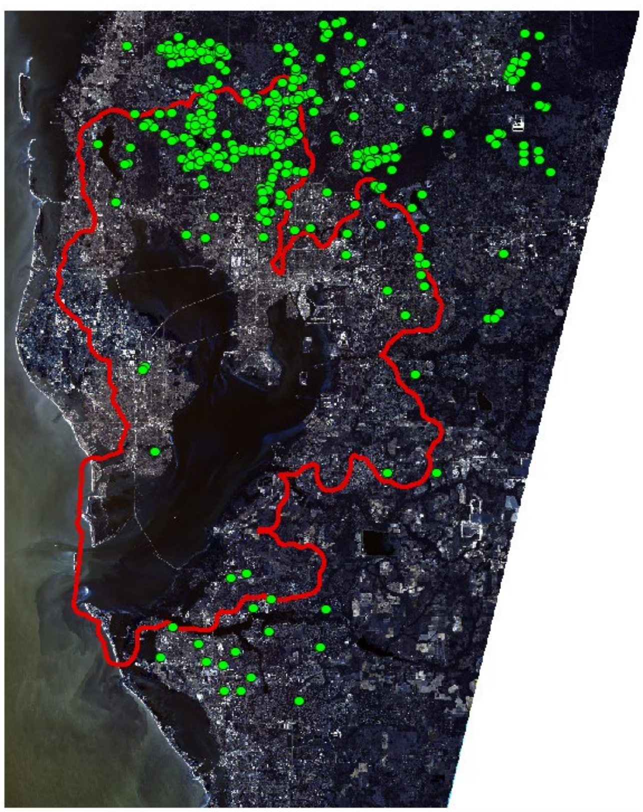


Figure 52. Surface water stations (a total of 352 stations, among which 173 are within the 1-mile buffer). Note that surface water is also not well distributed in Tampa Bay buffer.

2. Obtain tidal data for the specific date. Tidal data is obtained from NOAA, and for that specific date, maximum water level for each tidal station is found. For Tampa Bay, a total of 5 tidal stations are found, as shown in Figure 53. For tidal data selection, make sure NAVD 88 and feet are used to obtain the maximum water level of that day. Date selection is detailed in well data processing.

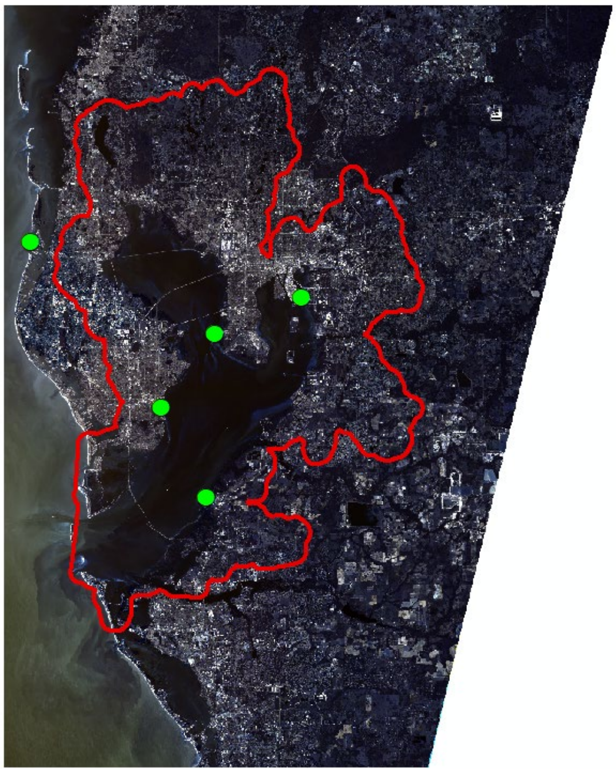


Figure 53. Tidal stations in the Tampa Bay Basin.

3. Obtain elevations of streams, canals, boundaries of waterbodies. Note that surface water stations may not be uniformly distributed for the project area. To generate a reasonable MINWTE, ground elevations along streams, rivers, boundaries of inland water bodies are used as pseudo-surface water elevation points. First, points along streams, rivers, boundaries of inland water bodies, and ocean shoreline are produced using the "Generate Points Along Line" function in ArcGIS to get points with 500 m in distance. Second, for points from streams, rivers, canals, and inland water boundaries (e.g., lakes), the elevations of these points are assigned as DEM using extract value to point function in ArcGIS. For points along ocean shorelines, elevations are assigned to the closest tidal station observed elevation using Point to Point spatial join function in ArcGIS. All rivers, streams, boundaries of water bodies, and shorelines are displayed in Figure 54.

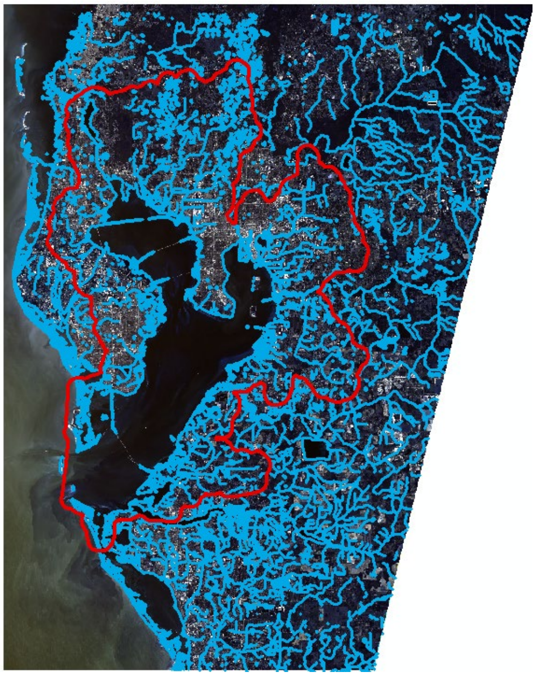


Figure 54. Streams, rivers, canals, boundaries of water bodies (e.g., lakes, reservoirs), ocean/manmade shorelines for the project area.

Points generated from the lines of streams, rivers, canals, boundaries of water bodies are shown in Figure 55. Green points are identified as points along streams, rivers, canals, inland water boundaries. Red points are identified as points along coast which are assigned as tidal elevation. Green points are assigned as DEM. The line feature has an attribute that can delineate manmade shorelines, streams, rivers, etc.

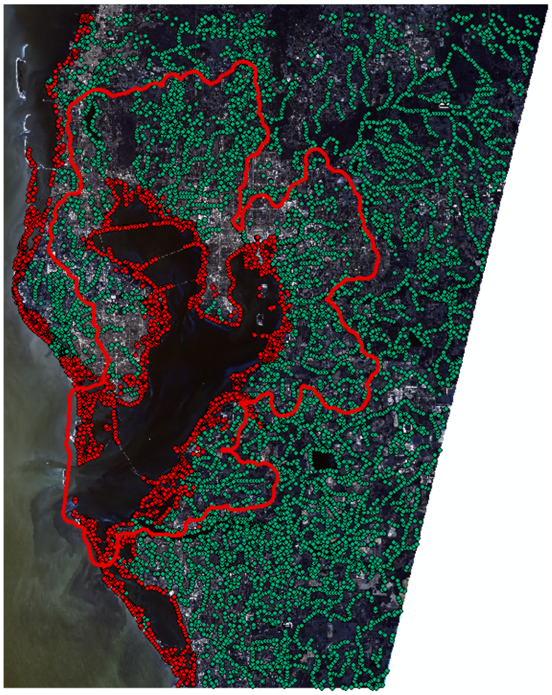


Figure 55. Points generated from the lines of streams, rivers, canals, boundaries of water bodies. Green points are identified as points along streams, rivers, canals, inland water boundaries. Red points are identified as points along coast which are assigned as tidal elevation. Green points are assigned as DEM.

4. Generate MINWTE raster layer. Merge surface station observation data, and pseudo point elevation data derived from step 3 (all are point features with elevation attribute), and then use the merged point dataset to run interpolation algorithms in ArcGIS. Note that the project area has many streams, rivers, etc. Thus, adequate points exist to run interpolators to produce an ideal MINWTE surface. Based on the literature, the local polynomial interpolation is selected, and resolution is set to 10 m. An example of the MINWTE created is shown in Figure 56.

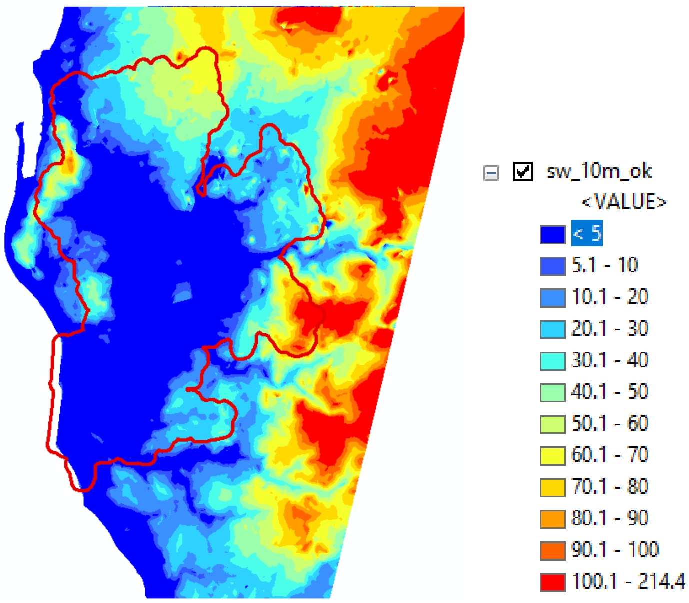


Figure 56. Generated 10-m MINWTE

5. Generate Depth-to-MINWTE raster layer. Depth to-MINWTE is created by subtracting MINWTE from DEM. Note that negative values may be generated, and the conditional function in ArcGIS should be used to set negative values to 0 and keep other pixel values as is. This is conducted using raster calculator function in ArcGIS. Before the calculation, 3-m DEM is resampled to 10-m first. An example of a final Depth-to-MINWTE is displayed in Figure *57*.

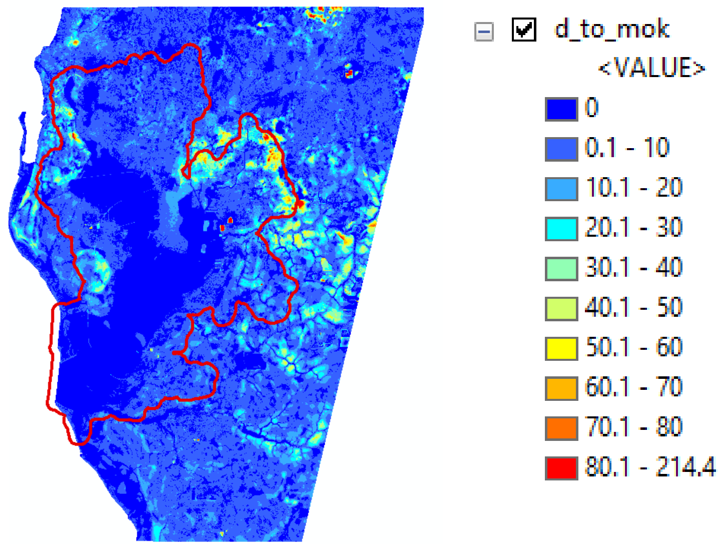


Figure 57. 10-m depth-to-MINWTE. Negative values are assigned to 0.0 because water table cannot exceed ground elevation). Regions with 0 values are expected for water bodies, rivers, streams, canals.

3.2.3.2 Well groundwater data processing and multiple linear regression modeling

The intent is modeling and predicting the maximum groundwater elevation for risk and vulnerability analysis. The original well groundwater data for the southwest region is daily maximum of each well. The project requires to find a common date in which most of wells have their maximum 5% or 1% top of time series records. For the southwest region groundwater data, both NAVD 88 and NGVD 29 data are provided in Excel, and some wells have two duplicate records, and some have four duplicate records. To find the date, the following preprocessing steps are used in Excel: 1) records with NGVD are dropped through sorting, and deleting function; 2) duplicate records are dropped using drop duplicate data function; 3) wells have no data are dropped; and 4) all data collected since 2000 to current are merged into one dataset to be used as input for programing (this dataset include three columns: well ID, date, elevation. This is a dataset covering southwest region). After these preprocessing in Excel, in ArcGIS, the wells within the project domain (Tampa Bay) are selected and well ID are remained to be connected with the elevation dataset (this dataset include well ID) to be used in programing. After data preparation, in programing, through the well ID to connect each well with the elevation dataset, and then for each well, all elevations are sorted from maximum to minimum, and by specifying 5% or 1%, the 5% or 1% top maximum elevation of each well and date can be found; once the 5% or 1% date are identified for each well, the frequency of the date of all wells are counted. By sorting the frequency from maximum to minimum, the common date can be identified. The date used in the project should be avoided hurricane/storm date. For example, 9/11/2017-9/18/2017 are the most frequent date within the 5% maximum, but these are the time window when Irma occurred, thus these dates are not considered. Consequently, for the project domain, 8/19/2015 is selected.

For groundwater table generation, the following two factors should be considered: 1) in theory, well elevation data for the specific date should be used for kriging or modeling for risk analysis, but in practice, for the specific project domain, only limited wells have data for that specific date. For example, there are more than 300 wells with data since 2000 in Tampa Bay, but only 70-80 wells have data for 8/19/2015, this means more than half of the wells should be dropped. Note that in interpolation, to generate a robust result, there should be adequate observations. Each well data is valuable in this context. Thus, for wells have data for the selected date, we definitely keep that well; for wells which do not have data for that specific date, we can find a closest date to use, or use the average of the 5% maximum; 2) for using spatial interpolation techniques in GIS such as Kriging, the observations should be well distributed in the project domain because all the spatial interpolation algorithms are based on the first law of geography and use spatial relationship of the observations (distance between points) to estimate. Thus, if the wells are well distributed in the project domain, kriging is good choice; however, if the data are not well distributed in the project domain, spatial extrapolation should be considered. For example, in Tampa Bay, wells are mainly distributed in the north part, while west part and south part have limited or no wells at all. Thus an ideal groundwater pattern could not be produced for Tampa Bay. For Tampa Bay, the MLR approach is selected which is also a benchmark approach in spatial interpolation and extrapolation.

In MLR, well observed groundwater data is used as the dependent variable, while MINWTE, and depth-to-MINWTE are used as independent variables to develop the model. Using extract Multi Values to Points function in ArcGIS to extract MINWTE, and depth-to-MINWTE values to match groundwater well elevations. After extraction, the well observed groundwater elevations should be larger than MINWTE values. If a well MINWTE value is larger than this well's observed elevation (we are estimating maximum elevation for risk analysis/inundation), this well should be dropped. Only wells with an observed elevation larger than MINWTE are used for model development. The remained well point data will be then exported as ASCII file and run multiple linear regression in any software packages which have the regression functions. A model is produced, and accuracy of the model can be also assessed using k-fold cross validation function.

3.2.3.3 Soils

Soil can store water if there is adequate distance between the topographic surface and the groundwater, and the soils are capable of absorbing the water. Two steps are required here. Soil data is needed from USDA or other agencies. The soils data needs to be interpreted to determine whether water can be absorbed or will runoff. This is a critical issue for precipitation modeling. The soils maps should be incorporated as a layer in the overall mapping effort.

Along with these important advantages, the gSSURGO format has a few disadvantages:

- File geodatabases such as gSSURGO are NOT compatible with the NRCS Soil Data Viewer application.
- The file geodatabase format supports a limited subset of the standard query language (SQL) that the Microsoft® Access® database format or Microsoft® SQL Server® uses.
- Unlike vector layers, the geodatabase is unable to store permanent table relates for raster layers.

3.2.3.4 Obtaining SSURGO Data

gSSURGO can be obtained as one or more statewide tiles via free download from the USDA-NRCS Geospatial Data Gateway (GDG) website located at https://gdg.sc.egov.usda.gov/. Depending on file size, the data may also be available in different formats. The conterminous United States national collection of gSSURGO data was obtained by contacting the USDA-NRCS National Geospatial Center of Excellence (NGCE) representative Rosemary Rivera (rosemary.rivera@ftw.usda.gov) at (817) 509-3371. The cost for this service is $250 for non-USDA or non-partnering entities. The customer provides the external storage device and pays shipping costs. Additional information and ArcGIS™ tools for working with the data may be found on the gSSURGO webpage.

Download data from the Geospatial Data Gateway as follows:

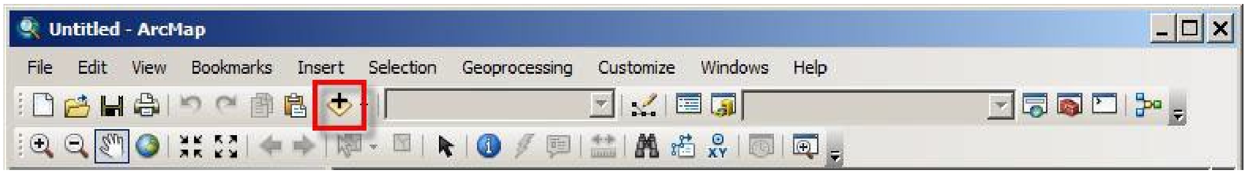
1. Using a web browser, open https://gdg.sc.egov.usda.gov/.

2. Click the **Order by State** link.
3. On the Gateway Order by State web page, select the desired state from the list.
4. Scroll down and click **Gridded Soil Survey Geographic (gSSURGO) by State** and click **CONTNUE**.

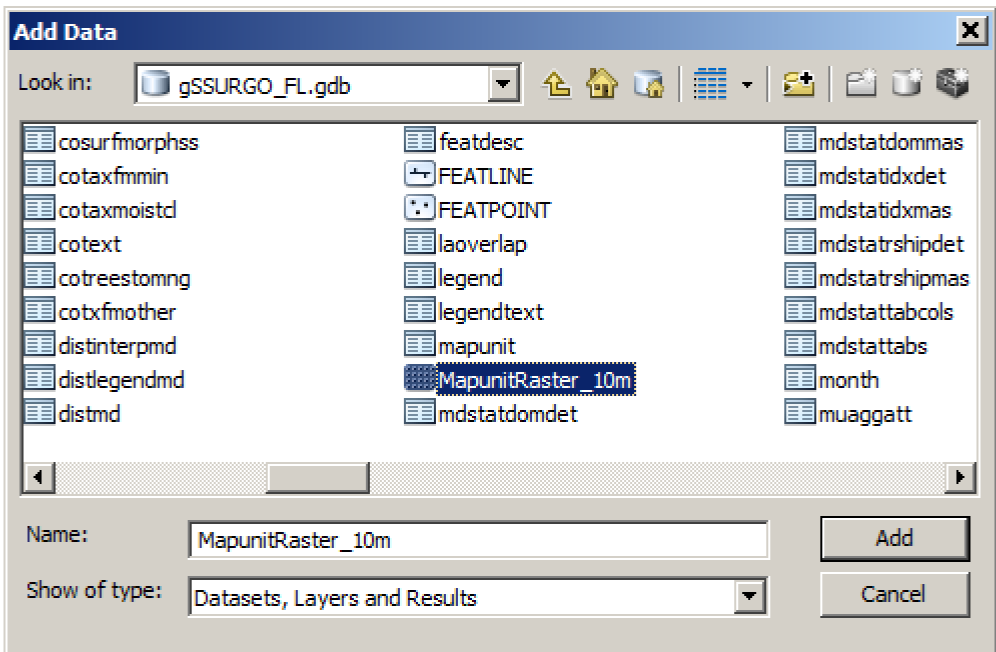
Working with the Raster Soils Layer (MapunitRaster_10m) in ArcMap™:

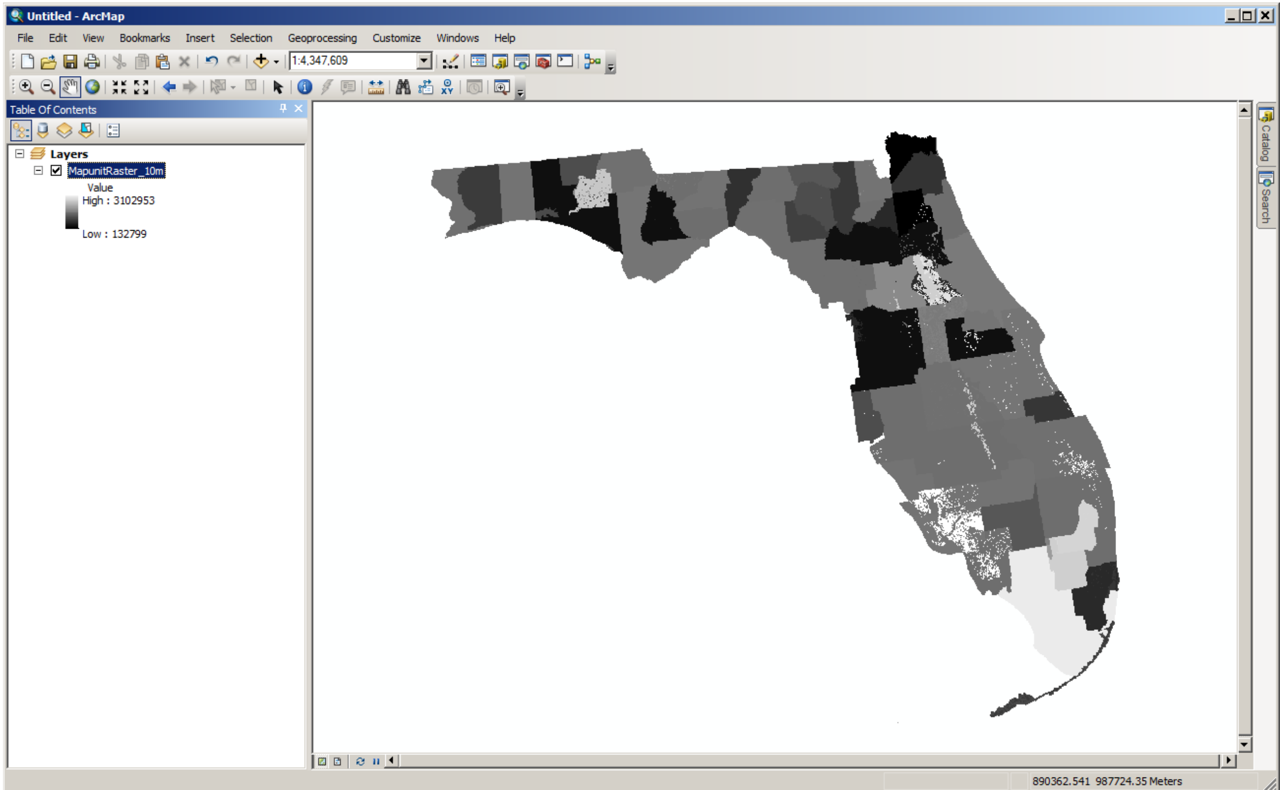
- Joining gSSURGO Data with the Muaggatt Table Using the MUKEY Field
- The following example shows how to join the gSSURGO spatial data to the map unit aggregated attribute (muaggatt) table using the MUKEY field.

1. **Start ArcMap** with a new blank map.
2. On the Standard toolbar, click the **Add Data** button.

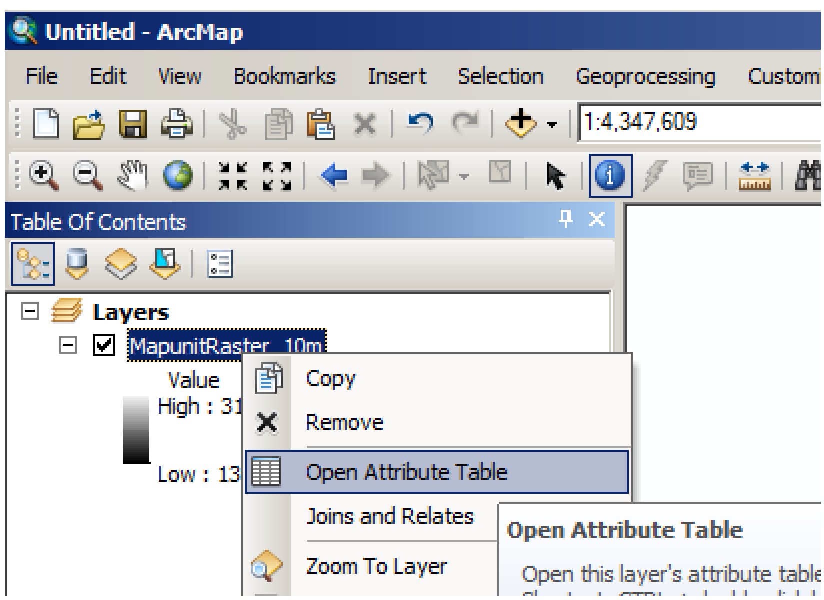


3. From the appropriate file geodatabase (e.g., gSSURGO_FL.gdb), select the raster feature class (e.g., MapunitRaster_FL_10m), and click the Add button.





4. Right-click on the raster feature class (e.g., MapunitRaster-WV_10m) and select **Open Attribute Table**.

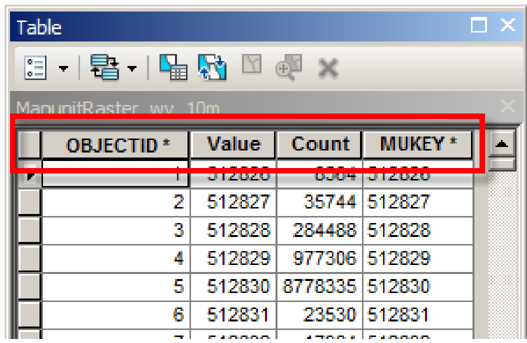


The raster attribute table contains three default fields: OBJECTID, Value, and Count.

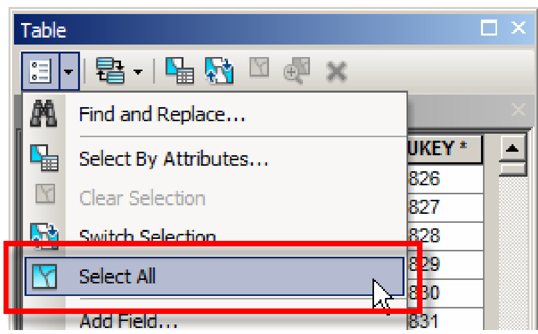
- OBJECTID uniquely identifies each row in the table.
- Value uniquely lists each cell value contained in the raster.

- Count lists the number of cells that contain the cell value.

The MUKEY field will be used to join with other soil attribute tables containing the MUKEY column.

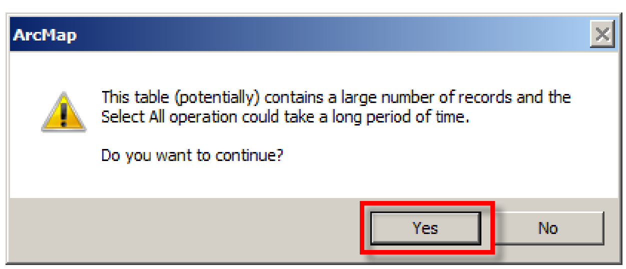


5. In the Table Options drop-down menu click Select All.

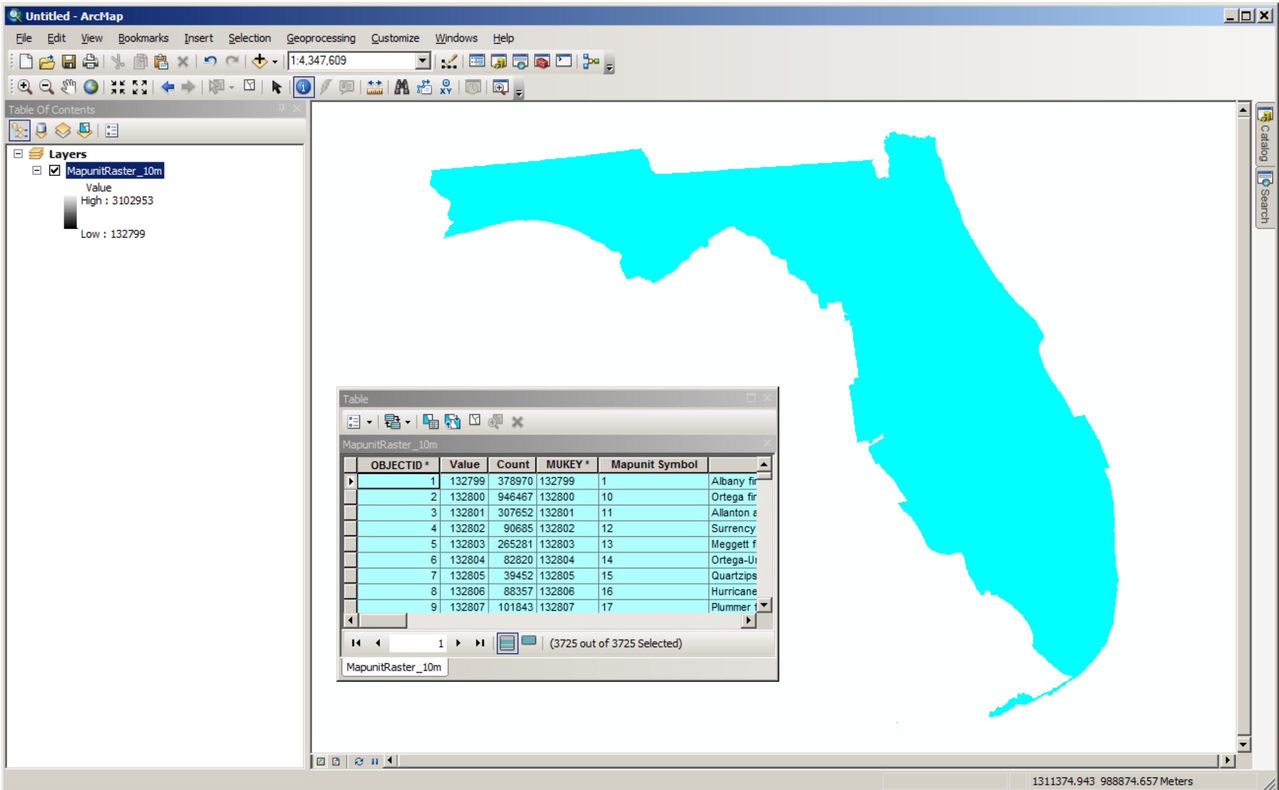


A warning may pop up indicating that the table may contain a large number of records and that the select operation may take significant time.

6. Click **Yes** to continue.

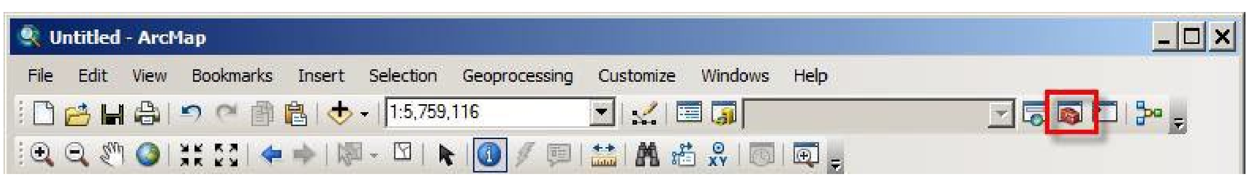


7. Both the ArcMap display and attribute table windows now show all records selected. Close the table.

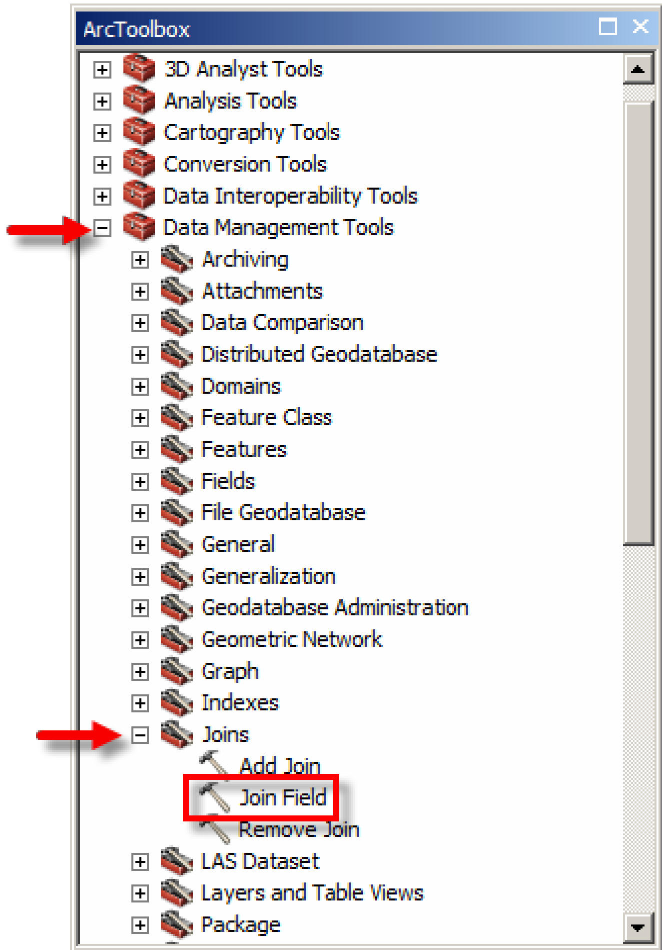


A join is typically established using the **Add Join** tool. This will temporarily append the fields of one table to another with a common attribute, e.g., MUKEY. It may be best to use the **Join Field** tool to permanently add the fields to the table for symbolization purposes. The fields can be dropped later, if necessary.

8. Open **ArcToolbox** located on the Standard toolbar.

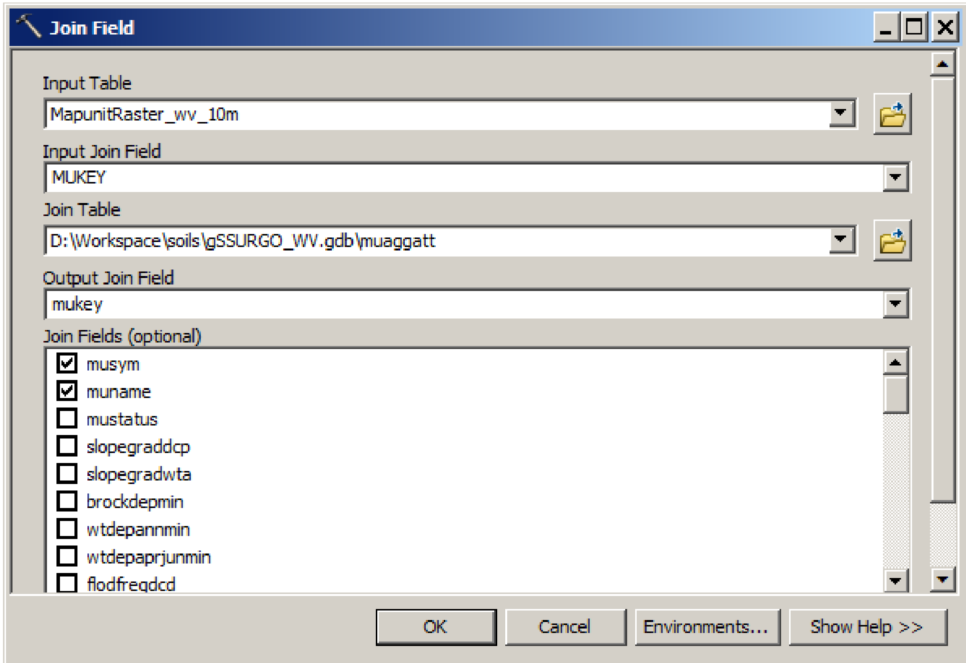


9. In ArcToolbox, expand the **Data Management Tools**, expand the **Joins** tools, and double-click on the **Join Field** tool to open a dialog box.



10. In the Join Field dialog:

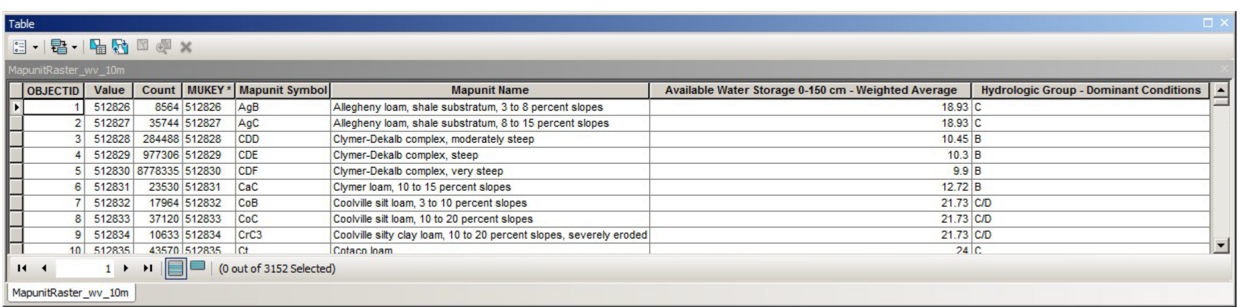
- For the Input Table, select **MapunitRaster_WV_10m.**
- For the Input Join Field, select **MUKEY.**
- For the Join Table, browse to **muaggatt.**
- For the Output Join Field, select **mukey.**
- For the Join Fields (optional), check **musym**, **muname**, **aws0150wta**, and **hydgrpdcd.**
- Click **OK.**



The attribute table will now contain the additional fields:

- Mapunit Symbol (musym)
- Mapunit Name (muname)
- Available Water Storage 0-150 cm – Weighted Average (aws0150wta)
- Hydrologic Group – Dominant Conditions (hydgrpdcd).

If the attribute table does not display, the additional columns after processing is complete, exit and restart ArcMap™. Add the raster and open the attribute table. The additional columns will appear.



Table

MapunitRaster_wv_10m

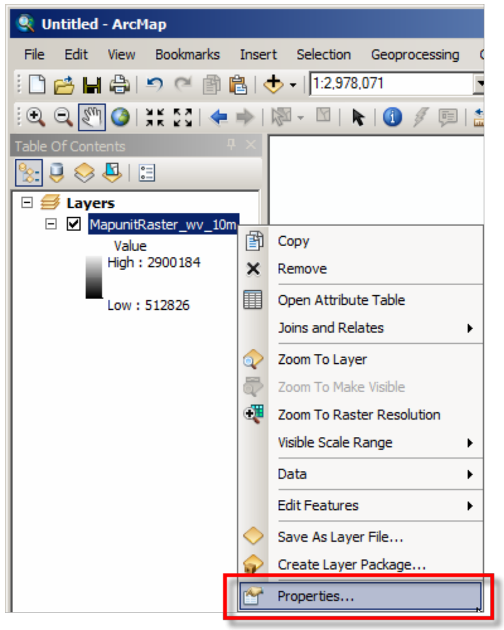
OBJECTID	Value	Count	MUKEY *	Mapunit Symbol	Mapunit Name	Available Water Storage 0-150 cm - Weighted Average	Hydrologic Group - Dominant Conditions
1	512826	8564	512826	AgB	Allegheny loam, shale substratum, 3 to 8 percent slopes	18.93	C
2	512827	35744	512827	AgC	Allegheny loam, shale substratum, 8 to 15 percent slopes	18.93	C
3	512828	284488	512828	CDD	Clymer-Dekalb complex, moderately steep	10.45	B
4	512829	977306	512829	CDE	Clymer-Dekalb complex, steep	10.3	B
5	512830	8778335	512830	CDF	Clymer-Dekalb complex, very steep	9.9	B
6	512831	23530	512831	CaC	Clymer loam, 10 to 15 percent slopes	12.72	B
7	512832	17964	512832	CoB	Coolville silt loam, 3 to 10 percent slopes	21.73	C/D
8	512833	37120	512833	CoC	Coolville silt loam, 10 to 20 percent slopes	21.73	C/D
9	512834	10633	512834	CrC3	Coolville silty clay loam, 10 to 20 percent slopes, severely eroded	21.73	C/D
10	512835	43570	512835	Ct	Cotaco loam	24	C

(0 out of 3152 Selected)

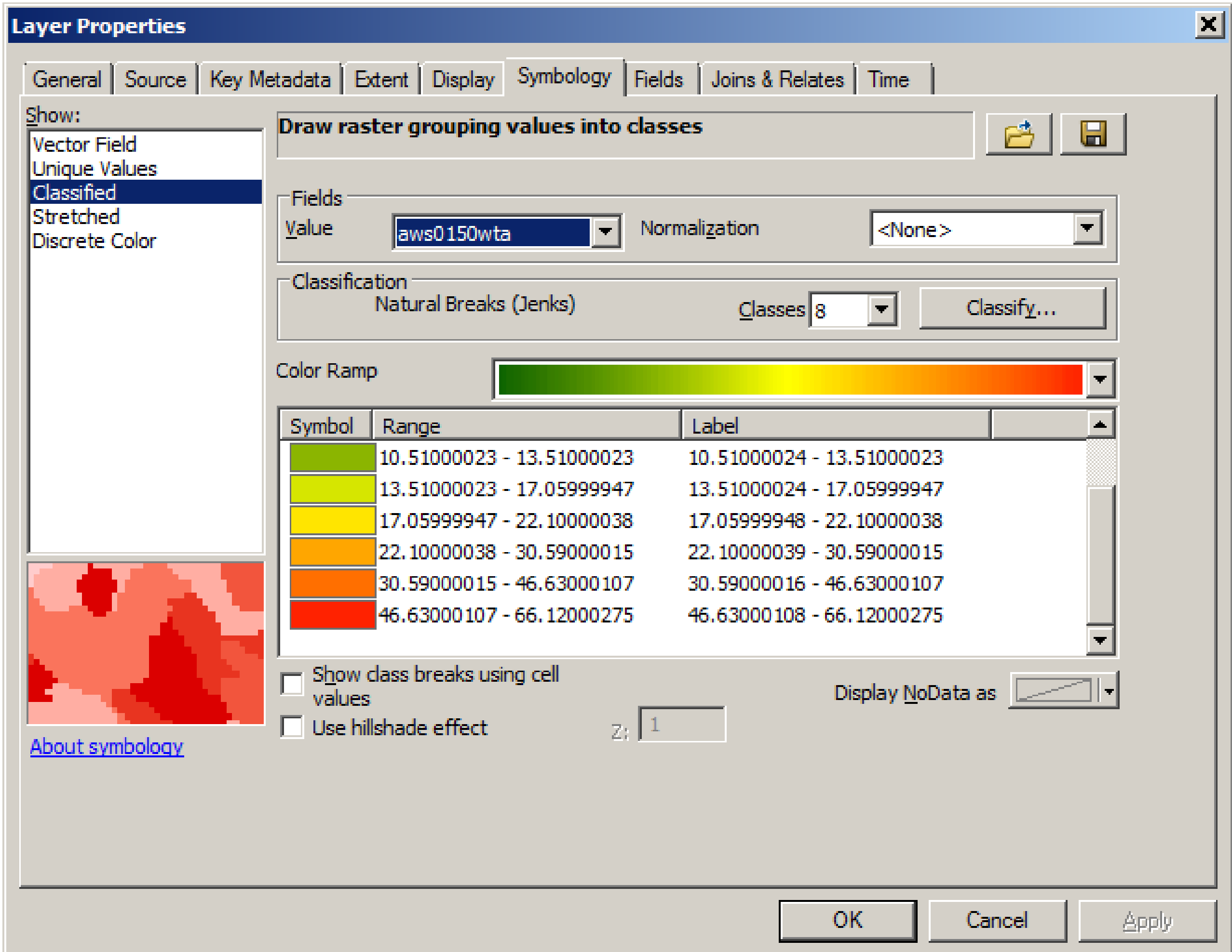
MapunitRaster_wv_10m

Symbolize the data based on the entries for Hydrologic Group – Dominant Conditions.

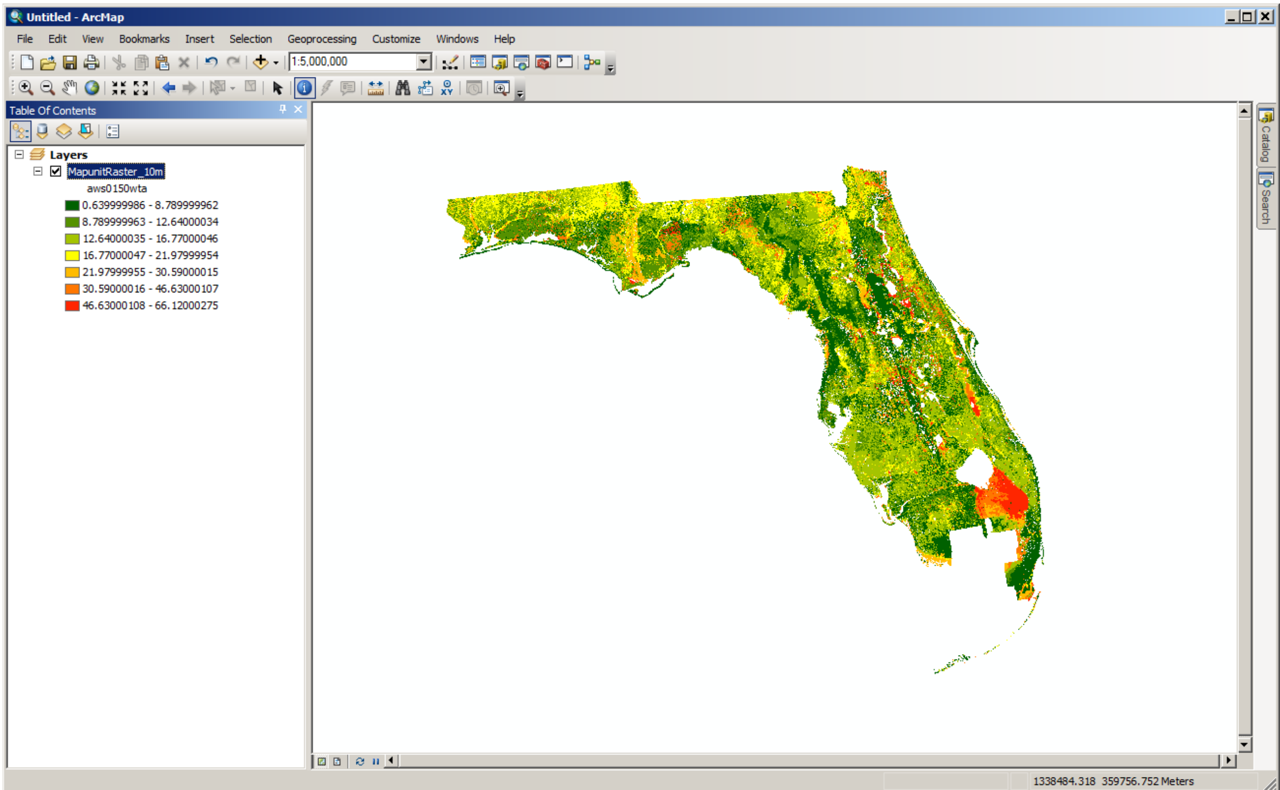
11. Right click on the raster layer and click Properties.



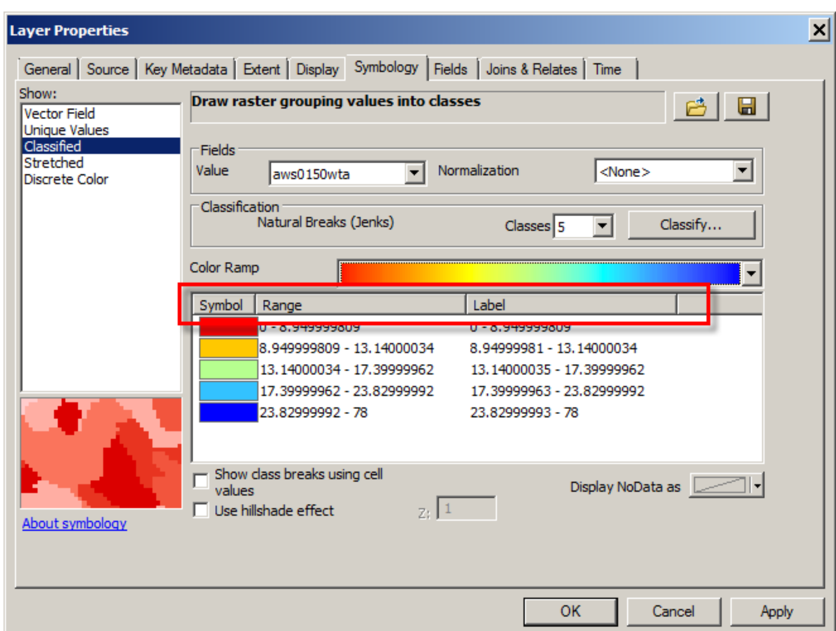
12. In the Layer Properties dialog:
    - Select the **Symbology** tab in the **Layer Properties** dialog box.
    - In the Show group, select **Classified**.
    - From the Value Field drop-down menu, select **aws0150wta**.
    - Choose a color palette from the **Color Ramp**.
    - Click **OK**.



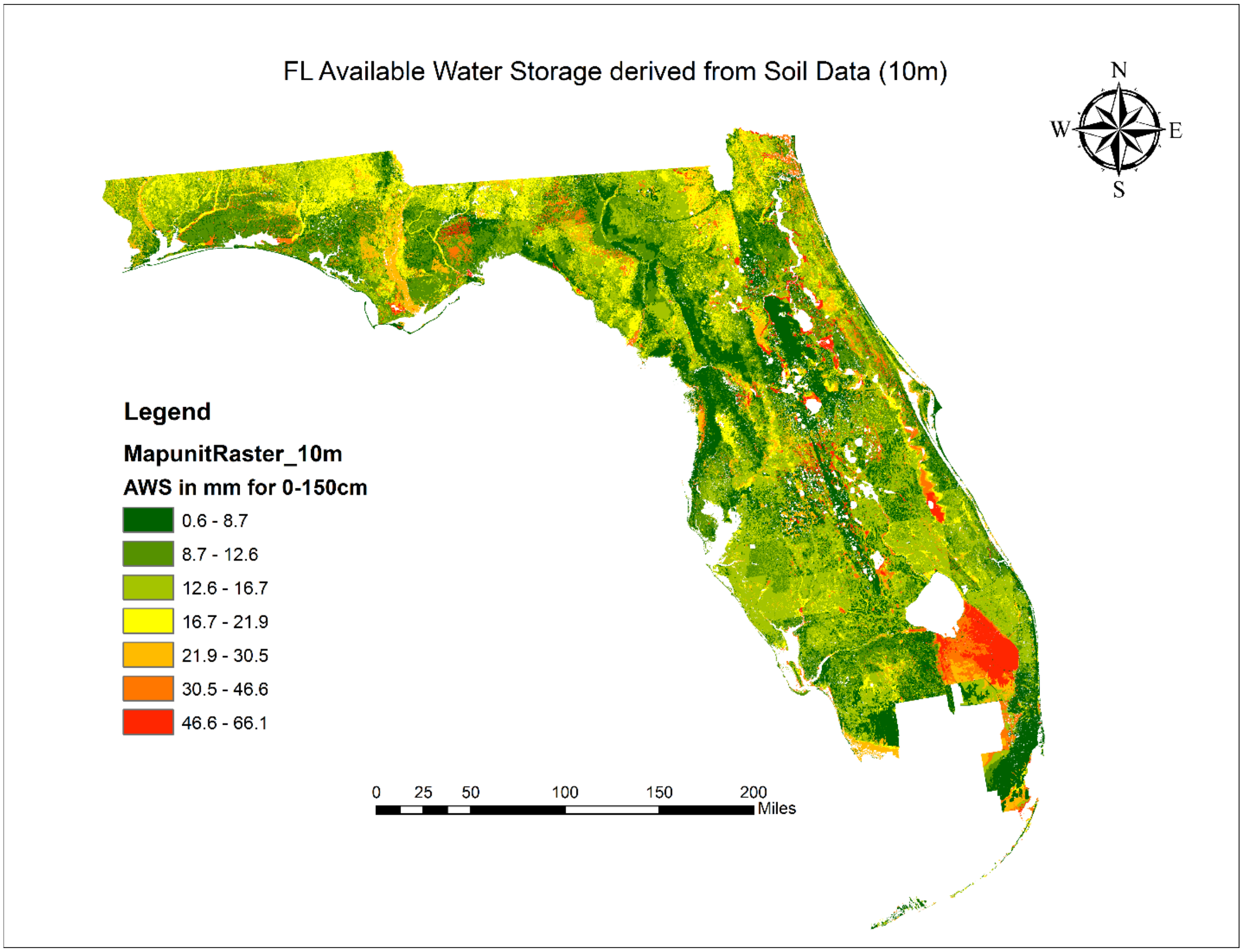
The weighted average for the map unit is rendered for Available Water Storage 0-150 cm. The unit is in mm.



Clicking on the Symbol, Range, or Label column heading in the Layer Properties dialog box allows the user to alter settings, such as the number of decimal places. Changing these settings will also change the layer's legend in the Table of Contents and make it easier to read.



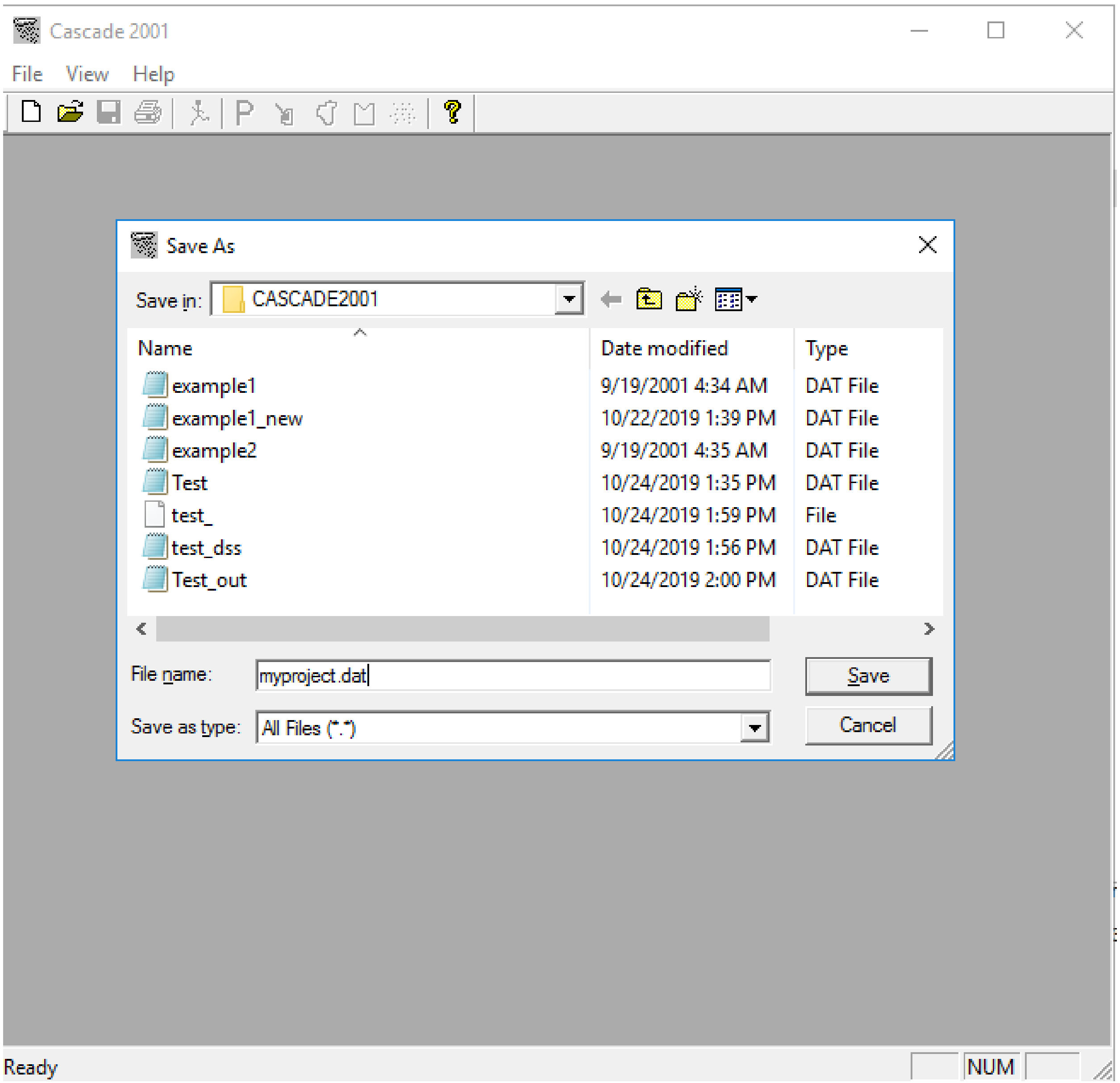
The available water storage derived for the soil layer (0-150cm) is shown below. It covers most of Florida with a spatial resolution of 10 m. The unit is in mm. The “no data area” is mainly due to a land cover of water body or wetland.



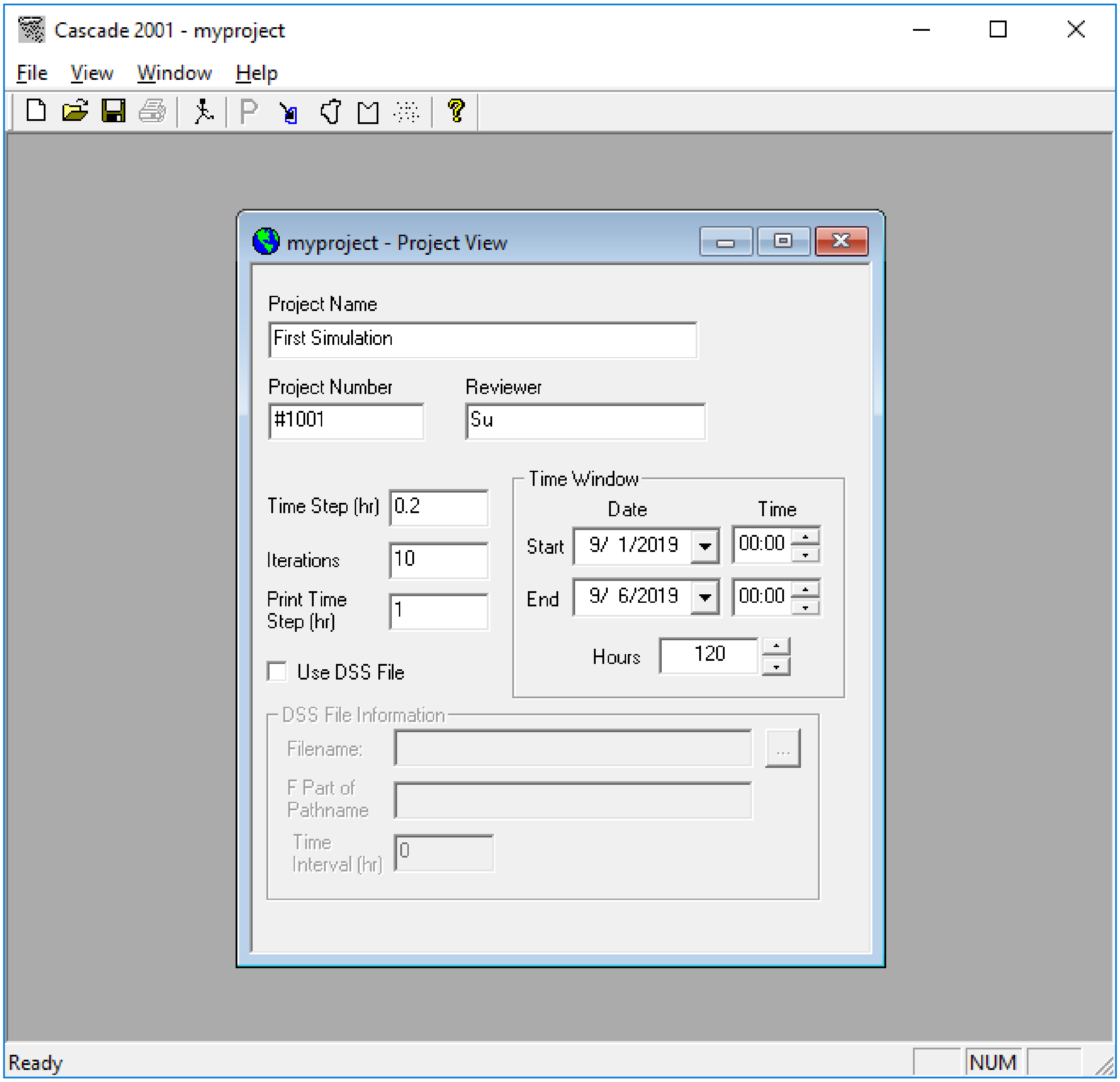
3.3 Vulnerability Maps

First, the difference between the surface topography and the groundwater layer is found. The US Army Corps of Engineers’ definitions were used to define vulnerability where the topography-groundwater level is 0 or less, potentially vulnerable at 0-2 ft, and less vulnerable if >2 ft difference between topography and the groundwater level (Romah, 2011; Bloetscher et al., 2010, 2011, 2012). The result is the vulnerability screening that is conducted to identify at-risk properties, at-risk infrastructure, and other features that are susceptible to flooding. The areas that show an intersection of groundwater and the topographic surface will be designated in red as vulnerable. Areas with less than two feet between the surface and the water table will be colored yellow and labeled potentially vulnerable. All other areas will be colored green and deemed less vulnerable.

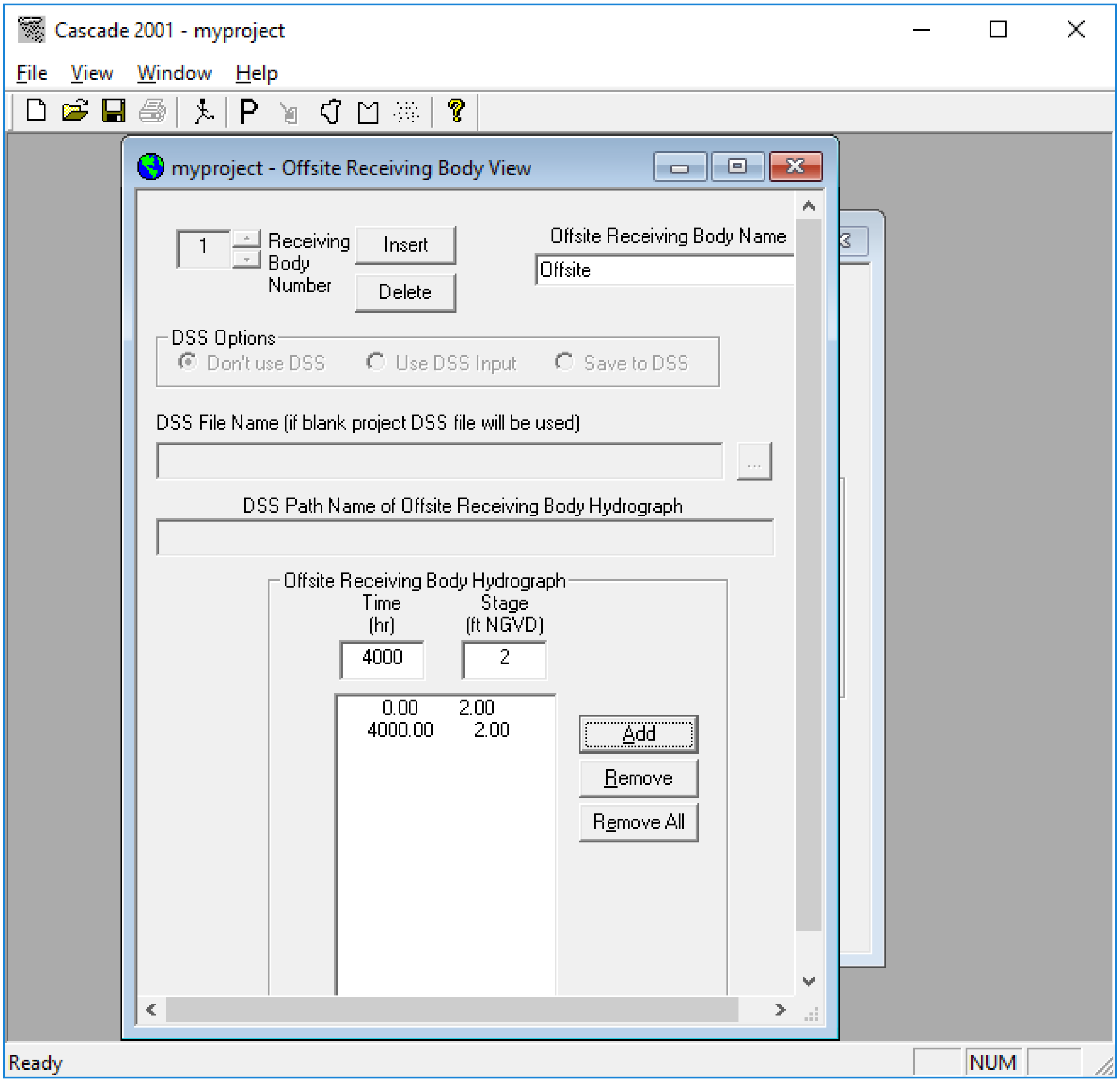
The first step is to create a **new project** in CASCADE 2001 by clicking on the first icon ("new page") under the File menu or using the shortcut key of CTRL+N. Then provide a file name to store the new project. In this example, the file name of "myproject.dat" is chosen. The project file is a text file that can be viewed and edited by any text editor.



Next, the user must fill in the necessary information to define the time period and time intervals of the simulation. In this example, we choose to simulate from September 1-6, 2019. The time interval of simulation is 0.2 hour, and the time interval of displaying the simulation result is 1 hour. The first time interval cannot be larger than the second one. The total number of hours for the simulation is calculated automatically and displayed accordingly.



Next, click on the icon named "offsite" that can be found below the Help menu, following the "P" icon. We will **define an offsite receiving body** by clicking on the "insert" button to add an offsite receiving body. We will input a name for the receiving body. In this case, we name it "Offsite". Then we define the offsite receiving body hydrograph in the bottom of the window. We will input a pair of time (in hours) and water stage (in feet NGVD). We assume that this offsite has a constant water stage level. At hour 0, the stage is 2 feet. At hour 4000, it remains the same. This offsite is defined to simulate the ocean, whose stage level does not change within a few days.



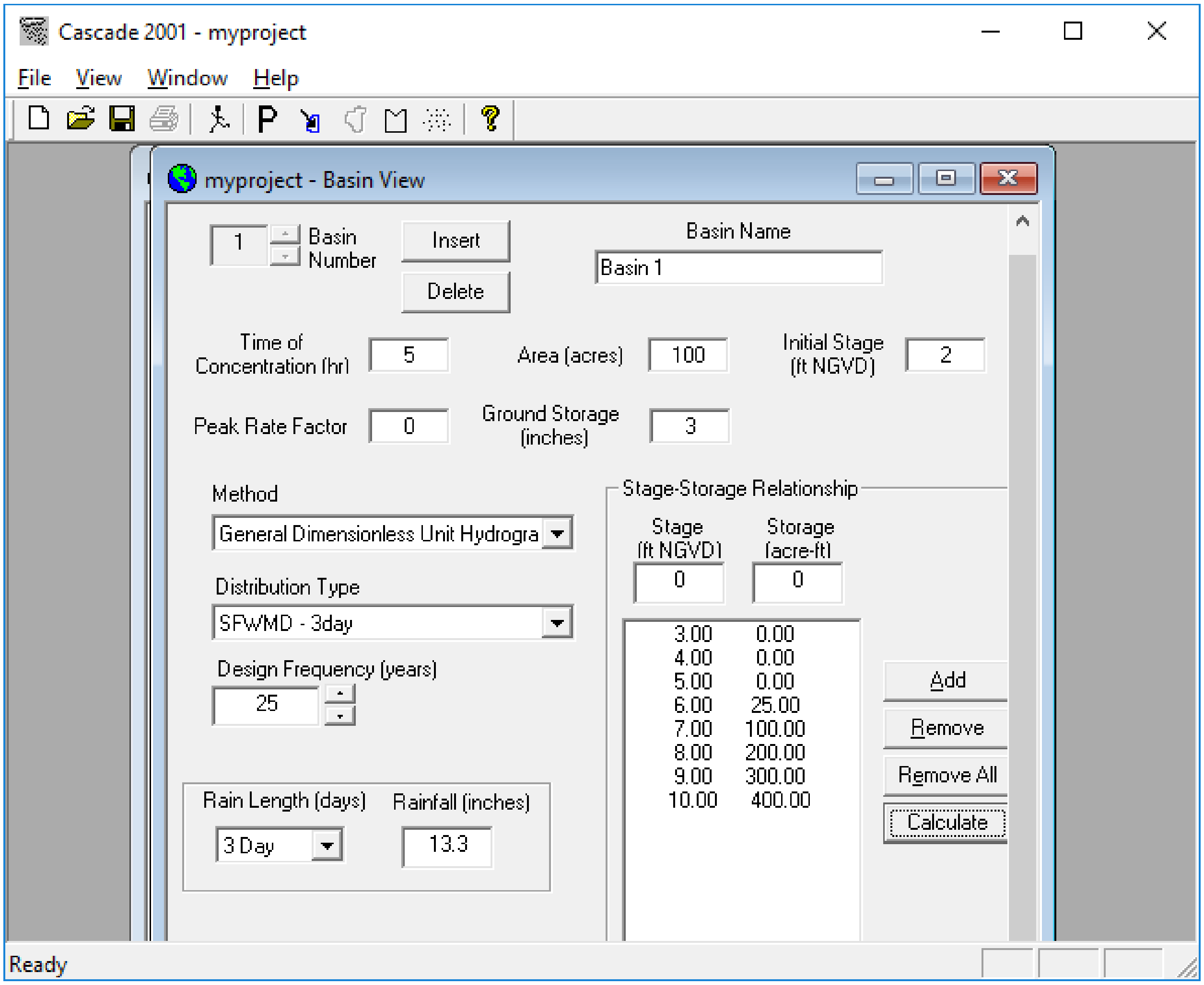
Then the basins are defined by clicking on the icon named "basin" next to the "offsite" icon below the Help menu. Create and **define a new basin** by clicking on the "insert" button. In this example, the basin has an area of 100 acres, and the initial ground water stage level is 2 feet. The basin is given a name "Basin 1". The longest time it takes the runoff to travel to the most distance point to reach the point of discharge is assumed to be 5 hours. This time can be calculated with the longest distance divided by the steady flow velocity.

The ground storage is estimated from the USDA gridded National Soil Survey Geographic Database (gNATSGO). The database was created by the USDA-NRCS Soil & Plant Science Division (SPSD), and the composite database provides complete coverage of the best available soils information for all areas of the United States and Island Territories. It was created by combining data from the Soil Survey Geographic Database (SSURGO), State Soil Geographic Database (STATSGO2), and Raster Soil Survey Databases (RSS) into a single seamless ESRI file geodatabase. The USDA soil database provides the available water storage (AWS) for a soil layer of 0-150 cm with a horizontal spatial resolution of 10 m. According to the Plant and Soil Science E-Library of the University of Nebraska-Lincoln (https://passel2.unl.edu/view/lesson/0cff7943f577/10), Water holding capacity refers to the amount of water held between field capacity and wilting point. Available water storage is the portion of the water holding capacity that can be absorbed by a plant. As a general rule, plant available water is considered to be 50% of the water holding capacity.

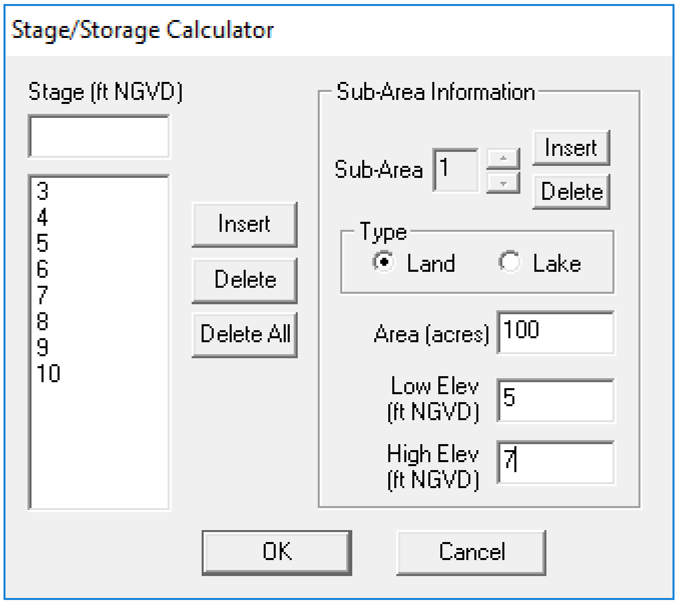
The average amount of precipitation that can be stored in the soil layer is calculated as follows:

$$\text{Ground storage} \approx \text{Water holding capacity} = 2 \times (\text{AWS for a soil layer of 0-150 cm})$$

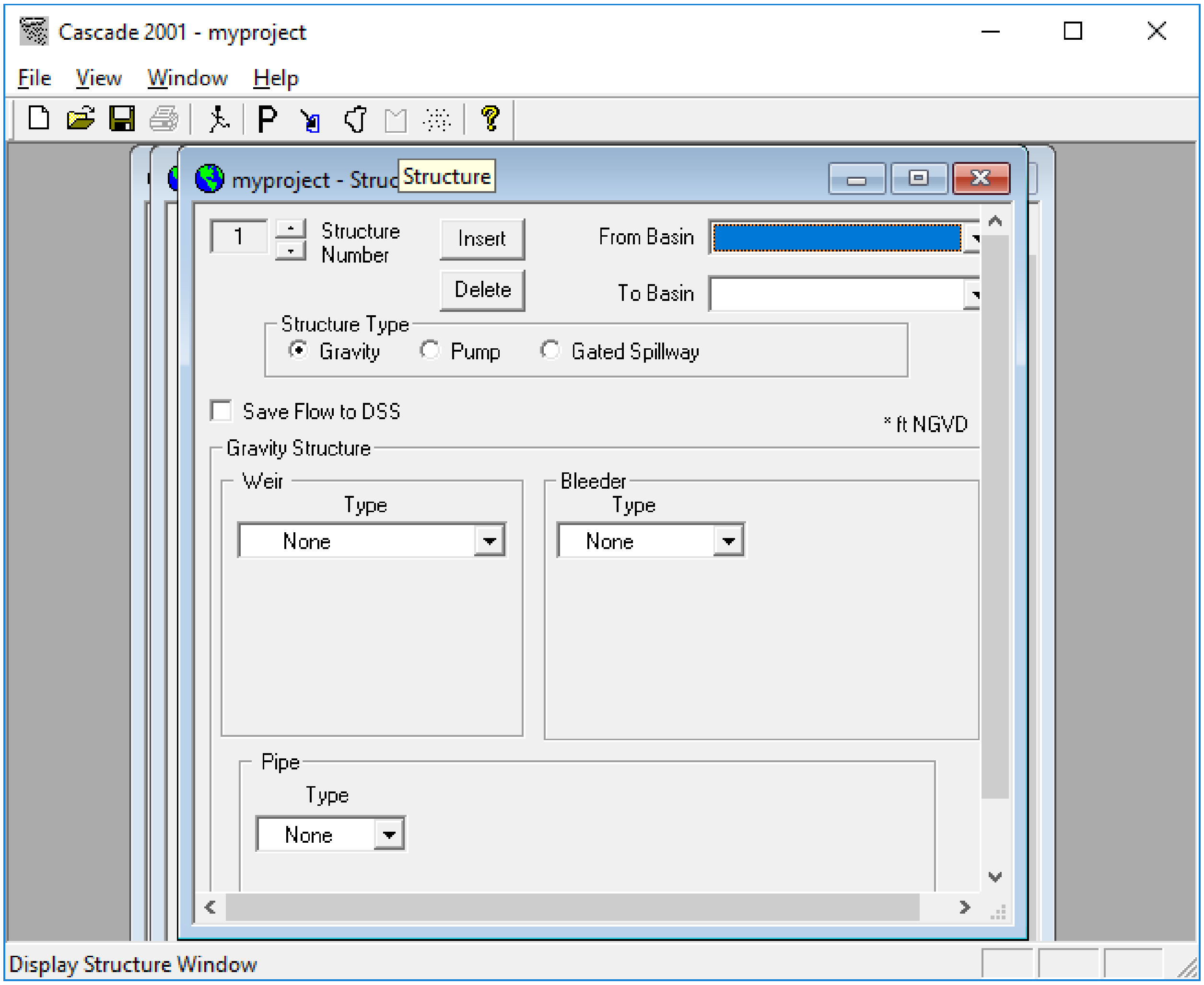
In this example, we use a value of 3 inches. For the unit hydrograph, we use the general dimensionless unit hydrograph. The distribution type uses SFWMD-3Day. The design frequency is assigned to be 25 years. The rain length is 3 days. The rainfall amount is obtained from the NOAA ATLAS 14 Point Precipitation Frequency Database hosted on the website at: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html We used the zip code to look up the rainfall of 3 days for a 25-year average recurrence interval.



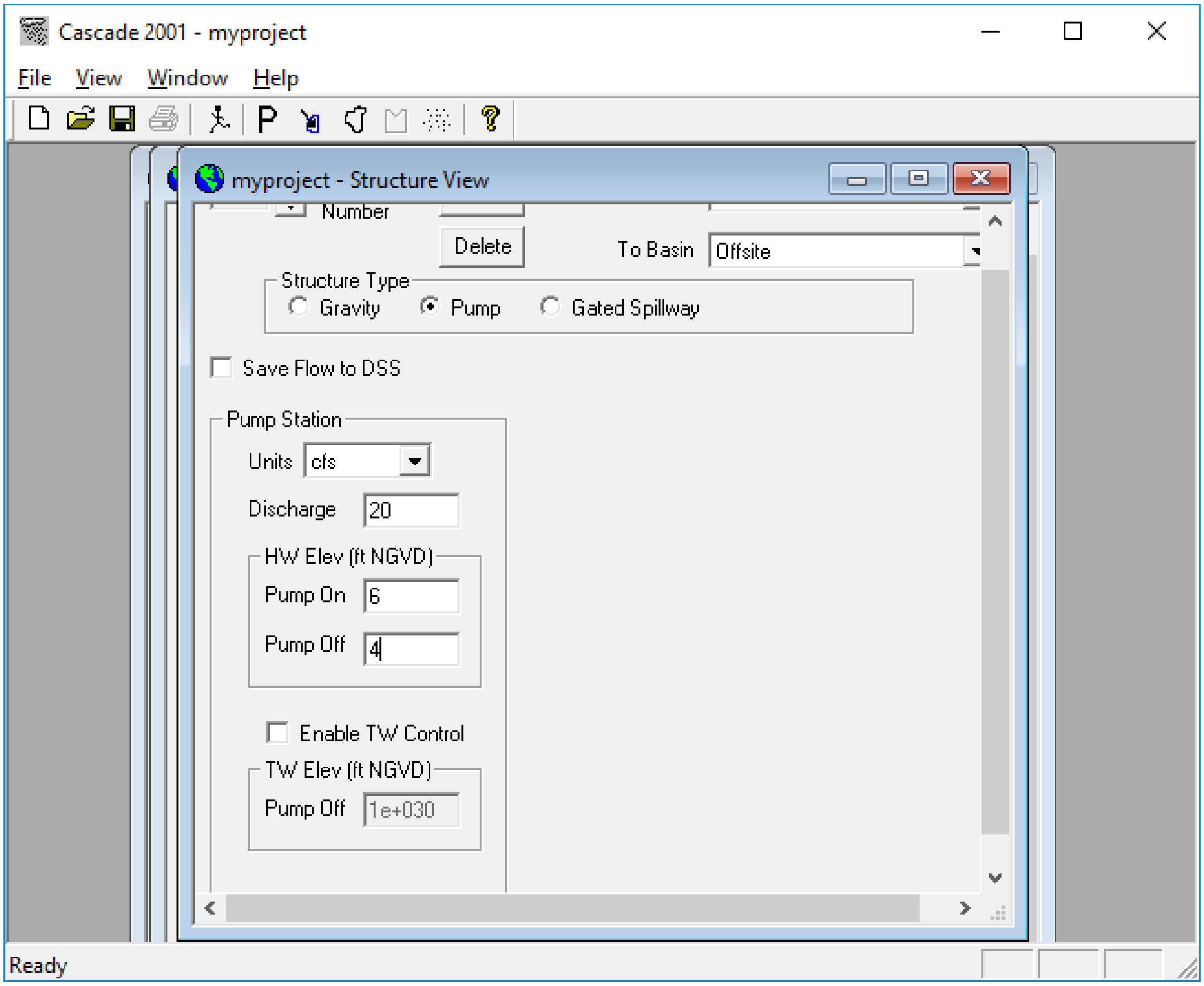
To define the stage-storage relationship, click on the "Calculate" button on the lower right corner of the dialog box window. The stage levels need to be inserted starting from the initial stage (ground water level) and increasing to an upper limit of elevation (local highest surface elevation plus rainfall amount) in feet. Then add the sub-area of land or water and provide the lowest and highest elevation of the land. Then click OK in the window of the stage-storage relationship calculator.



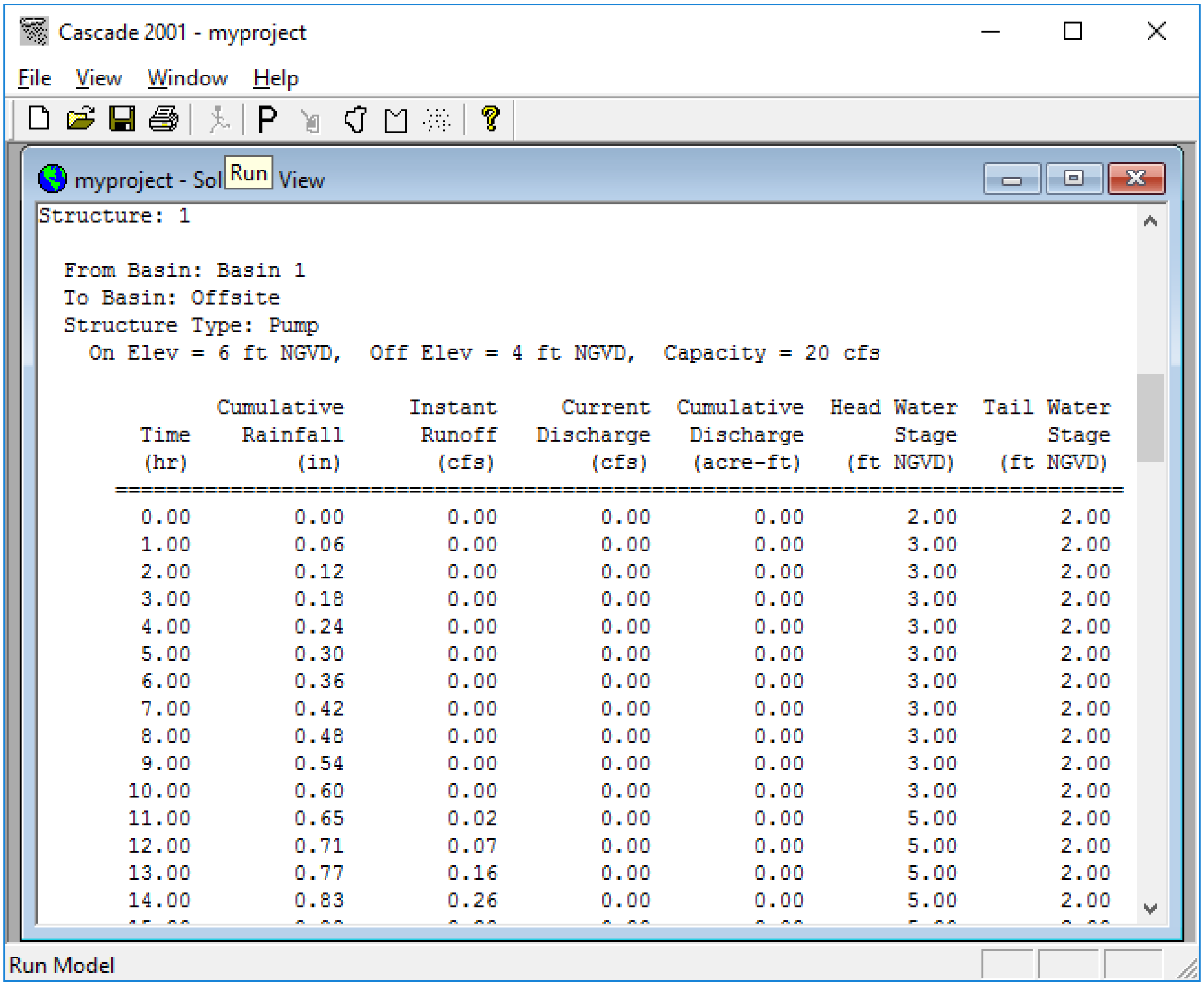
Next, click on the icon named "structure" will bring up the stormwater infrastructure dialog box.



Click on the "Insert" button. There are three types of structures available, a) gravity, b) pump and c) gated spillway. Choose the connections of the structure in the upper right of the window. In this example, we choose a pump structure, connecting Basin 1 and the Offsite receiving body. For the pump, we need specify the discharge rate and the unit, also the head water elevation to trigger a turn-on or a turn-off of the pump, as follows.



The self-defined precipitation setting can be skipped. Now, with the project set-up completed, click on "Run". After the simulation is finished, the output window named "myproject – Solution View", will appear. The output can be printed to a pdf document by clicking on the printer icon.

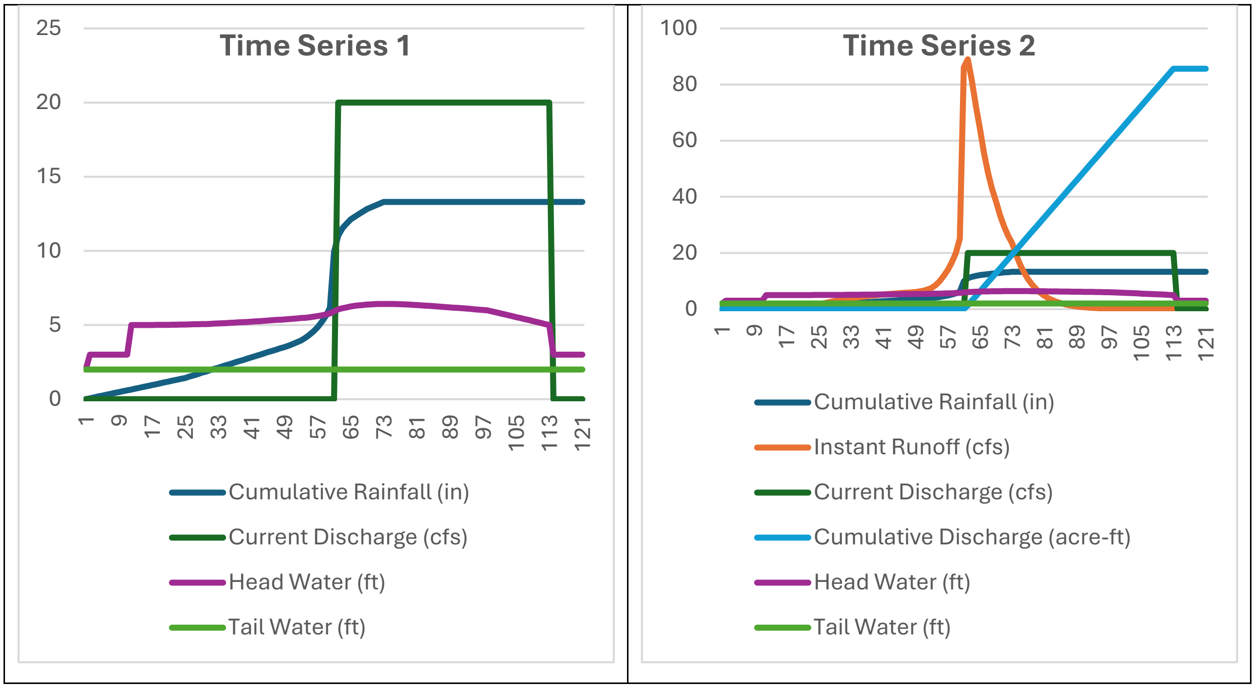


Structure: 1

From Basin: Basin 1
To Basin: Offsite
Structure Type: Pump
On Elev = 6 ft NGVD, Off Elev = 4 ft NGVD, Capacity = 20 cfs

Time (hr)	Cumulative Rainfall (in)	Instant Runoff (cfs)	Current Discharge (cfs)	Cumulative Discharge (acre-ft)	Head Water Stage (ft NGVD)	Tail Water Stage (ft NGVD)
0.00	0.00	0.00	0.00	0.00	2.00	2.00
1.00	0.06	0.00	0.00	0.00	3.00	2.00
2.00	0.12	0.00	0.00	0.00	3.00	2.00
3.00	0.18	0.00	0.00	0.00	3.00	2.00
4.00	0.24	0.00	0.00	0.00	3.00	2.00
5.00	0.30	0.00	0.00	0.00	3.00	2.00
6.00	0.36	0.00	0.00	0.00	3.00	2.00
7.00	0.42	0.00	0.00	0.00	3.00	2.00
8.00	0.48	0.00	0.00	0.00	3.00	2.00
9.00	0.54	0.00	0.00	0.00	3.00	2.00
10.00	0.60	0.00	0.00	0.00	3.00	2.00
11.00	0.65	0.02	0.00	0.00	5.00	2.00
12.00	0.71	0.07	0.00	0.00	5.00	2.00
13.00	0.77	0.16	0.00	0.00	5.00	2.00
14.00	0.83	0.26	0.00	0.00	5.00	2.00

The pdf document can then be converted to a text file, which can be imported to excel. In this example, the highest water level in the basin is found to be 6.42 ft. Two plots were created in Excel to show the time series of hydrologic responses of the 3-day rainfall event.

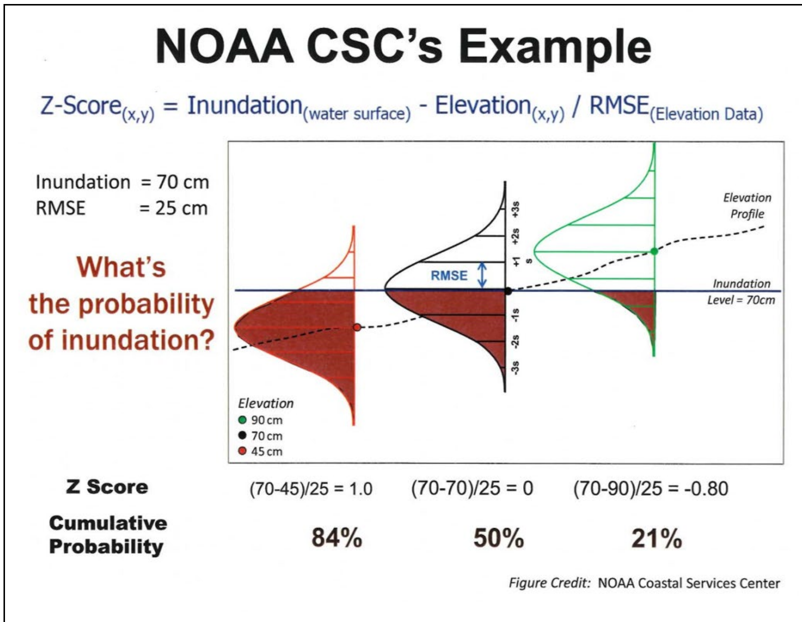


The goal of this methodology is to produce a spatially-temporally quantified understanding of nuisance-destructive flood potential in the area given observed values. "Risk," then, is a function of compounding geo-hydrological features, namely, surface water, groundwater, tides, topography, and time of year. A GIS-based algorithm and kriging spatial interpolation will produce layers of the highest observable hydrographic surfaces. These outputs can then be compared with the high-resolution topographic models informed by LiDAR to develop digital elevation models that reflect the observed risk landscape. These models can then be combined into CASCADE to produce vector and volume information, in combination with soils, vegetation, and percent impervious surfaces, allowing the observed model outputs to be extrapolated into a more predictive context. Comparative hydrographs can be created.

The initial goal for vulnerability maps was to highlight areas that are "Vulnerable," "Potentially Vulnerable," or "Less Vulnerable," using the USACE definitions. The same issues that apply to repetitive loss maps could be questions for vulnerability since the screening tool will focus on a tile level of 3 m × 3 m to accurately identify parcels that are vulnerable to flooding. As a result, the team suggests a modified approach that still involves using the high-resolution elevation DEM data layer and predicted headwater height such that flood risk would be defined as the probability of inundation based on ground elevation data. An advantage of this approach compared to simple bathtub mapping is that it takes into consideration the vertical accuracy error in the elevation datasets, which may vary depending on the available spatial resolution from the data. The uncertainties associated with the DEM vertical accuracy estimated depths to the groundwater table, and the modeling approach itself are incorporated in the RMSE computation as follows.

$$\text{SQRT}(\text{RMSE\_LidaDEM}^2+\text{RMSE\_CRT2001Model}^2)$$

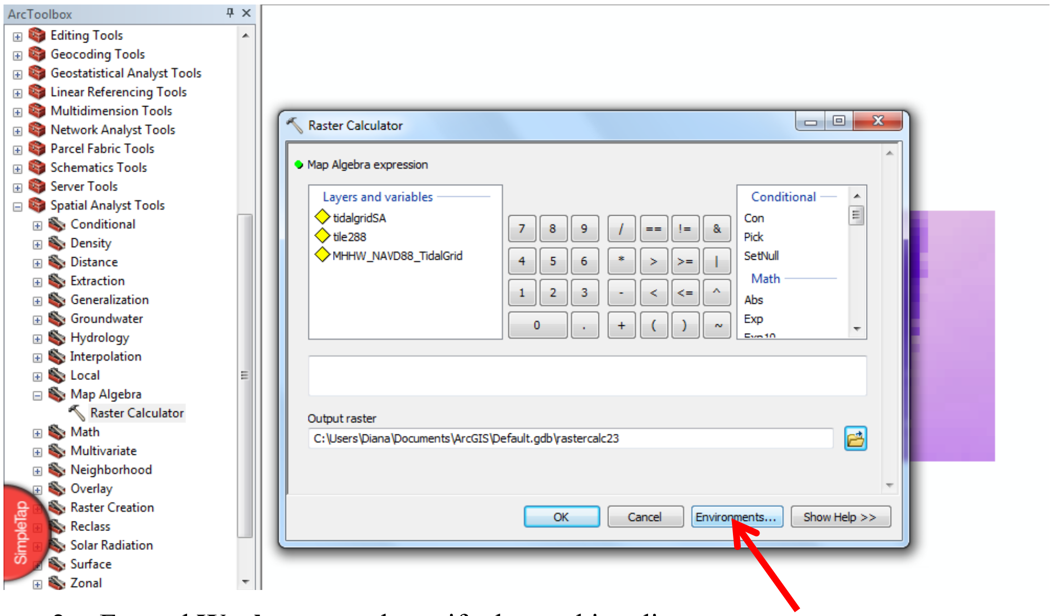
For purposes of this example, we will use the value suggested by NOAA for the compact counties coastal vulnerability assessments which is 0.46 to compute a z-score surface:



Confidence Level	**z*– value**
75%	**0.675**
80%	1.28
90%	1.64
95%	**1.96**
98%	2.33
99%	2.58

The steps to accomplish this are as follows:

1. Open the ArcToolbox and click on **Spatial Analyst Tools** > **Map Algebra** > **Raster Calculator (double-click)**



2. Expand **Workspace** and specify the working directory.
3. Expand **Processing Extent** and specify **Intersection of Inputs**
4. Expand **Raster Analysis** and specify **Cell Size** -> **Minimum of Inputs**
5. In the **Map Algebra** window enter the following equation:

Probability of Inundation=Standard_Normal_CDF(Z-Score) Z-Score=[(high headwater height)-(Ground Elevation from LiDAR DEM)]/ SQRT(RMSE_LidaDEM^2+RMSE_CRT2001Model^2) = ((Headwater Height –LIDAR DEM Elevation)/ 0.46

Note: The denominator in the equation (0.46) is the combined effect of the Root Mean Square Error (RMSE) in both the LiDAR and tidal grid datasets.

A z-score surface is now created from which the probabilities of inundation can be derived. The **value** of **z for the 75th percentile** is 0.675. Thus, the **75th percentile** is 0.675 standard deviations above the mean. The results will be manually classified into 3 buckets with cutoff points -0.675, 0.675, and [highest value] for color coding as follows.

- [No Color]. Unlikely to be Flooded (<50% Probability). Values that are **-0.675** and below
- [Light Green]. Likely to be Flooded (50-75%). Values that are between **-0.675** and **0.675**
- [Blue]. Certain to be Flooded with Greater than 75% Probability, Color-code values that are above **0.675**

An example is shown in Figure 58.

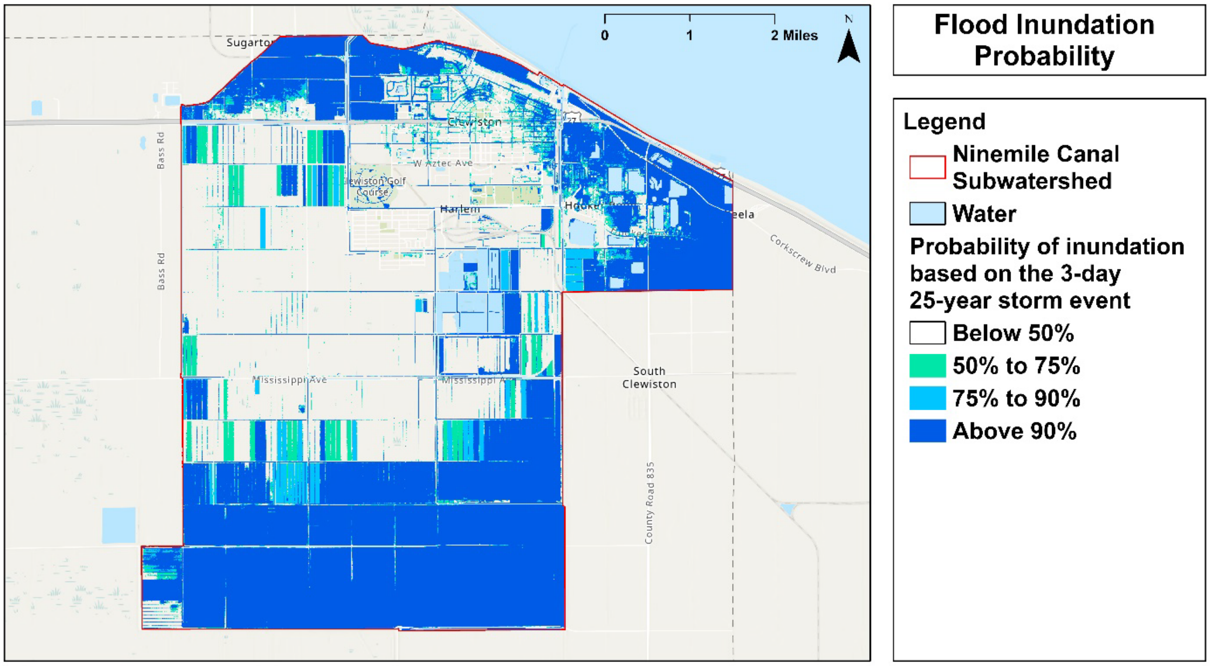


Figure 58. Example of a flood output from CASCADE 2001 for the Caloosahatchee East/Clewiston subwatershed, as processed by FAU

3.4 Challenges To Modeling

King tides in Florida typically happen within the same time each year between the months of September and November. This happens to coincide with the end of the wet season and the height of the hurricane season. This means that groundwater-related flood risks are greatest at this time, and generally speaking, rainfall and tidal influences on groundwater are most correlated at this time and can be quantified indirectly through observable groundwater levels alone. However, since this is an observation driven modelling effort with spatially explicit implications, discrete, observational values of groundwater, surface water, rain, tides, etc. are also required to inform a spatial model.

In the future, coastal areas may see increased flood risk due to increasing sea levels, so inundation predictions are affected in three ways: 1) directly, 2) indirectly from rising groundwater levels, and 3) indirectly from the inability of inland areas to drain. Soil storage may be limited because the coastal aquifer levels may be just below the surface in the wet season. It is this limited soil storage that can lead to flooding, necessitating extensive drainage works to facilitate discharge of larger volumes of water during the wet season.

In other areas, groundwater and surface waters are not connected because the groundwater is far deeper than surface water features. In low-lying coastal areas, there is the combination of a high groundwater table, king tides, heavy rains, and impervious conditions that can lead to localized nuisance flooding events that may be difficult to predict. In coastal areas with topography, groundwater may be connected along the coast and flow-ways. A third condition is where the ground and surface water levels are not related in any way. Another assumption relates to the boundary conditions of the spatial model. In the southeast Florida corridor, the boundary conditions, east and west, may be limited due to a paucity of data, by a lack of spatial dispersion (a lack of wells) or a lack of temporal dispersion to the east. In some regions of Florida, the groundwater monitoring well density is not spatially uniform or spatially extensive. Some key areas like the Keys and the Everglades have limited (if any) well coverage. Spatial interpolation using a stochastic variance-dependent interpolation (e.g., Ordinary Kriging) can be used to estimate groundwater levels at points of interest or for the generation of the surface. A subset of available data is used for the creation of validation dataset and the rest of the data is used for calibration (i.e., estimation of parameters of the interpolation model). Where the coast is present, the coast is used as a constant head boundary. For regions with spatially sparse or non-uniform groundwater wells, the groundwater levels are estimated using a multiple linear regression approach from auxiliary variables in addition to the limited ground well observations in a watershed. The watershed scale does not permit detailed analysis down to the level of a bridge culvert from the current data sets due to spatial extent. Low resolution LiDAR limits the interpretability of results; however, some assumptions can still be made by simply comparing tidal and rain influences on observed flooding events. Data must be in the same datum (the data used here is NAVD88) and units (ft). Spatially explicit rainfall data (NeXtRAD) and storm surge input are needed, but the records are lacking for some areas of the State.

Outliers (very high or low groundwater levels attributed to a variety of reasons) are noted at several sites. Outliers and anomalous groundwater levels in the database are initially evaluated, identified, and if found to be faulty, are replaced by region-specific mean values based on observations available from the nearest well. Missing data is also an issue at some monitoring wells. Missing date-specific data are estimated using simple temporal interpolation based on observations available in time. If a station (or monitoring well) data contains large amounts of missing data, it is not used in the generation of the groundwater surface.

FEMA relies on communities to provide notification of changing flood hazard information and to submit the technical support data needed to reflect the updated flood hazards. Although revisions may be requested to change any of the information presented on the maps, FEMA generally will not revise an effective map unless the changes involve modifications to Special Flood Hazard Areas (1% annual chance floodplains or flood elevations). Requests for revisions that involve other information (e.g., roads or corporate limits) will typically be filed for future use.

3.5 Impact Adjustment Map

An impact adjustment map is used to determine how much of the community's Special Flood Hazard Area (SFHA) is affected by a CRS-credited activity or element. There are 5 components to the impact adjustment mapping process:

1. Impact adjustment base map (Activities 410, 420, 430, and 440)
2. Impact adjustment for open space (Activity 420)
3. Other impact adjustments based on area (Activities 410, 420, 430, and 440)
4. Impact adjustments based on buildings (Activities 310, 520, 530, 610, 620, and 630)
5. Impact adjustments based on watershed area (Activity 450)

To calculate an impact adjustment, the total area of the floodplain or the total number of buildings in the floodplain must be determined (this is the denominator), and then the area or number of buildings that are affected by the activity must be determined (this is the numerator). The impact adjustment is a ratio from 0 to 1. For example, if a community has preserved 50 acres of its 250-acre SFHA, then the impact adjustment is $50 \div 250 = 0.2$ or 20%. The community will then receive 20% of the maximum credits for the activity of preserving open space. The base map has the corporate limits of the community showing all SFHA on the most current Flood Insurance Rate Map (FIRM).

Next, the areas to be excluded from SFHA must be marked out to make sure the denominator accurately reflects the area of the SFHA that is subject to development and also under the community's jurisdiction. The community is not held responsible for areas shown as SFHA on the FIRM that cannot be developed because they are under water or are beyond the community's authority to regulate because they are considered federal, tribal, or state land. A community generally has no authority over state land, but because the CRS credits state activities in a community, if the community would receive more credit by counting state land, it can keep state lands as part of the SFHA.

The following must be marked on the map:

- Waterbodies in the SFHA that are larger than 10 acres. This includes lakes, reservoirs, and river channels, but does not include wetlands, which are not considered waterbodies.
- Federal and tribal lands in the SFHA that are larger than 10 acres.
- State lands in the SFHA that are larger than 10 acres (differentiate state open space vs. all other state-owned property)

3.6 Repetitive Loss Properties Map

The repetitive loss properties maps are collected by zip code, as point locations. FEMA repetitive loss maps for 2010 to 2014 were used to verify the accuracy of the flood risk maps developed in this study.

Issues noted:

- The data cannot be released or used in its current form for privacy reasons as it would specify specific properties in violation of federal privacy laws.

Solutions:

- The data may be mapped as shapes such that point files are replaced with hotspots to create a kernal density map versus a vulnerability map.

3.7 Toolbox Options

Table 22 outlines potential options for communities to pursue to address flooding challenges. Included are options with benefits and limitations. For sea level rise, hard infrastructure is far more successful than green solutions. However, communities may have biases against hard solutions due to maintenance needs. These are community-specific discussions.

Table 22. Summary of benefits, costs, and barriers for each of the engineering alternatives in the toolbox

Strategy Class	Implementation Strategy	Applications	Benefits	Cost	Barriers to Implementation
Green	Bioretention planter	Local, small scale, easily implemented in developed areas	Protects property, treats runoff	$2500 ea	Limited volume disposed of, so many are needed, maintenance
Green	Tree box filter	Local, small scale, easily implemented in developed areas	Protects property, treats runoff	$2500 ea	Limited volume disposed of, so many are needed, maintenance
Green	Rainwater harvesting	Local, small scale, easily implemented in developed areas	Protects property, treats runoff	Under $5,000	Limited volume disposed of, so many are needed, maintenance
Green	Vegetated roof	Specific to a building, absorbs water, reduces runoff	Protects property, treats runoff	$100/sf	Requires irrigation if insufficient rainfall occurs Requires runoff control if too much rainfall occurs
Green	Bioswale	Parking lots, runoff from development - primarily treatment for discharge to another system	Protects property, treats runoff	$20K/ac	Maintenance, limited volume disposed of, used mostly for treatment
Gray	Pervious paving	Parking lots, patios, driveways, anything except paved roads due to traffic loading	Reduces roadway and parking lot flooding	$10-20/sf, requires bumpers and sub-base to maintain paver integrity	Must be maintained via vacuuming or the perviousness fades after 2-3 years
Green	Detention	Common for new development, but difficult to retrofit; limited to open areas	Removes water from streets, reduces flooding	$200K/ac	Land availability, maintenance of pond, discharge location Uses up land that could otherwise be developed
Green	Vegetated wall	Used on walls of buildings and retaining walls	Protects property, treats runoff	$30/sf	Requires irrigation if insufficient rainfall occurs Requires runoff control if too much rainfall occurs

Strategy Class	Implementation Strategy	Applications	Benefits	Cost	Barriers to Implementation
Gray	Exfiltration Trench	Any low-lying area where stormwater collects and the water table is more than 3 ft below the surface; densely developed areas where retention is not available, roadways	Excess water drains to aquifer, some treatment provided	$250/ft	Significant damage to roadways for installation, maintenance needed, clogging issues reduce benefits
Green	Dry Swale	Parking lots, runoff from development - primarily treatment for discharge to another system	Protects Property, treats runoff	$200K/mi	Maintenance, limited volume disposed of, mostly for treatment
Green	Retention Ponds	Common for new development, but difficult to retrofit; limited to open areas	Removes water from streets, reduces flooding	$200K/ac	Land availability, maintenance of pond, discharge location Uses up land that could otherwise be developed
Green	Rain Gardens	Local, small scale, easily implemented in developed areas	Protects property, treats runoff	$20K/ac	Limited volume disposed of, so many are needed, maintenance
Gray	Infiltration Trench	Low lying areas that collect stormwater, but the water table is just below the surface meaning that retention and exfiltration trenches will not work properly	Excess water is drained to pump stations, creating soil storage capacity to store runoff, soil treatment	$250/ft plus pump station	Significant damage to roadways for installation, maintenance needed, clogging issues - must discharge somewhere (pump station, detention pond)
Green	Oversized pipes	Local solution - not watershed level, holds water to reduce flooding	Protects property and roadways	$350/ft of more	Sediments, maintenance needs, lack of means to flush, cost
Gray	Central sewer installation	All areas where there are septic tanks. Mostly a water quality issue	Public health benefit of reducing discharges to lawns, canals, and groundwater from septic tanks	$15,000 per household	Cost, assessments against property owners, property rights issues
Green	Filter strips	Localized	Protects property, treats runoff	$50K/mi	Does not address flooding, treatment/water quality measure

Strategy Class	Implementation Strategy	Applications	Benefits	Cost	Barriers to Implementation
Green	Flood prone property acquisition	Regional agency - could be any low-lying areas	Removes flood prone areas from risk	$2K-$100K/ac depending on whether it is already developed	Difficult to implement if occupied, issues with willing sellers, cost, lack of funds for acquisition
Gray	Class I injection wells	Any low-lying area where stormwater collects, and there is sufficient land to permit, install and operate a Class I well - limited	Means to drain neighborhoods - potentially large volumes	$3-6 million depending on size/depth	Needs baffle box, injection zone may not be available, requires a permit, may compete with water users
Green	Underground storage	Common for new developments, but difficult to retrofit	Storage of excess runoff from rainfall, can be used for irrigation, can sit under parking lots, unobtrusive	$2/gal	If the tank is full, there is no storage
Green	Constructed wetlands	Where there is low lying flood prone land that can be converted into wetlands	Reduces flooding by providing a low-lying area for water to go	$200-$1M/ac	Water quality, permitting, monitoring costs, maintenance
Gray	Pump stations	Any low-lying area where stormwater collects, and there is a place to pump the excess stormwater to such as a canal; common for developed areas	Removes water from streets, reduces flooding	Start at $1.5 to 5 million each, number unclear without more study	NPDES permits, maintenance cost, land acquisition, discharge quality
Gray	Armored sewer systems	Any area where gravity sanitary sewers are installed	Keeps stormwater out of sanitary sewer system and reduces potential for disease spread from sewage overflows	$500/manhole	Limited expense beyond capital cost

Strategy Class	Implementation Strategy	Applications	Benefits	Cost	Barriers to Implementation
Gray	Raised roadways	Limited to areas where redevelopment is occurring areawide due to ancillary impacts on adjacent properties	Keeps traffic above floodwaters, access for emergency vehicles, commerce	$2 - 4 million/lane mile	Runoff, cost, utility relocation
Gray	Class V gravity wells	Any low-lying areas where stormwater collects and is located where saltwater has intruded the surficial aquifer beneath the site	Means to drain neighborhoods, limited volume	$250K each	Needs baffle box, limited flow volume (1 MGD), zone for discharge may not be available, permits, water supply wells
Gray	Canals	Limited	Means to drain neighborhoods, provides treatment of water	$2 million/mile	Land area, flow volume, maintenance, ownership, capacity issues due to sea level rise pressure
Green	Aquatic zones	Any low-lying or flood-prone area that is undeveloped and can store large volumes of water	Place to store large volumes of water	$200K/ac	Must be maintained, cost, impact on property owners
Gray	Levees	Regional issue - along rivers, lakes, impoundments	Protects widescale property	$ millions	Must be maintained, must be continuous, must be planned for extreme events (i.e. Hurricane Katrina showed that New Orleans planning horizon was not sufficient)
Gray	Lock structures	Regional (WMD) responsibility	Keeps seawater out, reduces saltwater intrusion	Up to $10 million, may require ancillary stormwater pumping stations at $2-5 million each	Permitting, private property rights arguments
Gray	Sea walls	Barrier islands and downtown coastal areas	Protects property	$1200/ft	Private property rights, neighbors

Strategy Class	Implementation Strategy	Applications	Benefits	Cost	Barriers to Implementation
Green	Polders	Barrier islands and downtown coastal areas	Provides storage for coastal waters	$200K/ac	Permitting, land acquisition
Gray	Surge barriers	Coastal communities – large footprint	Protects property	>$1B	Cost, open ocean access challenges, property rights
Green	Enhanced wetlands	Where there is an existing wetlands area that can be augmented	Reduces flooding by providing a low-lying place for water to go	$200-$1M/ac	Water quality, permitting, monitoring costs, maintenance, ecosystem impacts
Green	Revetments	Retention, helps maintain the storage volume, in conjunction with other measures	Improves walls of retainage	Varies based on material, depth, wall height	Land area, maintenance
Policy	Changes in land use	Applicable universally	Achieves flood risk mitigation by adjusting permitted land use	Low but may incur private property rights conflicts and litigation	Private property rights conflicts and litigation
Gray	Roadway base protection	Low-lying areas, coastal communities	Protects roads and access routes	$1 million per lane-mile	Cost, adjacent properties become uninsurable
Policy	Enhanced elevation of buildings	Developers would implement this for new construction	Reduced flood risk	Varies	Potential issues with building structure or latticework, and existing homes that are not elevated
Policy	Abandon land for development	Land that cannot be protected would be taken out of circulation	Reduced flood risk	Potentially $ billions, and loss of tax revenue for local governments	Potential issues with private property rights, potential high costs, lack of political will, and major reduction in the value of neighboring properties

4.0 EXAMPLES OF WATERSHED MASTER PLAN SOLUTIONS

Activity 420 - Open Space Preservation
2,020 Maximum Possible Points (2017)

The objectives of this activity are to prevent flood damage by keeping flood-prone lands free of development and to protect and enhance the natural functions of floodplains. Much of the credit for this activity comes from regulatory structures that restrict development, deeds, or building codes to reflect the ever-present hazards of floodways.

The CRS Coordinator's Manual summarizes the following list of criteria required to achieve credit for this activity:

> Credit is given for areas in a regulated floodplain that are permanently preserved as open space. Additional credit is given for parcels of open space that are protected by deed restrictions or that have been preserved in or restored to their natural state. Credit is also given for measures that require or encourage less development in floodplains, and for the protection of natural channels and shorelines.
>
> The first five elements provide credit for parcels that qualify as preserved open space. The credit can be based on development restrictions placed by the property owners or those found in local regulations.
>
> (1) Open space preservation (OSP) provides credit for keeping vacant lands vacant through ownership by a public agency, non-profit organization (such as a church camp), or restrictive regulations. To qualify, a property must be open, meaning there are no buildings, filling, or storage of materials.
> (2) Deed restrictions (DR) provides extra credit for ensuring that parcels credited for OSP will never be developed. This is done via a legal restriction that prevents subsequent owners from changing the use of the property.
> (3) Natural functions open space (NFOS) provides extra credit for parcels credited for OSP that are preserved in or restored to their natural state. There are bonus credits for additional attributes of the parcel.

Two elements provide credit for the protection of areas subject to special flood-related hazards and coastal erosion.

(4) Special flood-related hazard open space (SHOS) provides extra credit for OSP-credited parcels that are in areas subject to a special flood-related hazard.

(5) Coastal erosion open space (CEOS) credits a community for protecting areas most at risk from coastal erosion.

The next two elements credit local regulations that encourage minimal floodplain development.

(6) Open space incentives (OSI) credits a community for having requirements and/or incentives that keep flood-prone portions of new developments open through techniques such as density transfers.

(7) Low-density zoning (LZ) provides credit for zoning districts that require lot sizes of 5 acres or larger, resulting in fewer buildings constructed in the floodplain.

The eighth element credits programs that protect natural channels and shorelines. As with the first five elements, this credit can be based on shoreline protection practices put in place by public property owners or on protection requirements embodied in local regulations.

(8) Natural shoreline protection (NSP) credits programs that protect natural channels and shorelines, the areas most valuable for protecting the natural functions of floodplains. The programs can be local policies that are adhered to on public lands and/or regulations that govern development on private lands.

At the time of the verification visit, the ISO/CRS Specialist will review the documentation and visit a sample of the parcels in the field.

Activity 420 Case Study

The top three scoring communities were relatively urbanized coastal municipalities. However, we did manage to obtain a 2018 CRS verification report for the inland City of Ocala as a top-scoring community for this activity.

Ocala

CRS Score 3 (2019)

874 total points out of 2,020 in activity 420 (2018)

Ocala may have inherited some of their open space preservation value by virtue of being a small town where much of the flood hazard areas have already been preserved as national and state preserves. However, the municipality of Ocala has also made several notable regulatory contributions. Ocala has several ordinances that raise standards for development to maximize the preservation of adjacent open spaces as buffers and restrict certain types of development in key areas, especially SFHA. In addition, the complexities of these zoning regulations are disseminated and enhanced by a program for public information (PPI). To quote the 2018 CRS verification report for Ocala: “Credit is provided (for activity 420) for preserving approximately 50 percent of the Special Flood Hazard Area (SFHA) as open space and preserving open space land in a natural state. Credit is also provided for regulations and incentives that minimize development in the SFHA. Credit is enhanced by having a PPI. (874 points)”

Juno Beach

CRS Score 5 (2019)

773 total points out of 2,020 in activity 420 (2013)

Juno Beach has ordinances that limit and dictate the types and intensity of development along the coastal ridge, which is one of this community’s main SFHAs. The limitations and requirements of development in the Coastal Construction Control Line (CCCL) include everything from the necessary amount of setbacks for structures to the manner that pathways are constructed through beach dunes, to the types and numbers of plants required, to the landscaping practices with those planted areas.

West Palm Beach

CRS Score 5 (2019)

749 total points out of 2,020 in activity 420 (2013)

Similar to Juno Beach, West Palm Beach has ordinances that restrict and dictate how land adjacent to waterbodies are developed.

In addition, there are certain barriers to moving above a score of 9 or above a 6:

Activities that can increase a community’s points include (but are not limited to):

- Public outreach and flood preparedness programs
- Infrastructural and building code improvements
- Conducting floodplain mapping and higher-standard studies
- Enacting ordinances and permitting requirements to increase flood resilience

There are a set of pre-requisites that are needed to achieve certain rating scores:

- **Class 9:** There are six prerequisites to become and stay a Class 9 or better community. They include being in full compliance with the minimum requirements of the (NFIP), receiving credit for maintaining FEMA Elevation Certificates, and meeting repetitive loss criteria.
- **Class 6:** To become a Class 6 or better community, a community must have received a classification of 5/5 or better under the Building Code Effectiveness Grading Schedule.
- **Class 4:** To become a Class 4 or better community, a community must demonstrate that it has programs that minimize flood losses, minimize increases in future flooding, protect natural floodplain functions, and protect people from the dangers of flooding.
- **Class 1:** To become a Class 1 community, a community must have had a successful Community Assistance Visit conducted by FEMA within the previous 12 months and demonstrate that it has a "no adverse impact" program by receiving a certain number of points for designated activities.