Factors Contributing to Persistent Flooding in Northwest Florida: 2018 through 2022

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Water Resources Special Report 23-01
February 2023

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Resource Management Division

This report is the product of multiple individuals. Contributing authors include Katheen Coates, Kenneth Friedman, Jesse Gray, Trey Grubbs, Garrett Ifland, Katie Price, Paul Thurman and Paul Thorpe, with editorial assistance from Toni Devencenzi and technical review by Resource Management Division Director, Carlos Herd.

Suggested citation:

Northwest Florida Water Management District, 2023. Factors Contributing to Persistent Flooding in Portions of Northwest Florida: 2018 through 2022. Water Resources Special Report 23-01. 75 pp.

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List of Acronyms

AMO	Atlantic Multidecadal Oscillation
Cfs	Cubic feet per second
ENSO	El Niño Southern Oscillation
ET	Evapotranspiration
EVI	Enhanced vegetation index
FDACS	Florida Department of Agriculture and Consumer Services
ft	feet
HUC	Hydrologic Unit Code
IAS	Intermediate aquifer system
ICU	Intermediate confining unit
Km	Kilometers
NDVI	Normalized difference vegetation index
NLCD	National Land Cover Dataset
NAVD	North American Vertical Datum of 1988
NOAA	National Oceanic Atmospheric Association
NWFWMD	Northwest Florida Water Management District
NWS	National Weather Service
PRISM	Parameter-elevation Regressions on Independent Slopes Model
SAS	Surficial aquifer system
SSeBop	Simplified surface energy balance
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey

Executive Summary

From the fall of 2018 until the fall of 2022, persistent flooding affected residents across a substantial portion of northwest Florida. Affected areas include the Sand Hill Lakes region of Washington and Bay counties, the Bear and Bayou George Creek basins in Bay County, and the Wetappo Creek basin in Gulf County. The Sand Hill Lakes, situated within the Dougherty Karst Region, are predominantly internally drained. Bear and Bayou George creeks are tributaries of Deer Point Lake Reservoir, primarily receiving surface water runoff and surficial aquifer baseflow. Wetappo Creek, to the east, is a tidally influenced blackwater stream within the coastal plain of Gulf County. In Washington County, areas where flooding has been specifically reported include Piney Lake, Sand Lake, Wages Pond, Spring Pond, Radcliff Circle, and the Sunny Hills community in the vicinity of Gap Lake and Watering Lake. In Bay County, repeated flooding has been documented in the vicinity of Bear Creek and Bayou George Creek near U.S. Highway 231. In Gulf County, the Pleasant Rest community has been particularly impacted.

The purpose of this report is to provide an evaluation of the underlying causes and factors driving the flooding that has been experienced. This information is intended to increase understanding and assist in the development of both near-term responses and long-term planning and mitigation. It should be recognized that other regions of northwest Florida have also experienced increased flooding in recent years. This report, however, is focused on specific impacts and issues affecting the areas described.

This report is divided into four major sections:

Rainfall – Seasonal and annual rainfall patterns and trends are described, as are tropical storms and hurricanes that have affected the region. These patterns and events are placed within the context of multiyear climate cycles.

Changes in Land Cover and Evapotranspiration – Multiple sources of data and analytical techniques are applied to describe changes in land cover and evapotranspiration (ET) across the region.

Hydrogeology, Groundwater Levels, and Lake-Groundwater Interactions – The hydrogeology of the region is described, detailing interactions between groundwater systems and lakes and implications for flooding.

Stream Hydrology and Riverine Flooding – Trends and associations between rainfall, stream baseflow, and flooding are detailed for specific streams within the study area.

The primary factor driving the flooding experienced in each of the areas described has been rainfall. Beginning in 2013, the region experienced multiple years of above-normal precipitation. This was exacerbated by several major storm systems bringing extreme rainfall including Hurricane Michael, the period of December 2018 to January 2019, Hurricane Sally, and Tropical Storm Fred. Groundwater levels have risen accordingly, responding to the cumulative rainfall during this period. From 2015 through fall 2022, both rainfall and groundwater levels have reached and persisted at or near period-of-record highs. Stream baseflow and water levels of karst lakes have consequently remained high.

Compounding the effects of rainfall trends have been physical changes caused by Hurricane Michael. In October 2018, this hurricane brought intensely destructive winds that devastated forests across the region. Immense numbers of fallen trees and associated debris smothered stream channels and floodplains. This reduced the conveyance capacity of affected streams and raised stream stages for any given flow. For affected streams, both the magnitude and extent of flooding increased near stream channels and within and proximal to floodplains. The state of Florida removed more than 82,000 cubic yards of debris from Econfina Creek in 2019, and stage-flow relationships subsequently recovered to a more normal condition along much of this stream. Impaired conditions may persist, however, in other streams and stream reaches. Bay County reported that Bear and Bayou George creeks have been acutely impacted by debris, and Gulf County has expressed concerns that the same may be true for Wetappo Creek.

Another effect of Hurricane Michael on forestland was to convert, at least temporarily, large areas from trees to shrub and herbaceous cover. National Land Cover data indicate Hurricane Michael caused the loss of nearly 80,000 acres of evergreen forest and 28,000 acres of woody wetlands, resulting in lower evaporation rates during 2019 and 2020. Immediately following Hurricane Michael, ET rates decreased substantially in the hurricane impact zones. Forest losses were largely offset by increases in scrub/shrub and herbaceous vegetation by 2019. Similarly, ET partially recovered in most areas by 2021, likely associated with the growth of shrub/herbaceous cover and potentially forest regrowth. While declines in ET contributed to higher groundwater levels, thus indirectly contributing to flooding within areas impacted by Hurricane Michael, the magnitude of excess rainfall has had a greater contribution to flooding.

The Sand Hill Lakes region is inherently variable and dynamic with respect to both water levels and flows, and lakes are naturally subject to periodic inundation during wet periods and drying out during droughts. Close connection between the land surface and underlying aquifers and the coupled interactions between surface waters and groundwater are typical throughout much of the region. Flood risks are highest for the lowest lying properties adjacent to a waterbody. Most of the properties reporting flooding were lakefront properties or properties on or adjacent to wetlands at the lowest topographic elevations relative to levels of adjacent waterbodies. Antecedent rainfall, groundwater levels, the elevation of properties relative to adjacent water levels, lake bathymetric characteristics, the topographic slope near a lake's shoreline, and the proximity of areas of concern to the typical shoreline location may be the most important variables for predicting flooding in the Sand Hill Lakes region. Management and mitigation efforts are challenging given that water levels are highly variable and substantially driven by geology, climate, and cyclic weather across a large region.

1 Introduction

Pronounced and persistent flooding affected many residents across a substantial area of northwest Florida from the fall of 2018 until the fall of 2022. Areas affected include the Sand Hill Lakes region of Washington County, properties in the vicinity of Bear and Bayou George creeks in Bay County, and the Pleasant Rest community near Wetappo Creek in Gulf County (Figure 1-1). Flooding has also been reported in localized areas within Jackson, Calhoun, and Gadsden counties.

Within the Sand Hill Lakes region, flooding was documented in the vicinity of Piney Lake (Piney Pond), Sand Lake, Wages Pond, and Spring Pond (Figure 1-2). Additional affected areas include communities on Radcliff Circle and Rolling Pines Road in the vicinity of Sand Pond, as well as the Sunny Hills community in the vicinity of Gap Lake and Watering Lake. All the aforementioned areas are located within the White Oak Creek, Porter Creek, and River Lake sub-watersheds. Within the Bear Creek and Bayou George Creek watersheds, affected sites are in the vicinity of Bear Creek and Bayou George Creek, just east of US 231 (Figure 1-3). Structural flooding from Hurricane Sally has been documented by Bay County.

The purpose of this report is to provide an evaluation of the factors that have contributed to the recent flooding in northwest Florida. The analyses presented herein are focused on Gulf, Bay, and Washington counties, as these areas are where the most persistent recent flooding was reported. The report is organized into several sections. Section 1 provides an introduction, Section 2 provides a review and analysis of rainfall data, tropical events (storms and hurricanes), and long-term cycles in rainfall patterns. Section 3 provides analyses of changes in land cover resulting from Hurricane Michael, an analysis of evapotranspiration data, and changes in ET rates. Section 4 provides a description of the hydrogeology of the area, with a focus on the Sand Hill Lakes region, and discusses surface water-groundwater interactions and flooding near lakes. Section 5 provides an overview of stream hydrology and discusses flooding impacts near selected streams. Section 6 presents a summary of the findings.

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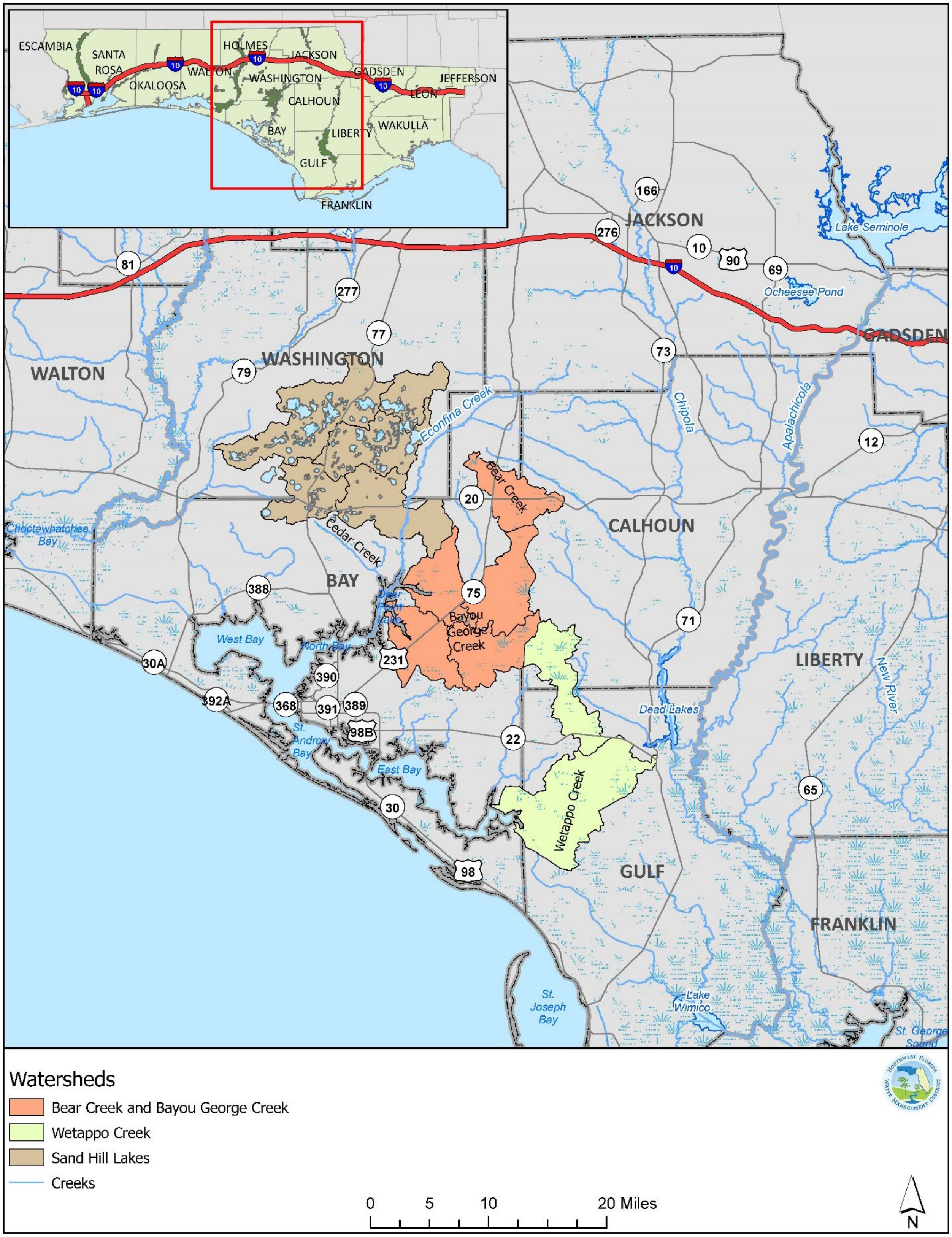

Figure 1-1. Affected watersheds in Bay, Gulf, and Washington counties: 2018 - 2022

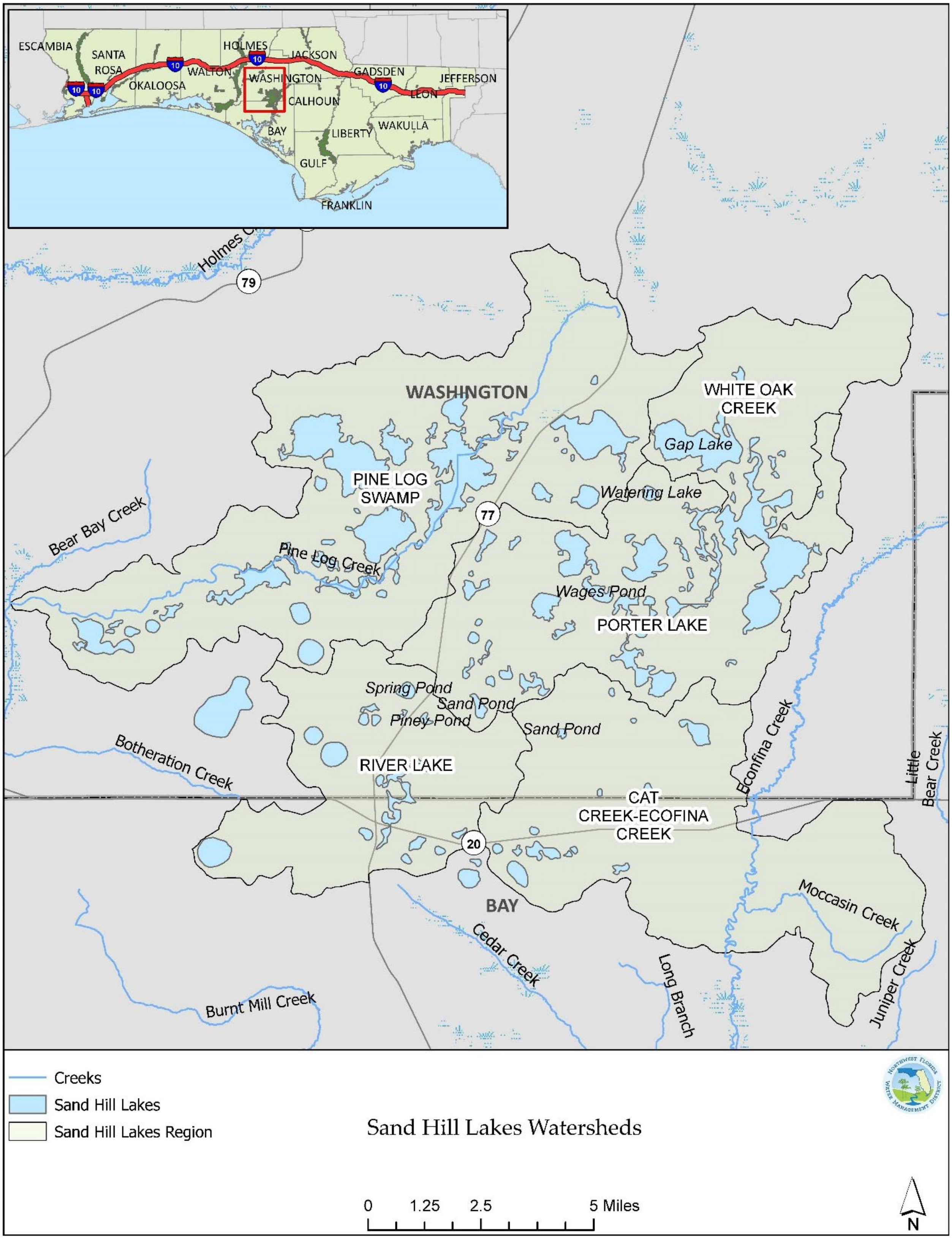

Figure 1-2. Sand Hill Lakes Watersheds

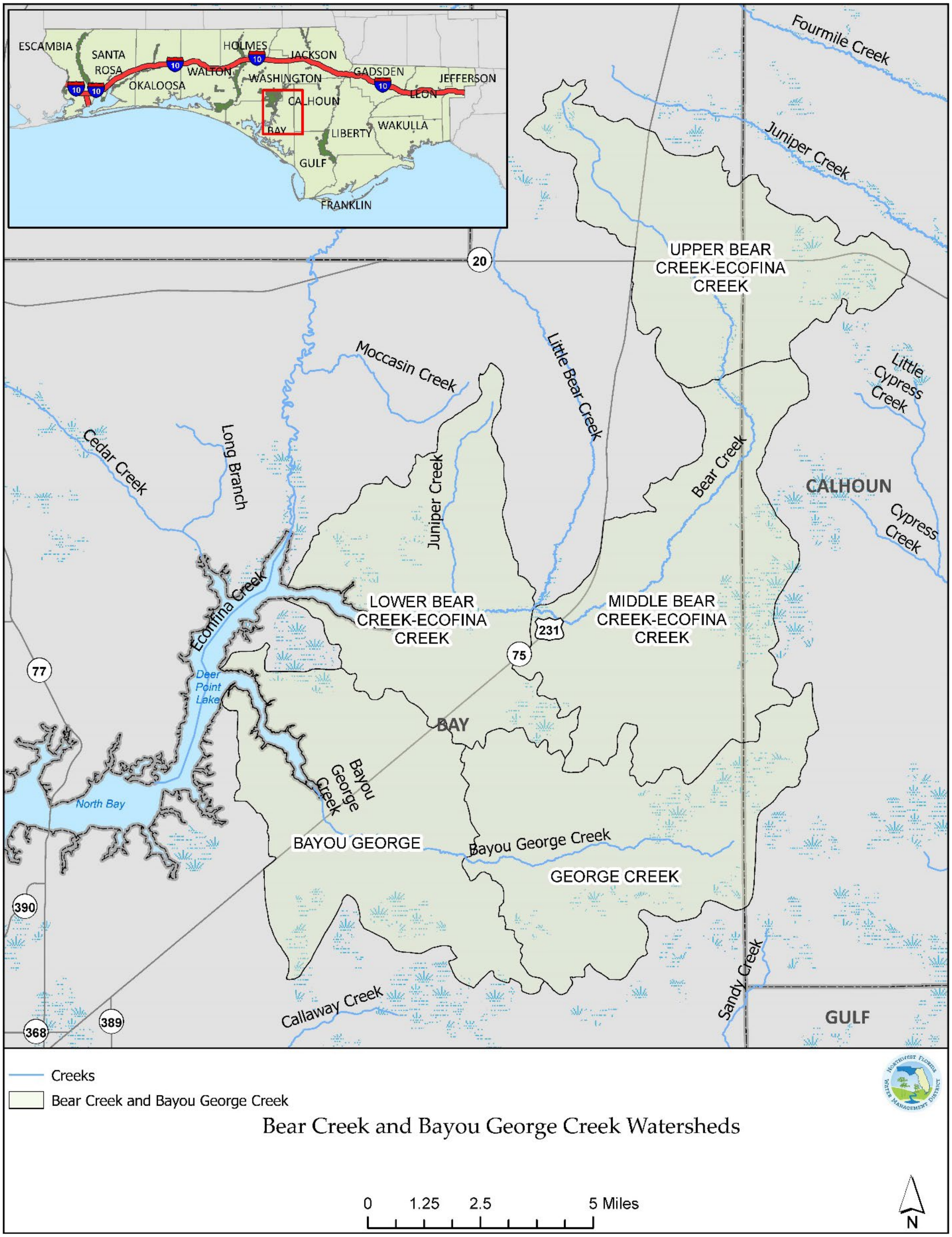

Figure 1-3. Bear Creek and Bayou George Creek Watersheds

2 Rainfall

Climatic patterns across northwest Florida are influenced by variables and processes acting across multiple spatial and temporal scales. Rainfall and evapotranspiration are the two largest components of the water budget and can directly or indirectly affect the risk of flooding. Rainfall can directly cause flooding when the amount of rainfall occurring within a given period exceeds the infiltration capacity of the soils, raises the water table to levels near or above land surface, or exceeds the conveyance capacity of a stream or other conveyance system. Rainfall can also indirectly contribute to flooding by increasing surface and groundwater levels and thereby decreasing the amount of storage available to prevent or attenuate flooding. The duration, intensity, and frequency of rainfall events can influence the likelihood of flooding and changes in any of these factors can increase or decrease the likelihood of flooding.

2.1 Seasonal and Annual Rainfall Patterns

Over the past decade, precipitation levels across Bay, Gulf, and Washington counties have remained high. Data from the PRISM Climate Group (2022) indicate that in eight of the last ten years, annual precipitation totals have exceeded the 30-year (1991-2021) precipitation normals in at least one of these counties (Figure 2-1). Additionally, these data indicate that during the past five years, each county recorded its highest yearly rainfall for the past three decades. Bay and Washington counties received their highest rainfall during the past thirty years in 2018. In that year, total annual rainfall in Washington County was 52 percent higher than its 30-year normal, and Bay County was 42 percent higher than its 30-year normal (Table 2-1). The rainfall total in Gulf County in 2021 was 37 percent higher than its 30-year normal, and higher than any other annual total estimated for the past three decades.

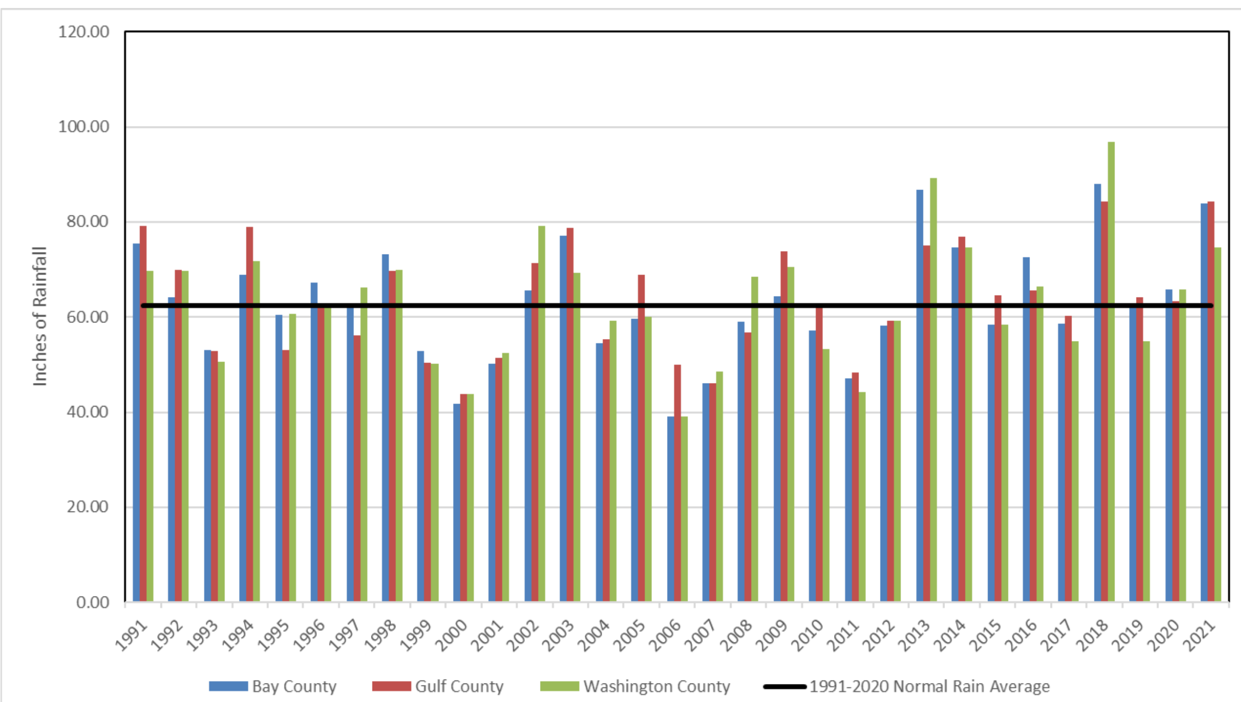

Figure 2-1. Average yearly PRISM rainfall totals for Bay, Gulf, and Washington counties

2. Rainfall

Table 2-1. Thirty-year precipitation normals and annual rainfall totals expressed as a percentage above or below the 30-year normals for the past five years in Bay, Gulf, and Washington Counties

	30-year Precipitation Normals, (1991- 2020) (inches)	2017	2018	2019	2020	2021
Bay County	62.07	-5.58%	41.87%	0.55%	6.14%	35.17%
Gulf County	61.43	-1.89%	37.18%	4.47%	3.18%	37.19%
Washington County	63.73	-13.88%	52.06%	-13.79%	3.38%	17.10%

There are two major rainy seasons in northwest Florida: a winter season characterized by frontal systems and a summer season characterized by convective storms with occasional tropical storms and hurricanes. A small peak in precipitation also typically occurs during March. Monthly 30-year normal precipitation totals for the combined areas of Bay, Gulf, and Washington counties are shown in Figure 2-2. For this analysis, the year was divided into a rainfall period extending from January through May and a second rainfall period extending from June through December. When examining total rainfall amounts for these two seasons during the past three decades, slight changes in seasonal precipitation emerge. Rainfall totals for the first five months of the year are trending slightly downward (Figure 2-3), while the rainy season totals for June through December (Figure 2-4) are trending upward.

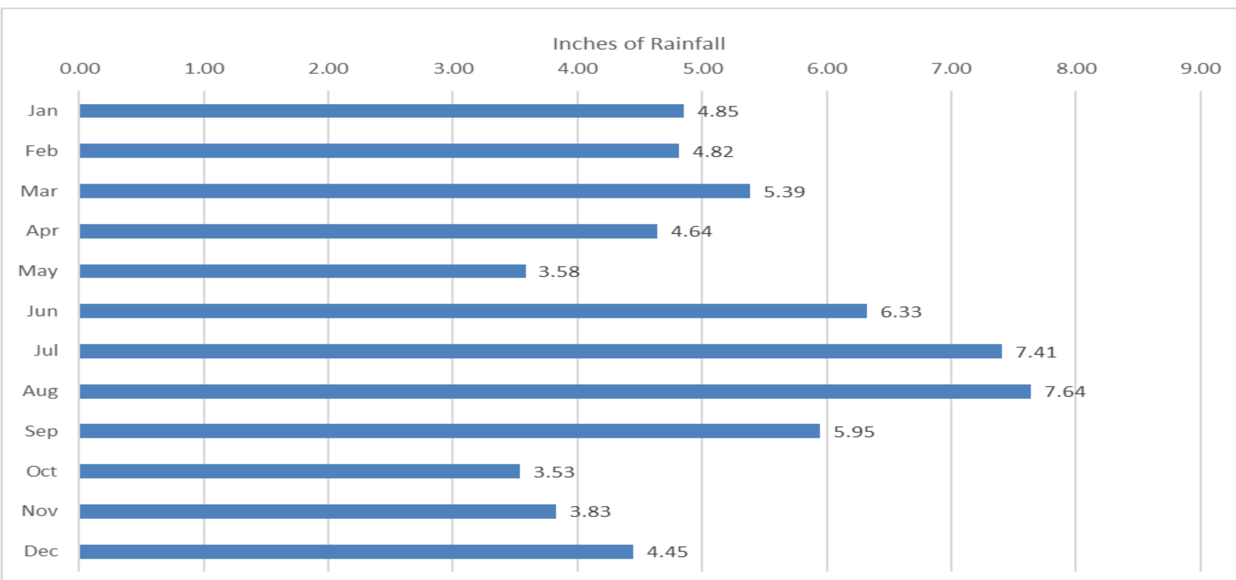

Figure 2-2. Monthly PRISM rainfall averages (1991-2020) for Bay, Gulf, and Washington counties

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2. Rainfall

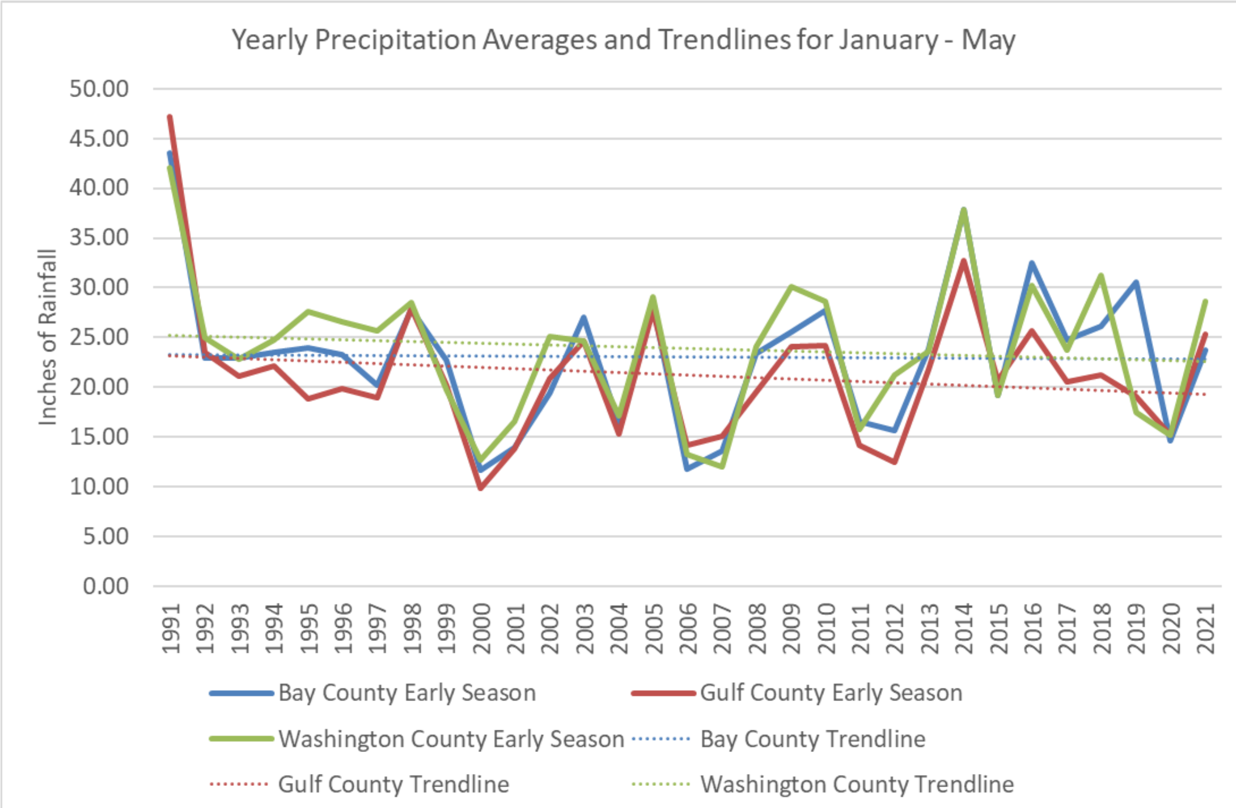

Figure 2-3. 1991 – 2020 yearly precipitation averages and trendlines, January – May

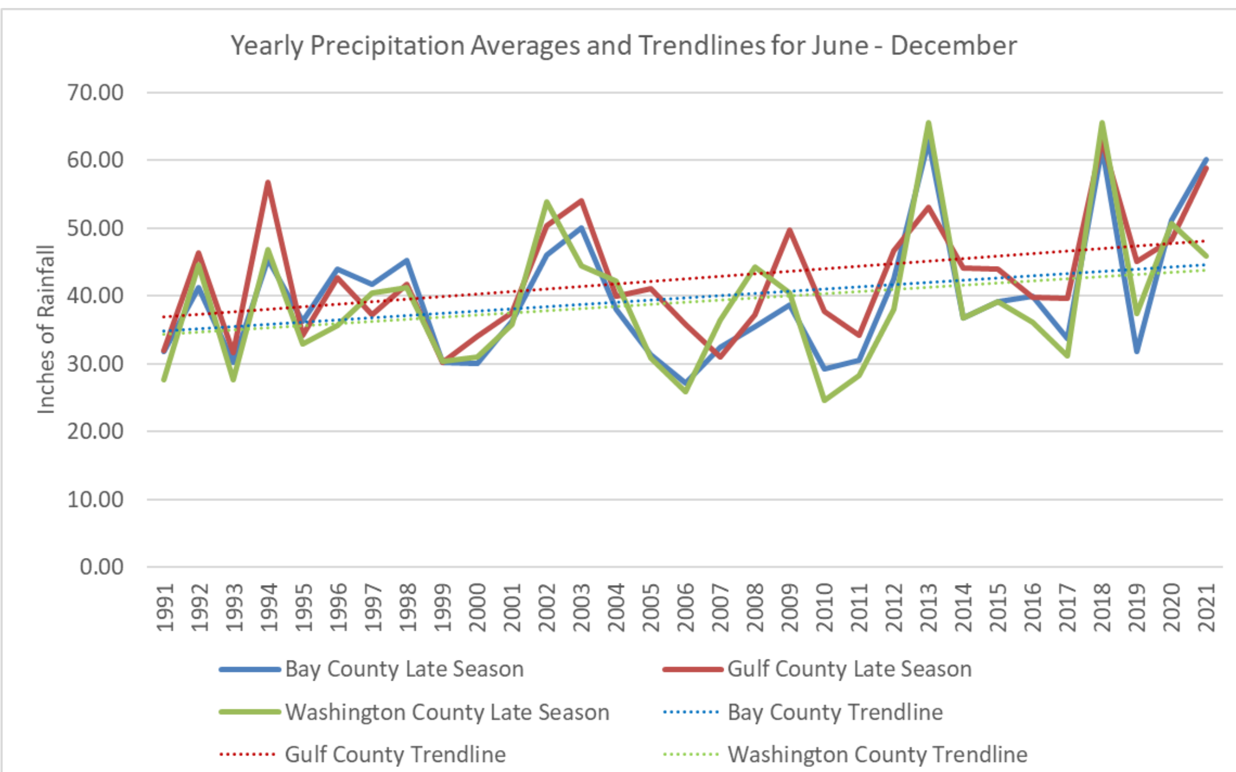

Figure 2-4. 1991 – 2020 yearly precipitation averages and trendlines, June – December

2. Rainfall

Precipitation totals for the first five months of 2022 have been quite variable (Figure 2-5). During February and April of 2022, Bay, Gulf, and Washington counties received less than the normal amount of rainfall. February rainfall was especially low, with all three counties each receiving less than two inches of total rainfall. However, all three counties received more than the 30-year monthly normal rainfall in March and May. May rainfall was exceptionally high, with Bay, Gulf, and Washington counties all receiving more than twice the 30-year monthly normal rainfall amounts. Multiple severe thunderstorms hit north Florida during March and May 2022. These storms accounted for much of the rainfall totals occurring during these months (Table 2-2). From January to May 2022, rainfall totals in Bay, Gulf, and Washington counties were all greater than their respective 30-year normals. Both Gulf and Bay counties averaged around four and a half inches more precipitation than their 30-year normals. The rainfall total for this period in Washington County was only half an inch more than the 30-year normal.

Table 2-2. Monthly rainfall for the first six months of 2022 in Bay, Gulf, and Washington counties, expressed as a percentage above or below 1991-2020 30-year normals

	Jan	Feb	Mar	Apr	May	June	Total % Above Average, Jan 22 - June 22
Bay County	1.38%	-70.73%	83.39%	-50.93%	147.62%	-2.17%	13.29%
Gulf County	-22.79%	-71.54%	78.12%	-46.63%	167.74%	-18.72%	7.81%
Washington County	19.92%	-66.91%	7.66%	-7.66%	117.39%	-6.76%	5.32%

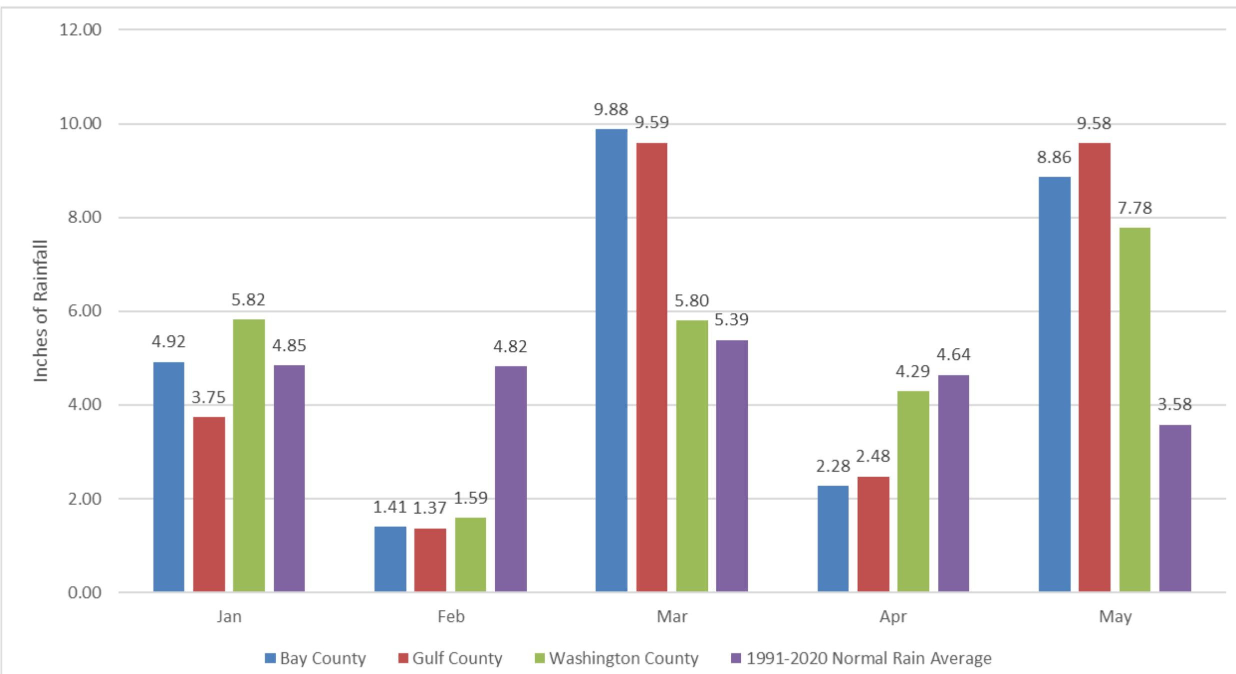

Figure 2-5 Monthly precipitation totals for Bay, Gulf, and Washington counties, January – June 2022

Much of the reported flooding in the study area has occurred in the Sand Hill Lakes region of southern Washington County. Residents in this area reported flooding in the months following Hurricane Michael and then flooding resumed again during 2021-2022. A longer-term analysis of the monthly PRISM precipitation data set (PRISM Climate Group, Oregon State University, 2023) for the period from January 1895 to April 2022 indicates that historically wet conditions have occurred in the region since mid-calendar year 2013, extending through April 2022, based on 24-month antecedent rainfall totals for a 4-

km square PRISM grid cell roughly centered in the area of reported flooding in the region. Data are from the PRISM Climate Group (2023). These data are shown for the period of record (Figure 2-6) and for the more recent period since January 2008 (Figure 2-7), respectively. This data indicates the 24-month rainfall total for the period prior to and including the month Hurricane Michael made landfall (October 2018) was higher than approximately 98 percent of other 24-month periods. For the 43-month period after Hurricane Michael (October 2018 to April 2022), the total rainfall for this same grid cell was higher than approximately 98 percent of other 43-month periods during the 1895-2022 PRISM dataset period of record. Some of the largest departures from typical monthly rainfall totals also occurred at this location during the period from August to December 2018 and during the fall of 2021.

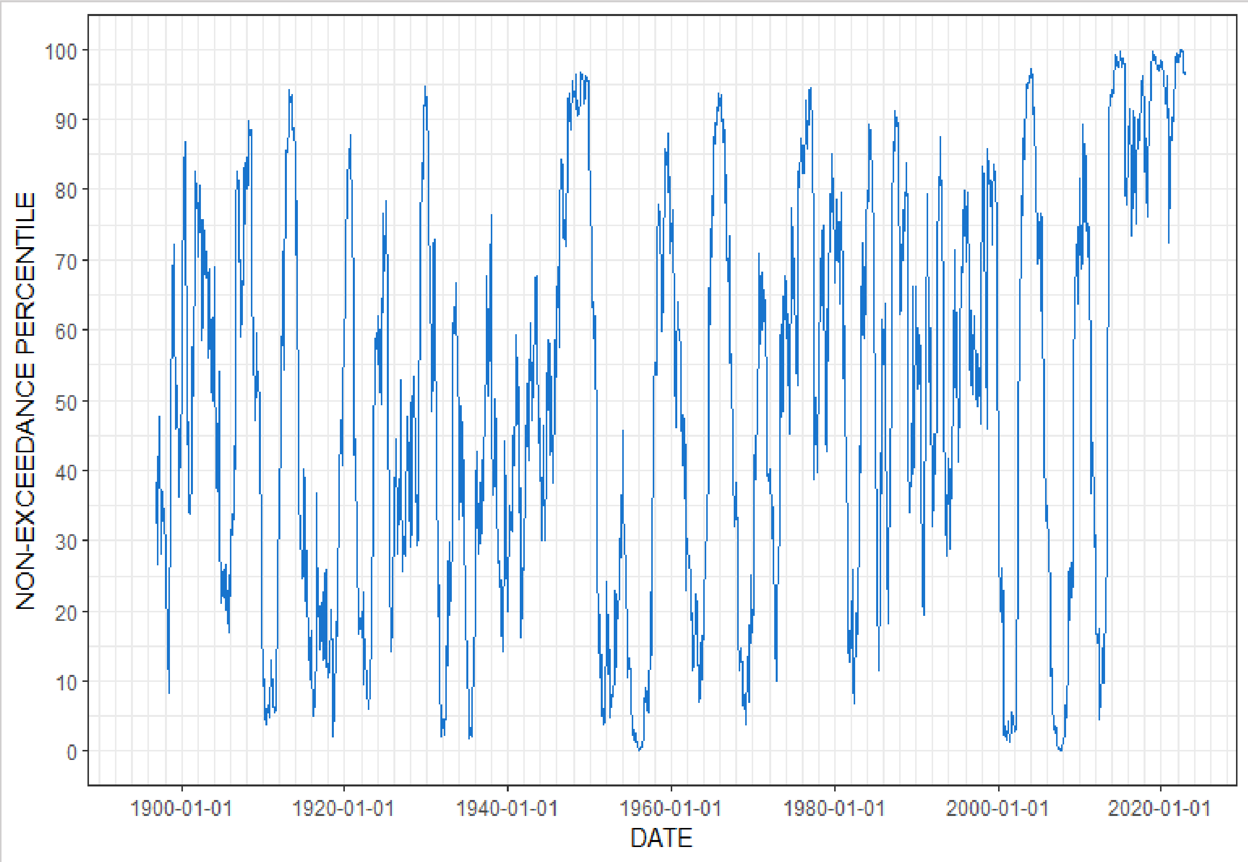

Figure 2-6. Estimated non-exceedance percentiles of 24-month antecedent precipitation for PRISM grid cell centered near Radcliff Circle in Washington County, Florida: January 1895 - November 2022

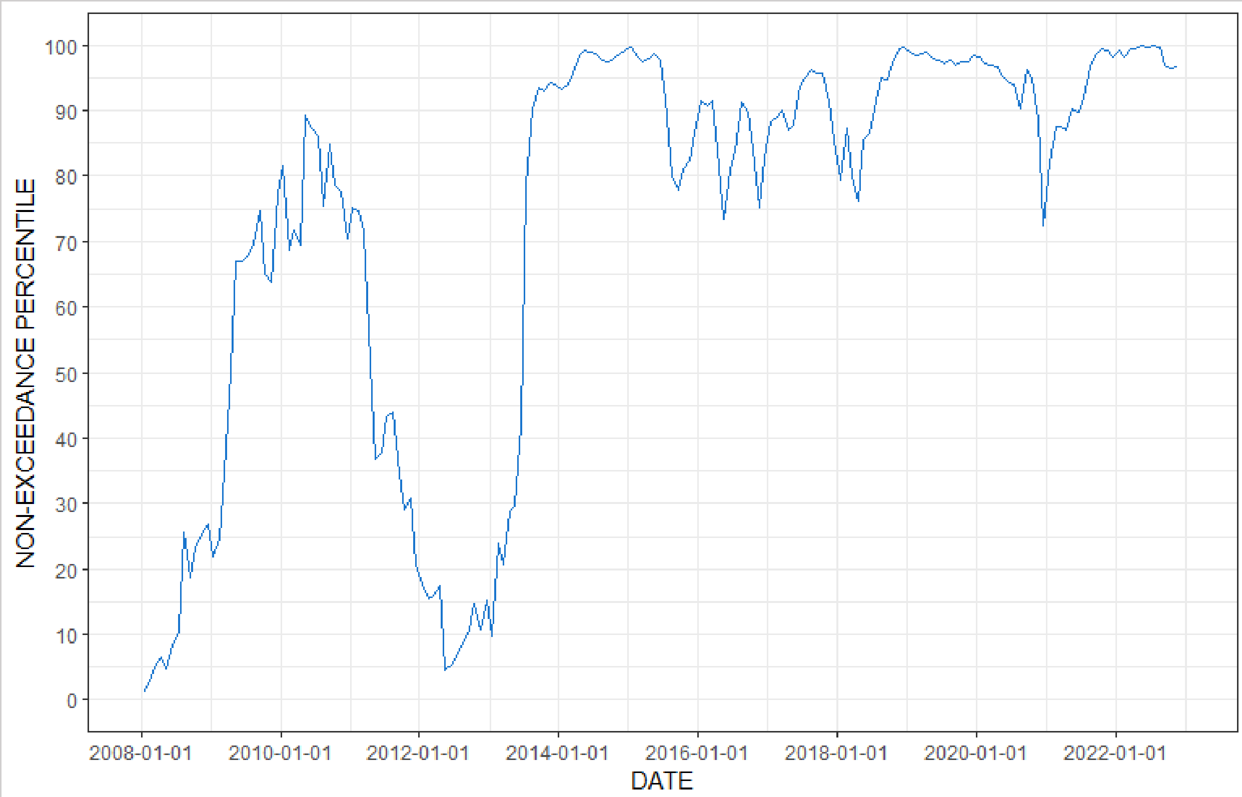

Figure 2-7. Estimated non-exceedance percentiles of 24-month antecedent precipitation for PRISM Climate Group grid cell centered near Radcliff Circle in Washington County, Florida: January 2008 - November 2022

2.2 Multi-year Climate Cycles

Seasonal and annual rainfall patterns in Florida are influenced by multi-year climate cycles including the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). The AMO pattern of oceanic-atmospheric changes is related to changes in sea surface temperatures in the middle to high latitudes of the Atlantic Ocean and was first documented during the mid-1990s (Curtis 2008, Kushnir 1994). An AMO cycle typically spans 20 to 40 years (Goly and Teegavarapu, 2014) but can extend 60 to 90 years (Knudsen et al 2011). AMO phases are typically referred to as either “warm” or “cool.” Researchers studying the effects of the AMO have reported increases in extreme precipitation indices in Florida and the coastal southeastern United States during the warm phase of the AMO (Curtis 2008, Teegavarapu and others, 2013; Goly and Teegavarapu, 2014). For example, Goly and Teegavarapu found that wet season rainfall indices (June – September) such as the one-day maximum, five-day maximum, and total seasonal precipitation were significantly higher in the central Florida panhandle during the warm phase of the AMO. During the fall/winter period (November to March), these same indices were higher in the Florida panhandle during the AMO cool phase (Goly and Teegavarapu, 2014). A warm AMO phase began in approximately 1995 and continues through the present day.

ENSO conditions generally span periods of two to seven years and are related to sea surface temperatures in the tropical regions of the Pacific Ocean (NOAA, 2022a). ENSO cycles include three phases: El Niño, La Niña, and neutral conditions. Transitions between phases generally occur over weeks to months. Changes in sea surface temperature and atmospheric conditions among the three ENSO phases influence weather conditions in many regions of the world, including Florida. The Oceanic Niño Index is one measure of ENSO conditions and reflects the three-month moving average temperature anomaly of surface waters in the tropical Pacific Ocean. Temperature deviations less than or equal to -0.5 are indicative of cooler La Niña conditions and deviations of 0.5 or greater are indicative of warmer El Niño conditions.

The Oceanic Niño Indices for 2010 through 2021 are shown on Table 2-3 (NOAA 2022b). When El Niño conditions occur during the winter (January through March) months, higher precipitation and streamflow may occur in the Florida panhandle (Schmidt et al., 2001). In contrast, La Niña conditions are reported to be associated with drier winters and slightly wetter summers (July through September) in Florida (Schmidt et al., 2001). An examination of Table 2-3 indicates that El Niño conditions occurred during the winters of 2010, 2015, 2016 and 2019. Winter rainfall exceeded 30-year normals (1991 – 2020) during these periods in Gulf, Bay, and Washington counties, consistent with predicted effects. La Niña winter conditions occurred during 2011, 2012, 2018, 2021, and 2022. Winter rainfall totals for these years were generally below 30-year normals.

La Niña conditions occurred during the summers of 2010, 2011, 2016, 2020, and 2021. Summer rainfall totals were above average during 2020 and 2021, as predicted, but below average during 2010 and 2011. Interestingly, the La Niña index for the summer of 2020 was -0.5, indicating mild La Niña conditions, however, summer rainfall in Bay, Gulf, and Washington counties represented maximums for the 1991-2020 period of record, with an anomalously high seasonal rainfall of 40 inches occurring in Bay County.

Winter rainfall generally appears to be consistent with ENSO cycles and associated rainfall predictions whereas summer patterns are variable. Three of the past five winters were El Niño (wetter) periods while one winter was a La Niña (drier) period and one was neutral. However, more rainfall occurs during the summer months than winter months. There do not appear to be any long-term trends in the frequency of El Niño, La Niña, and neutral periods (Table 2-3). However, there may be coupled effects between the AMO and ENSO cycles that influence rainfall patterns in northwest Florida (Goly and Teegavarapu 2014).

Table 2-3 Oceanic Niño Seasonal Indices, 2010 – June 2022(1)

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2010	**1.5**	**1.2**	**0.8**	0.4	-0.2	**-0.7**	**-1**	**-1.3**	**-1.6**	**-1.6**	**-1.6**	**-1.6**
2011	**-1.4**	**-1.2**	**-0.9**	**-0.7**	**-0.6**	-0.4	**-0.5**	**-0.6**	**-0.8**	**-1**	**-1.1**	**-1**
2012	**-0.9**	**-0.7**	**-0.6**	**-0.5**	-0.3	0	0.2	0.4	0.4	0.3	0.1	-0.2
2013	-0.4	-0.4	-0.3	-0.3	-0.4	-0.4	-0.4	-0.3	-0.3	-0.2	-0.2	-0.3
2014	-0.4	-0.5	-0.3	0	0.2	0.2	0	0.1	0.2	**0.5**	**0.6**	**0.7**
2015	**0.5**	**0.5**	**0.5**	**0.7**	**0.9**	**1.2**	**1.5**	**1.9**	**2.2**	**2.4**	**2.6**	**2.6**
2016	**2.5**	**2.1**	**1.6**	**0.9**	0.4	-0.1	-0.4	**-0.5**	**-0.6**	**-0.7**	**-0.7**	**-0.6**
2017	-0.3	-0.2	0.1	0.2	0.3	0.3	0.1	-0.1	-0.4	**-0.7**	**-0.8**	**-1**
2018	**-0.9**	**-0.9**	**-0.7**	**-0.5**	-0.2	0	0.1	0.2	**0.5**	**0.8**	**0.9**	**0.8**
2019	**0.7**	**0.7**	**0.7**	**0.7**	**0.5**	**0.5**	0.3	0.1	0.2	0.3	0.5	0.5
Year	**DJF**	**JFM**	**FMA**	**MAM**	**AMJ**	**MJJ**	**JJA**	**JAS**	**ASO**	**SON**	**OND**	**NDJ**
2020	0.5	0.5	0.4	0.2	-0.1	-0.3	-0.4	**-0.6**	**-0.9**	**-1.2**	**-1.3**	**-1.2**
2021	**-1**	**-0.9**	**-0.8**	**-0.7**	**-0.5**	-0.4	-0.4	**-0.5**	**-0.7**	**-0.8**	**-1**	**-1**
2022	**-1**	**-0.9**	**-1**	**-1.1**	**-1**							

[1]Blue shaded values indicate La Niña conditions and red shaded values indicate El Niño conditions (NOAA National Weather Service Climate Prediction Center, 2022b)

2.3 Tropical Systems

Tropical systems (tropical storms and hurricanes) are large storm systems with a low-pressure center surrounded by strong winds and heavy rainfall. These systems have a strong, counterclockwise rotation with rainbands that can extend several hundred miles from the storm center. Tropical systems require warm ocean surface waters to form and, as a result, are primarily observed in the North Atlantic Ocean in the mid to late summer, when temperatures are highest (Figure 2-8). The number of hurricanes observed annually since 1851 is highly variable, with periods of increased activity occurring roughly every 70 years (Figure 2-9). Currently, the north Atlantic is in a period of increased hurricane activity.

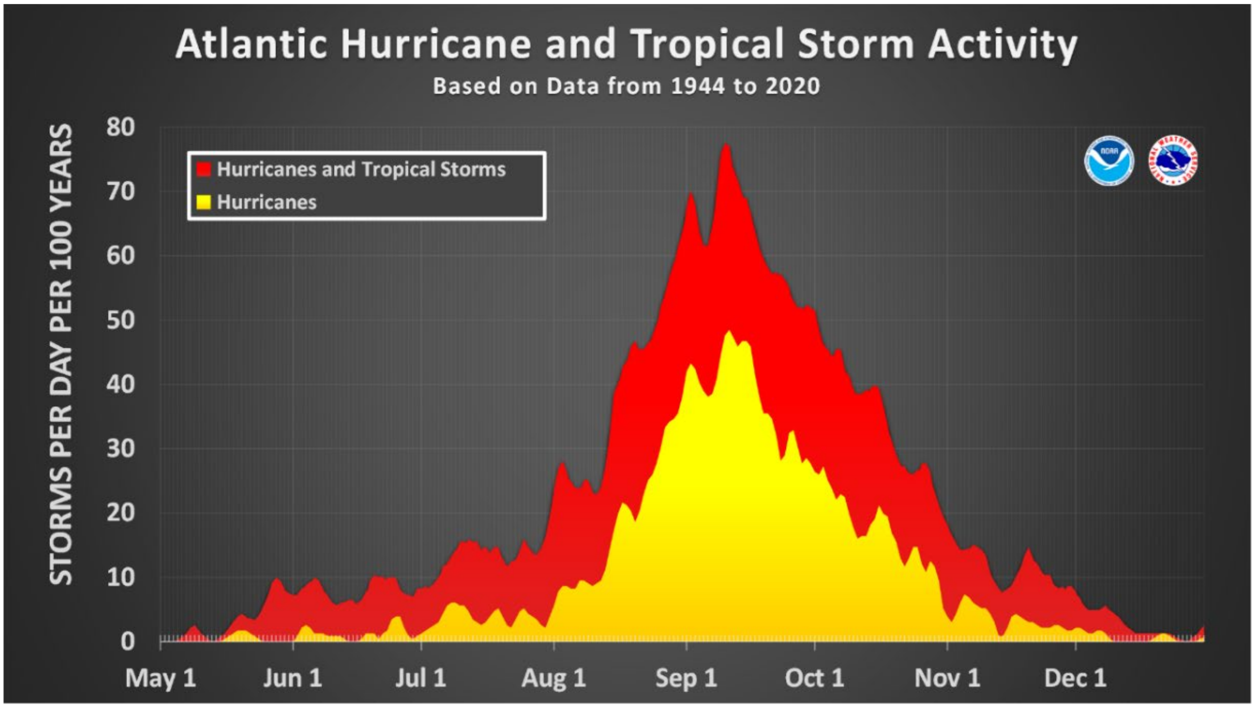

Figure 2-8. Number of tropical storms and hurricanes per day, 1944 - 2020 (NOAA 2022c, https://www.nhc.noaa.gov/climo/)

Typically, hurricanes produce widespread rainfall between six and 12 inches; however, local totals can vary widely. In general, rainfall is heaviest with slower moving storms and has little to do with storm intensity as it is traditionally measured. Traditionally, the intensity of hurricanes has been based on the Saffir-Simpson hazard scale, which ranks storms from a Category 1 (wind speeds ranging from 74 to 95 miles per hour) through Category 5 (wind speeds in excess of 157 miles per hour). Wind speed is not a reliable predictor of a storm's rainfall, however. Instead, the amount of local rainfall produced during a tropical system is more strongly associated with storm speed. For example, in 2018 Hurricane Florence made landfall near Wrightsville Beach, North Carolina as a Category 1 storm, where it produced upwards of 30 inches of rain in some areas over several days.

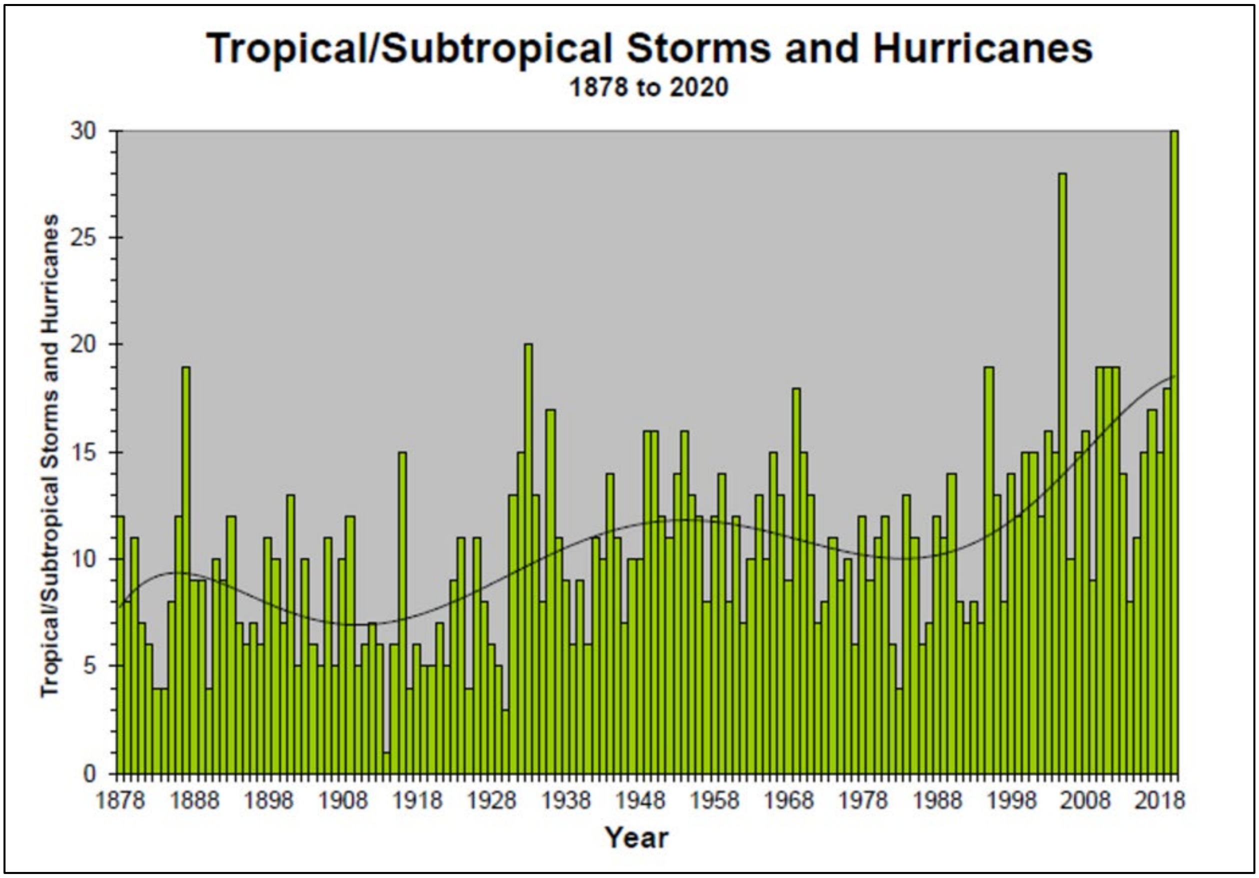

Figure 2-9. Observed annual number of tropical storms and hurricanes, 1878 - 2020 (NOAA 2022d)

Historically, there is about a ten percent annual probability that a county in the Florida panhandle (from Franklin in the east to Escambia in the west) will be hit by a hurricane (Figure 2-10). However, Bay, Gulf, and Washington counties were impacted by six named tropical weather events during the past five years. In September 2020, Hurricane Sally made landfall in Gulf Shores, Alabama, as a Category 2 storm. Due to the slow movement of the storm, Sally produced more than ten inches of rain across much of Bay, Washington, and Gulf counties (Figure 2-11). In addition, these counties were located east of the storm landfall location, and in the right front quadrant of the storm for an extended period. The front right quadrant of a tropical system contains the highest amount of rainfall. Hurricane Michael made landfall as a Category 5 hurricane near Mexico Beach, Florida, in October 2018. This storm produced widespread rainfall between three and six inches, with more than 11 inches of rain measured in Lynn Haven, Florida. Tropical Storm Fred made landfall near Port St. Joe, Florida in August 2021 and produced nearly nine inches of rain near Southport, Florida. Collectively, these named storms contributed 33.8 inches of rainfall in Bay County, 29.03 inches of rainfall in Gulf County, and 34.48 inches of rainfall in Washington County during 2018 through 2021. Rainfall associated with named storms contributed significantly to the higher-than-normal rainfall observed between 2018 and 2021.

2. Rainfall

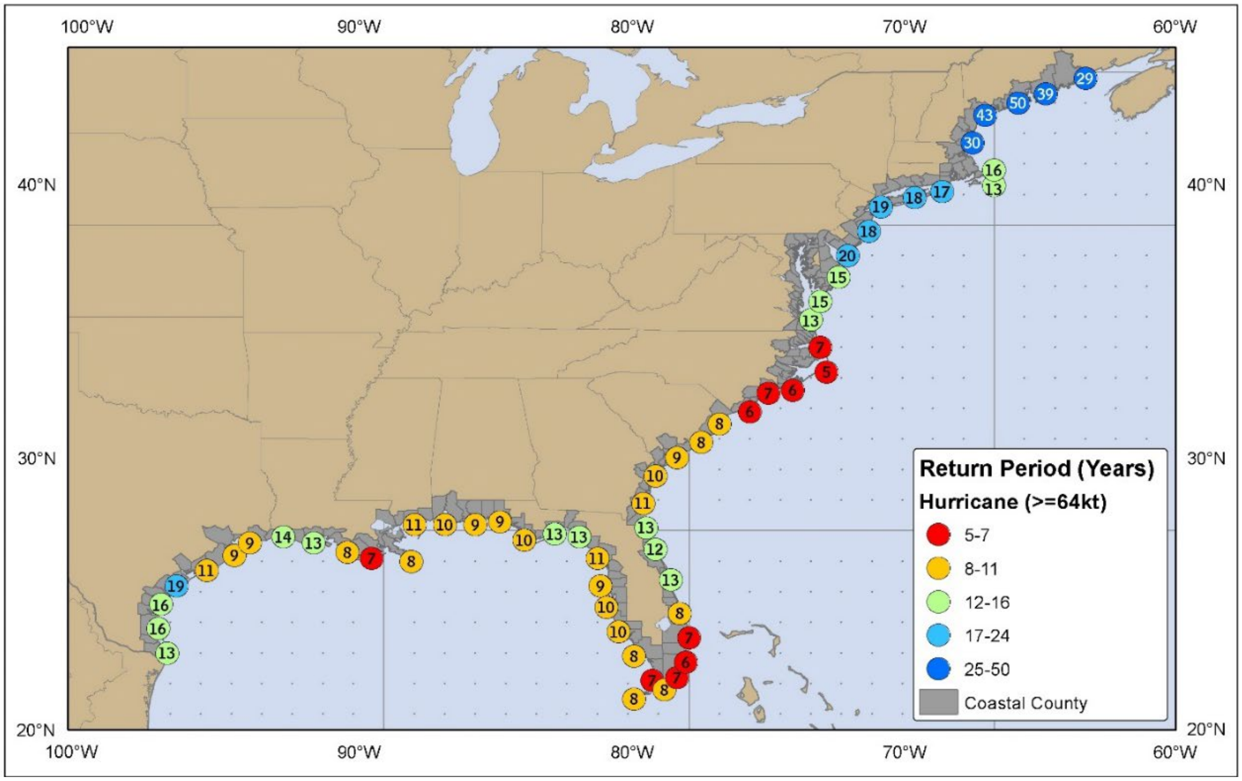

Figure 2-10. Annual hurricane return intervals for counties along the Southeast United States coastline (NOAA 2022c)

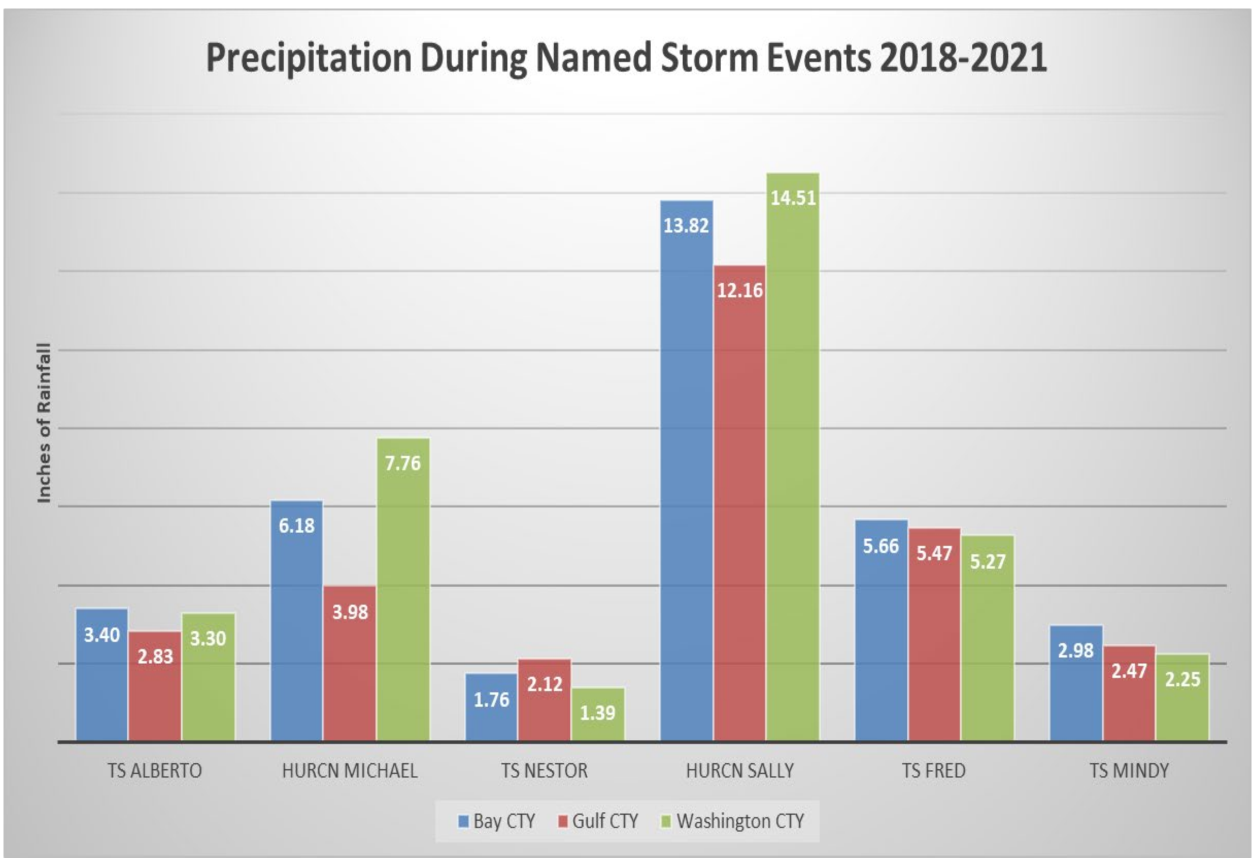

Figure 2-11: Average rainfall per county attributed to named storm events

3 Changes in Land Cover and Evapotranspiration

Evapotranspiration (ET) refers to the combined processes of evaporation and transpiration. Evaporation refers to the direct loss of water to the atmosphere from the land surface, open waterbodies, and the water table. Transpiration refers to the uptake of water by vegetation from the soil or aquifer system, and subsequent movement of water through the internal structures of plants (roots, stems, leaves) and return of water vapor to atmosphere through stomata structures on plant leaf surfaces. Next to precipitation, evapotranspiration comprises the largest component of the water budget in northwest Florida, with ET rates generally exceeding 35 inches per year. A review of land cover data, vegetation indices, and estimated ET was performed to assess whether there have been decreases in ET that contributed to the flooding reported in portions of Bay, Gulf, and Washington counties.

Although changes in land cover typically occur over periods of months or years as natural lands are converted to human uses, abrupt and catastrophic land cover changes were caused by Hurricane Michael. Hurricane Michael formed in the southwestern Caribbean Sea in early October 2018 before becoming a Tropical Depression on October 7, 2018. The storm rapidly intensified into a Category 4 hurricane by October 9 before making landfall on October 10, 2018, with maximum sustained winds of 160 mph and peak storm surge inundation between 9 and 14 ft. Hurricane Michael was later reclassified as a Category 5 hurricane, making it the fourth strongest storm to hit the contiguous United States and the strongest storm on record to hit the Florida panhandle (NWS, 2018). It is estimated that damages to Florida agriculture included $1.5 billion in losses across all categories including row crops, livestock, and aquaculture. However, the majority of this amount, totaling an estimated $1.2 billion, was in forestry losses (FDACS, 2018; University of Florida, 2018). Field reports from all agricultural industries also reference extensive loss of housing across the region (FDACS, 2018).

The area of northwest Florida most impacted by Hurricane Michael is mainly rural except for the coastal Panama City area (Figure 3-1). The primary land cover types in this open, sparsely populated geographic region were silviculture and agriculture, with towns of small populations scattered throughout. The geography, climate, and soils coupled with these rural characteristics make for prime areas of forestry and other agricultural uses. As seen in the data below, upland forests and other forested areas accounted for nearly one-fourth to one-half of all land cover types (Tables 3.1 and 3.2). While a portion these impacted areas include lands owned by the federal and state government, nearly two-thirds are privately owned (Florida Forest Service, 2019).

Analyses were performed to spatially locate and quantify areas impacted by Hurricane Michael as well as to calculate the overall “greenness” or quality of the vegetation before and after the hurricane. Measures of greenness such as the normalized difference vegetation index (NDVI) can be quantified using remote sensing methods and compared across space and time. Greenness indices have been found to be correlated with evapotranspiration (Cilar et at. 1991, Nagler et al. 2005, Wang et al. 2007). Thus, changes in vegetation indices may be indicative of changes in evapotranspiration.

Land cover changes caused by hurricanes have been analyzed using a variety of remotely sensed data and processing tools (McCarthy 2020, Hosannah 2021). The following datasets were utilized to assess the impacts of Hurricane Michael on land cover in northwest Florida:

- Hurricane Impact Zone (vector dataset from the Florida Forest Service, 2018)
- Landsat 8 Imagery (raster datasets from the USGS, May 2018, May 2019, and May 2020)
- National Land Cover Database (raster datasets from the USGS, 2016 and 2019

- Florida Land Use and Land Cover Database (vector datasets from the Florida Department of Environmental Protection, 2016 and 2021)

ESRI's ArcGIS Pro software was used for data viewing, analysis, geoprocessing, and creation of maps and tables. Geoprocessing included joining rasters, clipping raster and vector data, converting rasters to feature classes, calculating geometry, and creating summary tables to calculate fields.

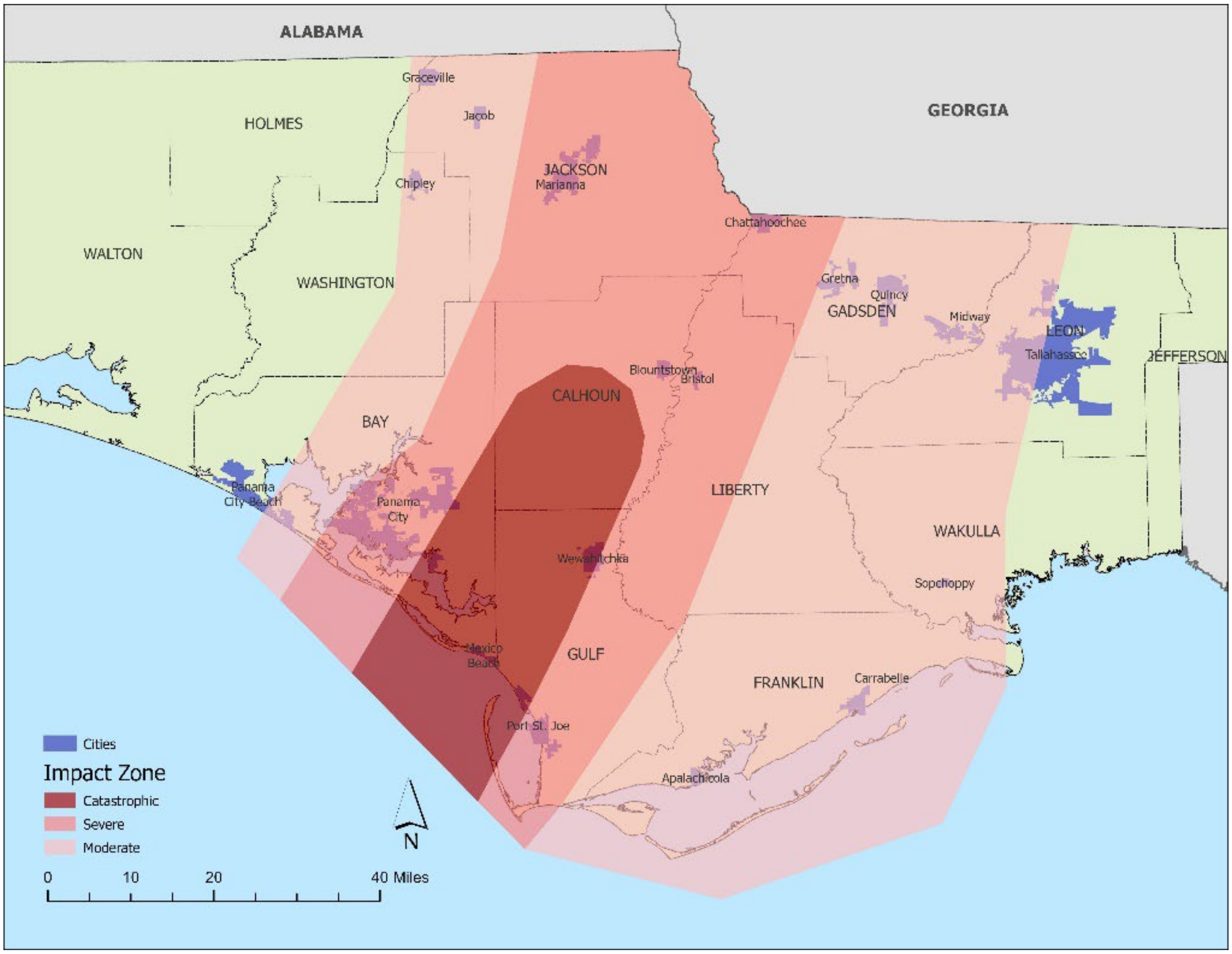

Figure 3-1. Hurricane Michael Impact Zones

3.1 Changes in Vegetation Based on Landsat 8 Imagery

Landsat 8 imagery was downloaded from the USGS Explorer website. This data is collected continuously by satellite at 30-meter resolution. Dates for study areas can vary as imagery is collected on a 16-day repeat cycle. This allows for multiple dates per month of available imagery across the study area. Multiple raster datasets were downloaded to cover the entire area of study and to cover three different periods of time to analyze data from before and after Hurricane Michael. These datasets were all from the month of May to ensure consistency in imagery from the same season and time of year and reduce variability due to seasonal changes in vegetation. Data retrievals included the years 2018, 2019, and 2020.

Geoprocessing included the use of the mosaic tool to mosaic rasters covering different areas for each year of coverage. Masking was then implemented to negate cloud cover and provide a more accurate greenness value, and the resultant raster was then clipped to the hurricane impact zone boundary. The Normalized Difference Vegetation Index (NDVI) calculation was then performed with bands 4 (red) and 5 (NIR) of each year to determine a greenness value for each year's raster. NDVI is calculated as a ratio of the difference between the red (Band 4) and near infrared (Band 5) values and the sum of these two values. For Landsat 8, the red and near infrared bands are Band 4 and Band 5, respectively, and the equation for calculating NDVI is: NDVI = (Band 5 – Band 4) / (Band 5 + Band 4) (USGS, 2016). The Landsat data indicates a loss of vegetation cover from 2018 to 2019, and a subsequent recovery of vegetation cover between 2019 and 2020.

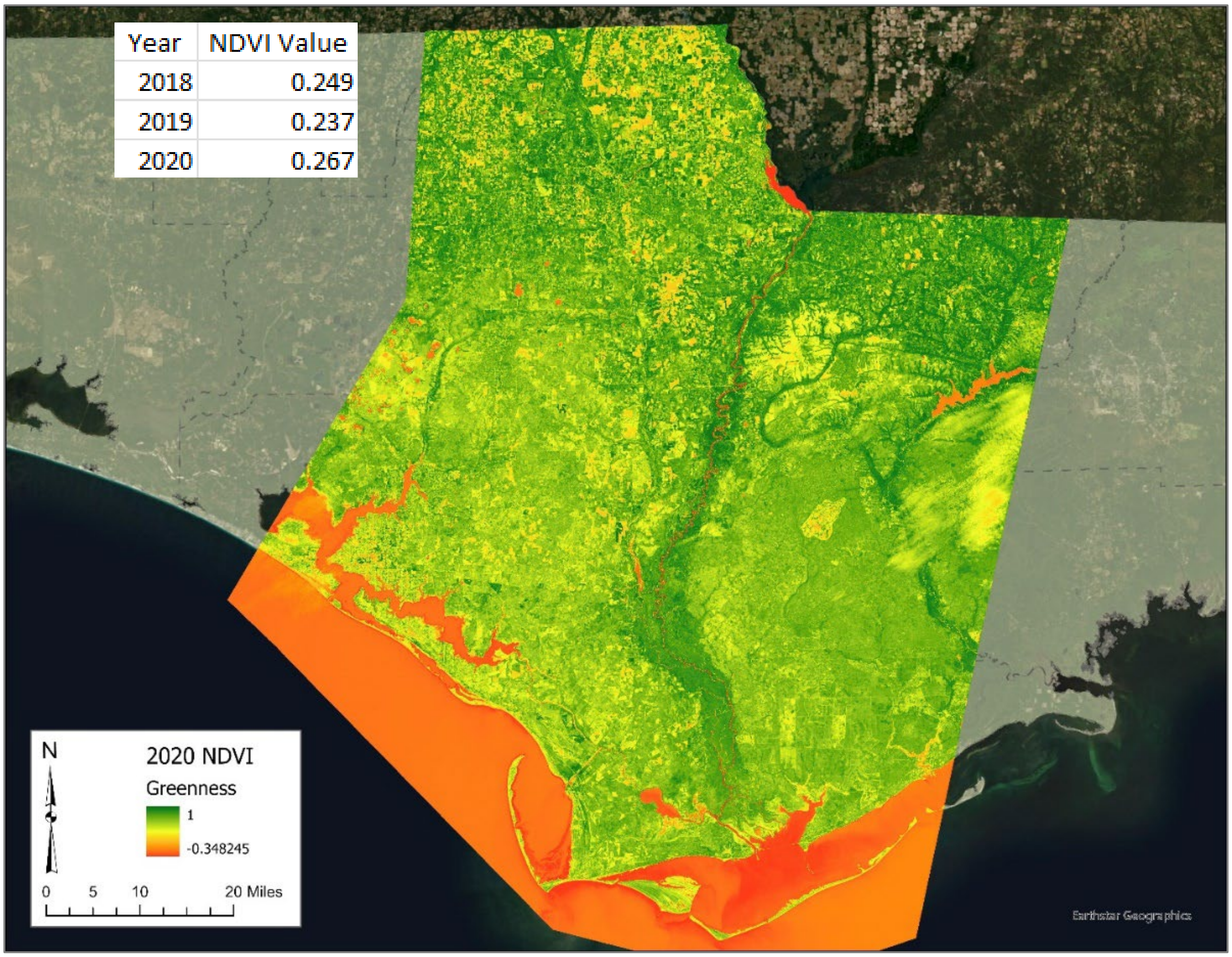

Figure 3-2. Normalized Difference Vegetation Indices for 2020 (Product of USGS Landsat 8; NAD 1983 UTM Zone 16N)

3.2 National Land Cover Database

The National Land Cover Database (NLCD) is created by the USGS, Earth Resources Observation and Science Center (USGS, 2018). The dataset contains land cover generated in cooperation with the Multi-Resolution Land Characteristics Consortium (MRLC), which is a partnership among federal agencies to produce a current, consistent land cover product for the entirety of the U.S. It contains raster data generated from satellite imagery at 30-meter resolution. The dataset is updated every five years beginning in 2001. The 2016 and 2019 datasets have overall accuracy assessments of 86% and 90%, respectively (USGS, 2021).

Data used for this analysis was from years 2016 and 2019. The raster datasets were downloaded and clipped to the hurricane impact zone boundary. Raster data was then converted to polygon feature classes before calculating the areas covered by each land cover classification. A summary table was then created for each year of data to compare land cover change across the impact area. As seen in Table 3-1, Evergreen Forest land cover decreased from 2016 to 2019, with much of that acreage offset by increases in the Herbaceous and Shrub/Scrub categories. Similarly, Woody Wetlands decreased by 28,411 acres with much of that acreage increasing in Emergent Herbaceous Wetlands. These changes show a loss of tree canopy and increases in herbaceous/shrub cover in both uplands and wetlands. Overall, there was a loss of nearly 80,000 acres of Evergreen Forest from 2016 to 2019 following Hurricane Michael (Table 3-2). However, this loss was almost completely offset by a similar increase in Herbaceous and Shrub/Scrub cover during that same period. The net change in the combined forest, shrub, and wetland cover during this period was fairly small (about 1.5 percent) when compared to the combined area of these land cover classes in 2016.

Table 3-1. NLCD Classification Summary Table

NLCD Classification	2016 Acres	2019 Acres	2016-2019 Change
Open Water	571,031	569,936	(1,096)
Developed	167,196	163,662	(3,534)
Developed, Low Intensity	68,332	69,347	1,014
Developed, Medium Intensity	27,974	31,957	3,983
Developed, High Intensity	8,287	8,942	655
Barren Land	19,927	21,938	2,011
Deciduous Forest	5,239	6,209	969
Evergreen Forest	915,610	835,629	(79,981)
Mixed Forest	11,569	11,920	351
Shrub/Scrub	178,706	219,196	40,490
Herbaceous	192,197	224,476	32,279
Hay/Pasture	42,190	42,243	52
Cultivated Crops	235,170	236,365	1,196
Woody Wetlands	1,432,070	1,403,659	(28,411)
Emergent Herbaceous Wetlands	113,492	143,512	30,021

Table 3-2. NLCD Reclassification for Figure 3.3

NLCD Land Cover Classification	Reclassification
Open Water	Water
Developed	Developed
Developed, Low Intensity	
Developed, Medium Intensity	
Developed, High Intensity	
Barren Land	Barren Land
Deciduous Forest	Upland Forest
Evergreen Forest	
Mixed Forest	
Shrub/Scrub	Herbaceous Shrub
Herbaceous	
Hay/Pasture	Agriculture
Cultivated Crops	
Woody Wetlands	Wetlands
Emergent Herbaceous Wetlands	

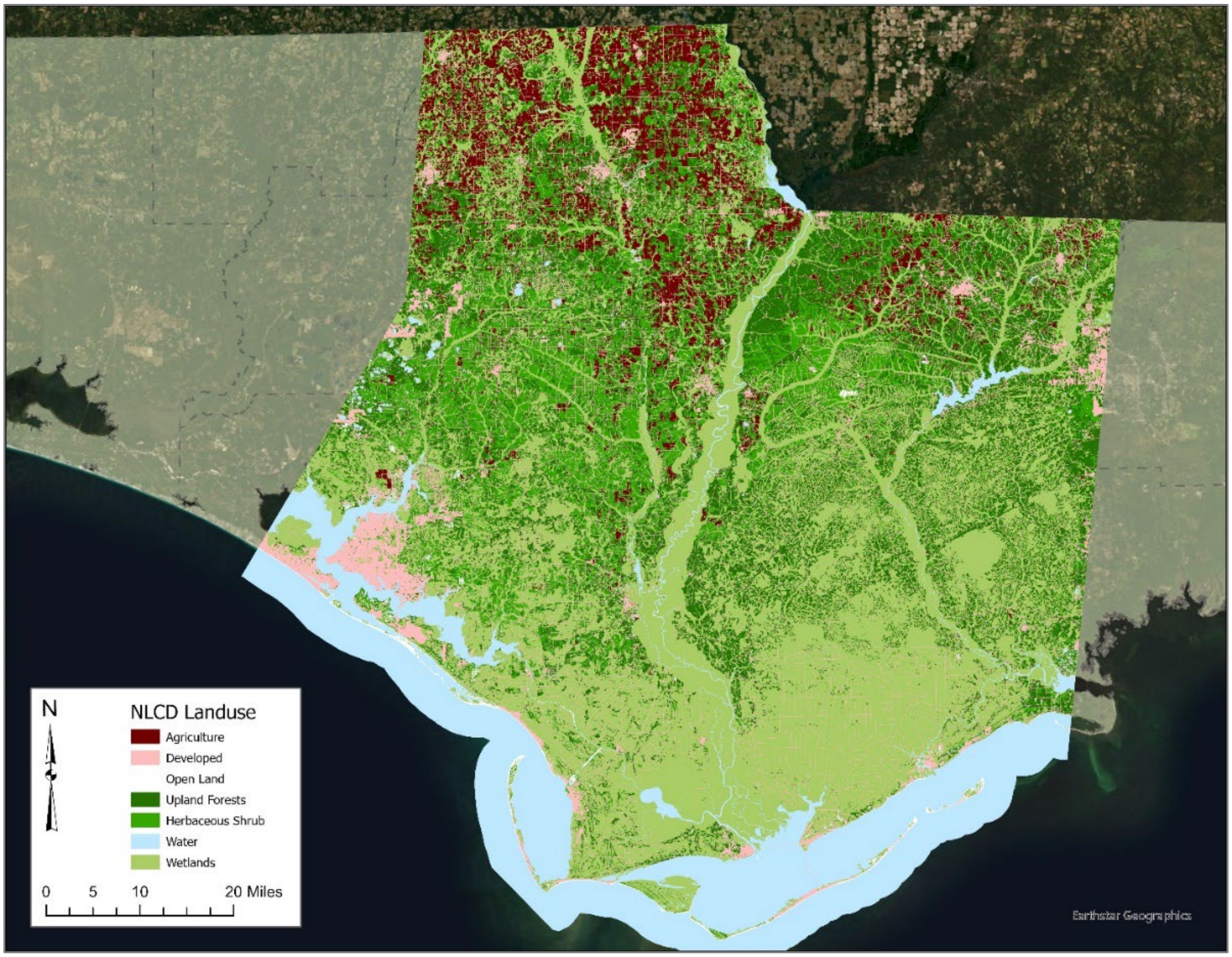

Figure 3-3. NLCD Land Use (Product of USGS NLCD; NAD 1983 UTM Zone 16N)

A similar analysis was attempted for the Florida Land Use & Land Cover Database. However, changes or refinements in the classification methodology between the 2015/2016 and 2019 datasets created inconclusive results.

3.3 Evapotranspiration

Estimates of mean monthly actual evapotranspiration (ET) for the available period of record (January 2000 through December 2021) were retrieved from the U.S. Geological Survey Geodata Portal https://cida.usgs.gov/thredds/dodsC/ssebopeta/monthly. The ET estimates are based on the Operational Simplified Surface Energy Balance (SSEBop) (Senay et al., 2013). This method uses MODIS satellite-based land surface temperature data together with air temperature, net radiation, and other climate data to estimate actual ET at a 1-km grid cell resolution. Because the SSEBop actual ET estimates are not dependent on land cover information, the data can be used to assess the impact of changes in land cover on ET, including potential changes in ET resulting from the widespread impacts to forested land cover caused by Hurricane Michael (Senay, June 10, 2022, digital communication).

While the SSEBop data comprises the best available data in northwest Florida, there is some uncertainty in these ET estimates. Comparisons of SSEBop monthly ET values to monthly ET values estimated from weather station data in Florida indicated that coefficients of determination (R^2) varied among land cover types, ranging from 0.59 for forested areas to 0.82 for pasture areas with a shallow water table (Sepulveda 2021). Root-mean square errors ranged from 0.6 in. per month for urban land cover to 1.08 in. per month for forested land cover (Sepulveda 2021). Comparisons of SSEBop-based ET estimates with ET based on data collected at Ameriflux tower sites indicated that SSEBop monthly ET estimates had relative errors of less than 20 percent. All ET estimation methods have some uncertainty and SSEBop errors appear to be similar in magnitude to errors associated with other surface energy balance methods (Chen et al., 2016).

The SSEBop ET datasets retrieved for each county, watershed, or impact zone contain time series of mean monthly actual ET rates. Each monthly value represents the SSEBop actual ET averaged across the area of interest. Monthly ET exhibits pronounced seasonal cycles (Figure 3-4). Average monthly ET totals for Washington County are depicted on Figure 3-5. These charts indicate that ET generally ranges from a winter minimum of an inch or less during December to a summer maximum of six inches or more during July. Other counties in northwest Florida exhibit similar seasonal patterns.

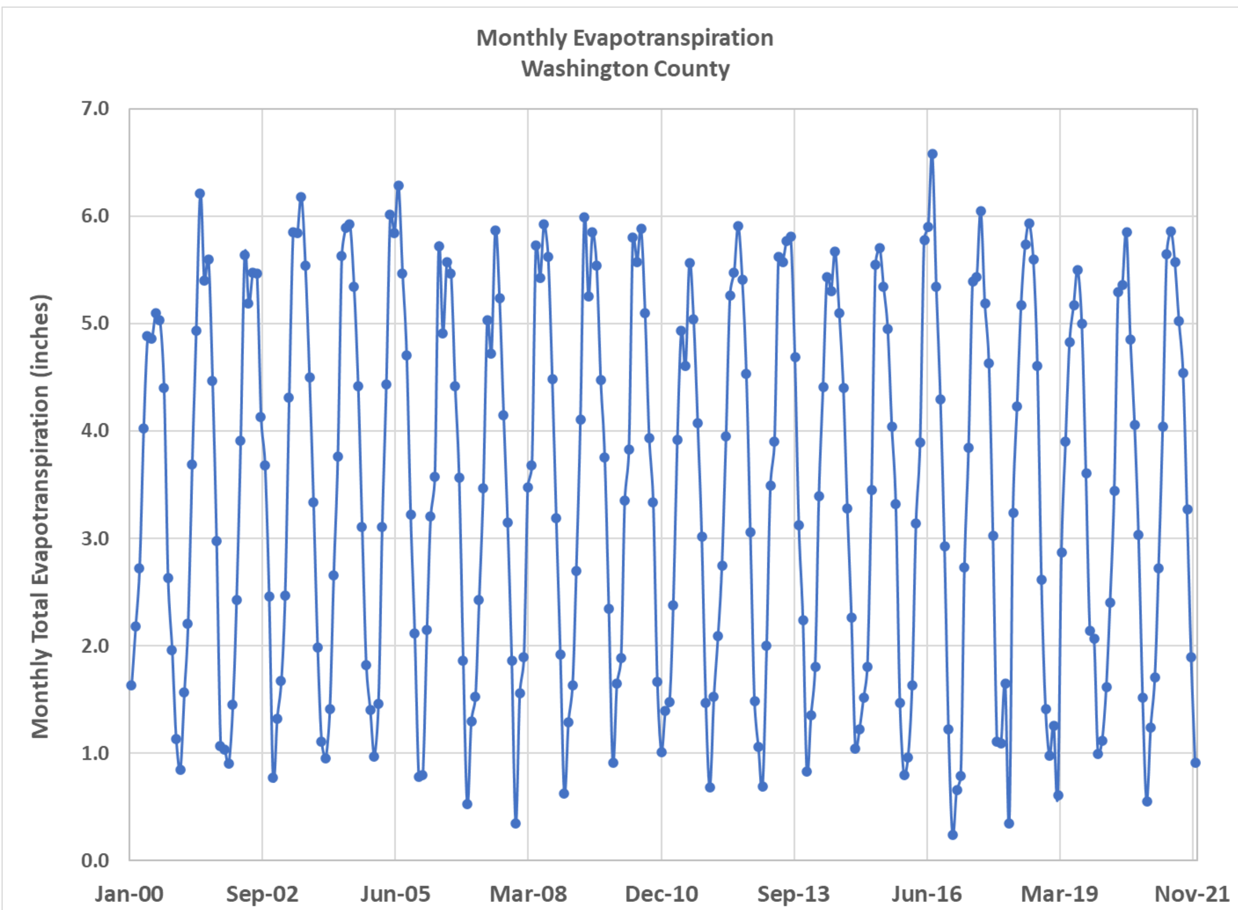

Figure 3-4. Monthly actual evapotranspiration in Washington County, Florida, January 2000 through December 2021

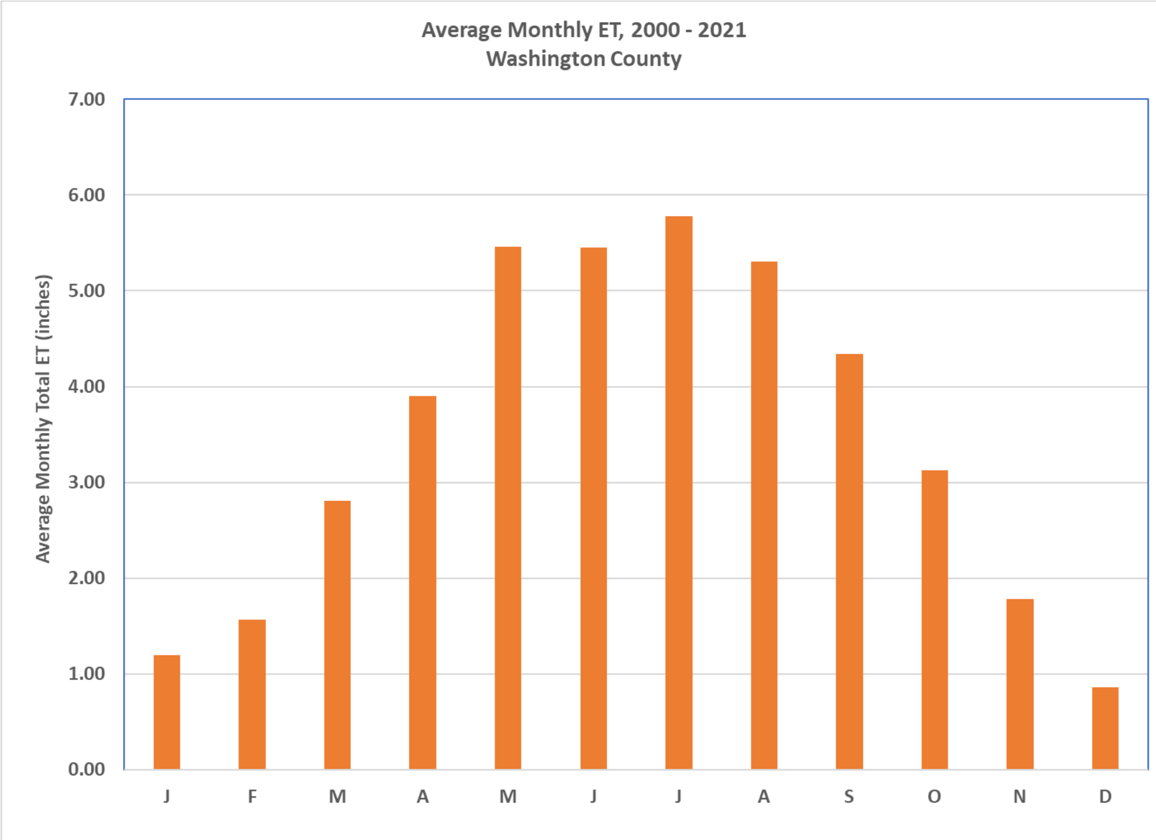

Figure 3-5. Average monthly actual evapotranspiration, Washington County, 2000 to 2020

Monthly values were summed for each year to determine annual ET. Annual ET totals were averaged from 2000 to 2021 to determine a long-term average for each county. Annual average ET ranged from approximately 37.7 inches per year in Okaloosa County to 48.7 inches per year in Franklin County (Figure 3-6). ET rates vary among counties due to differences in latitude, climate, land cover, and other factors. The ET rates also vary among years due to climatic variability and changes in land cover conditions. The average annual ET for the 16 counties comprising the District was 42.3 inches for the 2000-2021 period of record. Annual ET totals have been below average in most counties since 2015, including counties located outside of the Hurricane Michael impact zones. This indicates that climatic variation, changes in land cover, or other factors have contributed to lower ET rates during recent years.

To assess the potential effects of Hurricane Michael and the widespread loss of forested areas on ET rates, annual average ET rates were compiled for each of the three Hurricane Michael impact zones (Figure 3-7) and compared to the pooled average annual ET rates for counties located outside the impact zones (Escambia, Santa Rosa, Walton, and Jefferson counties). The ET rates within the catastrophic impact zone were 8.9 inches, 9.6 inches, and 8.9 inches lower during 2019, 2020, and 2021, respectively, than the average ET rates for counties outside the impact zone. In other words, although ET was below average for most counties within the District during 2019 regardless of the level of impact from Hurricane Michael, the total ET was an additional 8.9 inches lower within the catastrophic impact zone. Within the severe impact zone, ET rates were 4.8 inches, 4.1 inches, and 3.4 inches lower during 2019, 2020, and 2021 compared to the averaged rates for the unimpacted counties. Within the moderate impact zone, ET rates were 0.8, 1.0 and 1.2 inches lower during 2019, 2020, and 2021, respectively, compared to the averaged ET rates for unimpacted counties.

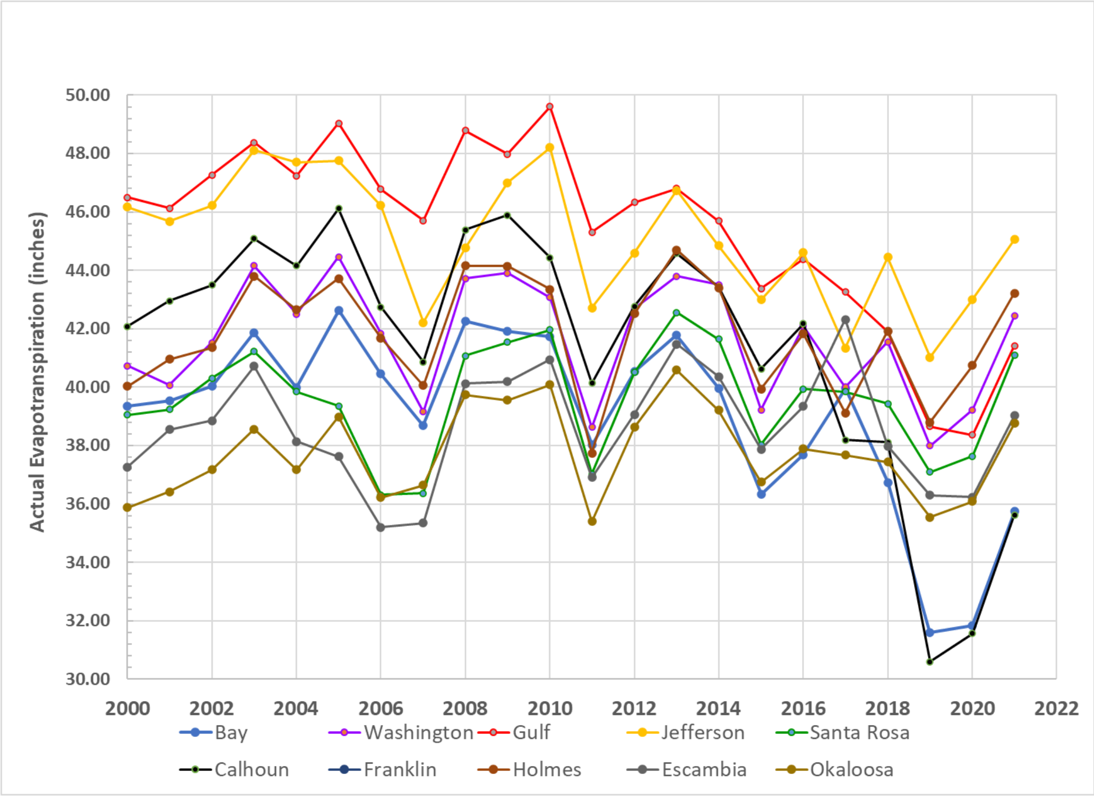

Figure 3-6. Annual total evapotranspiration for selected counties in Northwest Florida, 2000 – 2021

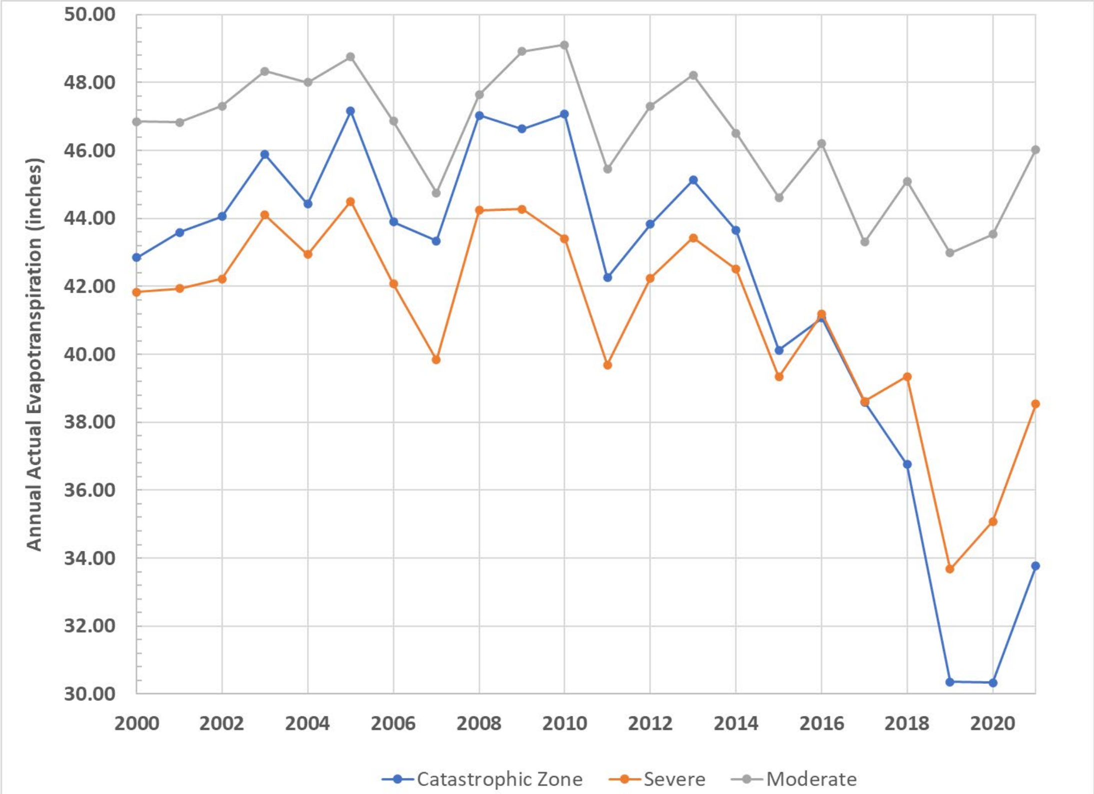

Figure 3-7. Annual total evapotranspiration for the Hurricane Michael impact zones, 2000 - 2021

The ET data, combined with the previously discussed changes in land cover and NDVI greenness between May 2018 and May 2019, indicate that the loss of upland forests and forested wetlands caused by Hurricane Michael resulted in lower evapotranspiration rates. Below average ET rates persisted through 2021 within the catastrophic and severe impact zones, despite a recovery in the NDVI values, suggesting that the herbaceous and shrub/scrub vegetation may exhibit lower ET rates than pre-hurricane forested land cover types. The large reductions in ET caused by Hurricane Michael contributed to higher groundwater levels in Bay, Gulf, and Calhoun counties and thus indirectly contributed to the flooding that occurred during 2019 through the fall of 2022. However, the magnitude of the excess rainfall that has occurred since 2013 is larger than the recent reductions in ET in most areas, indicating that rainfall is the primary driver of the observed flooding.

Similar patterns in ET are also evident when examining data for the Bear Creek, Bayou George Creek, Lower Wetappo Creek, and Sand Hill Lakes region watersheds. These declines in ET are shown on Figure 3-8 through Figure 3-11, which plot annual ET totals (thinner lines) and smoothed lines fitted to these annual totals (thicker lines) for each watershed. Annual ET totals for each watershed exhibit no obvious temporal trends from 2000 to 2014, but a pattern of generally declining ET values is evident after 2014. The enhanced vegetation index (EVI) values (ORNL DAAC, 2018a-d; Didan, K, 2015) from selected 3 km grid cell locations within the Bear Creek, Bayou George Creek, and Sand Hill Lakes watersheds exhibit no obvious temporal trends in the earlier part of the 2000 to 2021 period, with lower EVI values in the latter part of this period (Figure 3-12 through Figure 3-15). The EVI values from the sampled location in the Wetappo Creek watershed appeared to begin to decline earlier in the 2000 to 2021 period. Therefore, the ET declines in these sampled areas may be explained (at least in part) by a pattern of changes in land cover or changes in climatic conditions. Average ET rates in these watersheds for 2015 through 2021 were about 3 to 10 inches lower than average ET rates for 2000 through 2014. In comparison, average precipitation departures (based on 1991-2020 normals) for the 2015 to 2021 period were about 8 to 12 inches above normal. These data suggest that reductions in ET rates since 2014 could have exacerbated the effects of flooding from excessive rainfall that occurred during this period.

The potential for reduced ET to have exacerbated flooding caused by excessive rainfall is highest in the months and years following the passage of Hurricane Michael. As noted previously, cumulative rainfall totals prior to the passage of Hurricane Michael were very high and remained above average through late 2022. The lowest ET rates in the Bear Creek, Bayou George Creek, Wetappo Creek, and Sand Hill Lakes region watersheds occurred during 2019 through 2021 following Hurricane Michael. Average ET rates in these watersheds ranged from about 30 to 33 inches per year from 2019 to 2021, which were about 4 to 10 inches per year below the long-term averages for the 2000 to 2021 period of record. In comparison, average annual precipitation totals during 2019 to 2021 ranged from about 72 to 79 inches in these watersheds, which were about 7 to 17 inches higher than their respective 30-year rainfall normals. Average ET rates during 2021 recovered about 50 to 80 percent of the decline that occurred from 2018 to 2019. Steeper declines in EVI values from 2018 to 2019, followed by some post-2019 recovery in EVI values was also evident, so the post-Hurricane Michael ET patterns appear to reflect some regrowth of vegetation in hurricane damaged areas. Declines in post-Hurricane Michael ET rates were higher for the Bear Creek, Bayou George Creek, and Wetappo Creek watersheds than for the Sand Hill Lakes region. The latter watershed is outside of the moderate, severe, or catastrophic impact zones so this spatial pattern of ET reductions is also consistent with the hypothesis that most of the apparent decline in ET since 2014 was caused by damage from Hurricane Michael. It should be noted that inferences regarding changes in ET should be made with some degree of caution due to some uncertainty in the SSEBop ET rates.

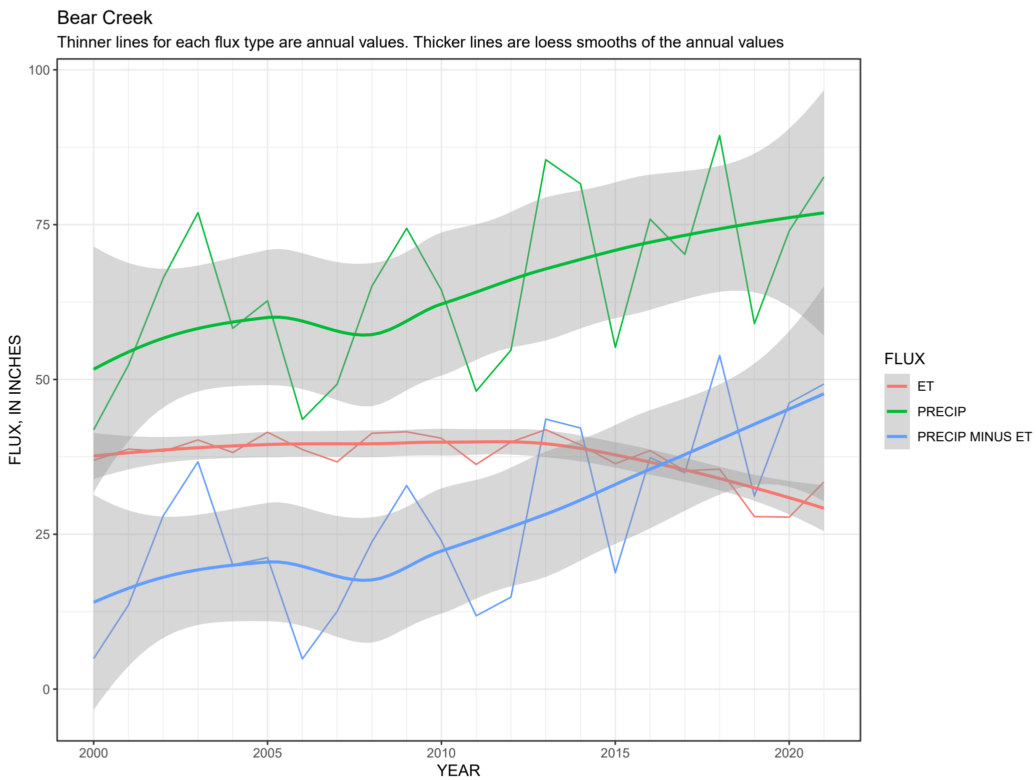

Figure 3-8. ET, precipitation, and precipitation minus ET for the Bear Creek watershed, 2000 – 2020

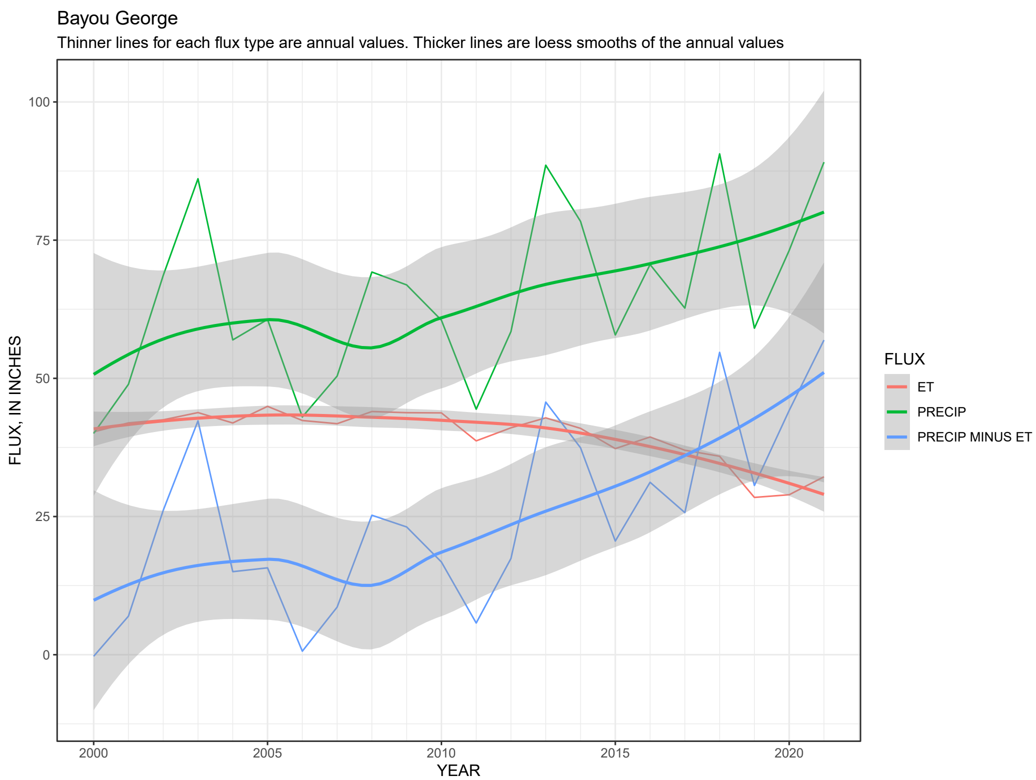

Figure 3-9. ET, precipitation, and precipitation minus ET for the Bayou George Creek watershed, 2000 - 2020

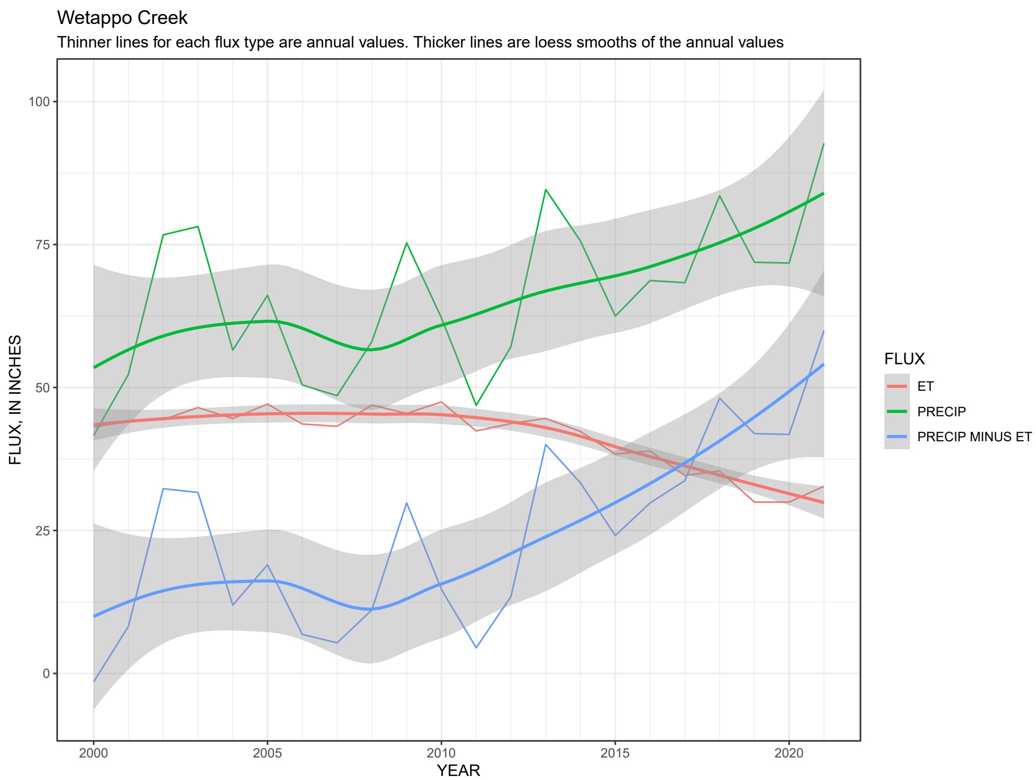

Figure 3-10. ET, precipitation, and precipitation minus ET for the Wetappo Creek watershed, 2000-2021

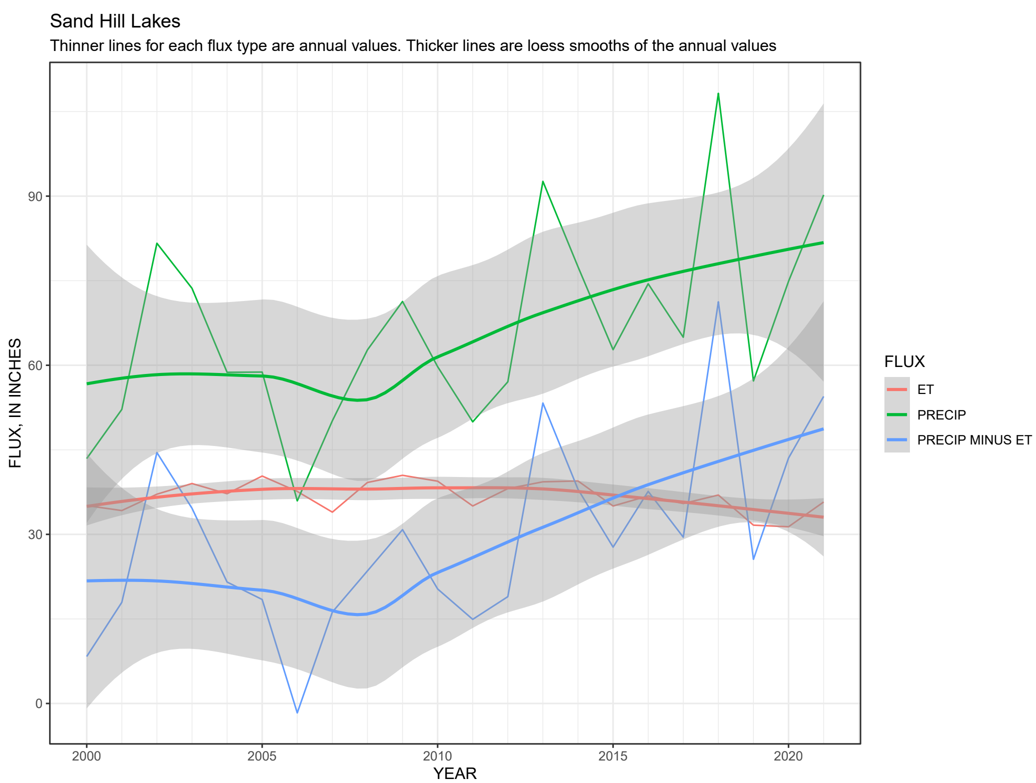

Figure 3-11. ET, precipitation, and precipitation minus ET for Sand Hill Lakes region watersheds, 2000-2021

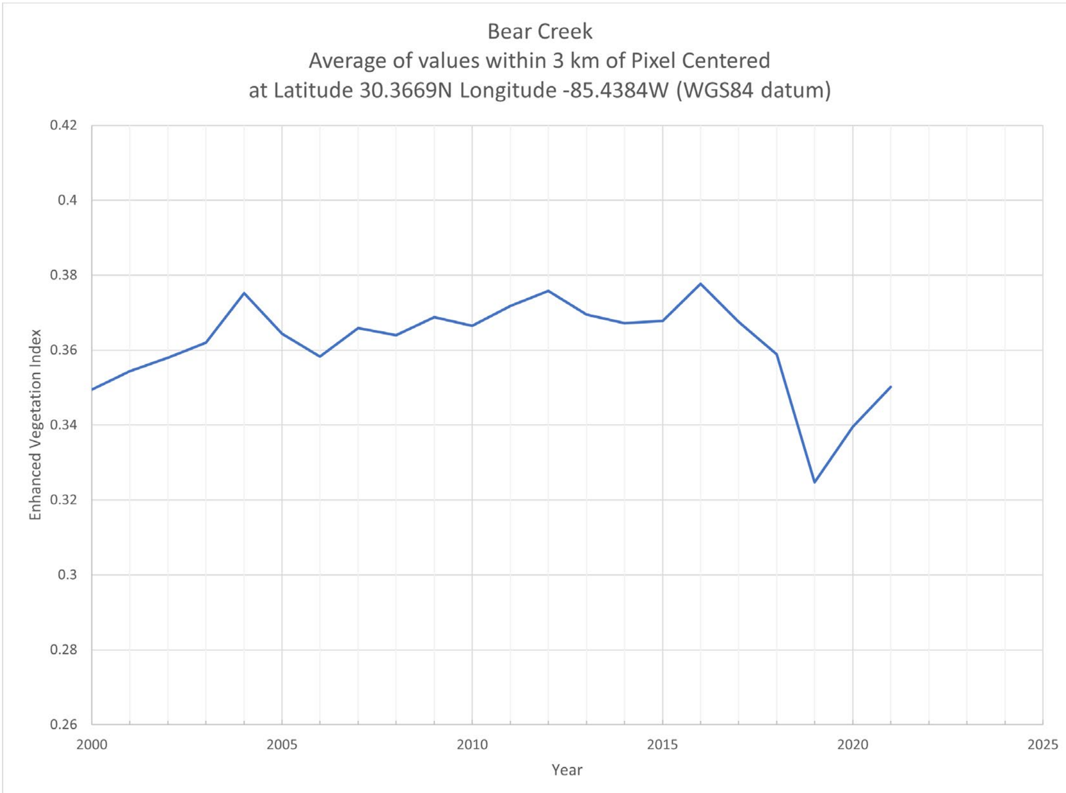

Figure 3-12. Enhanced vegetation index (EVI) values for the Bear Creek watershed, 2000 – 2021

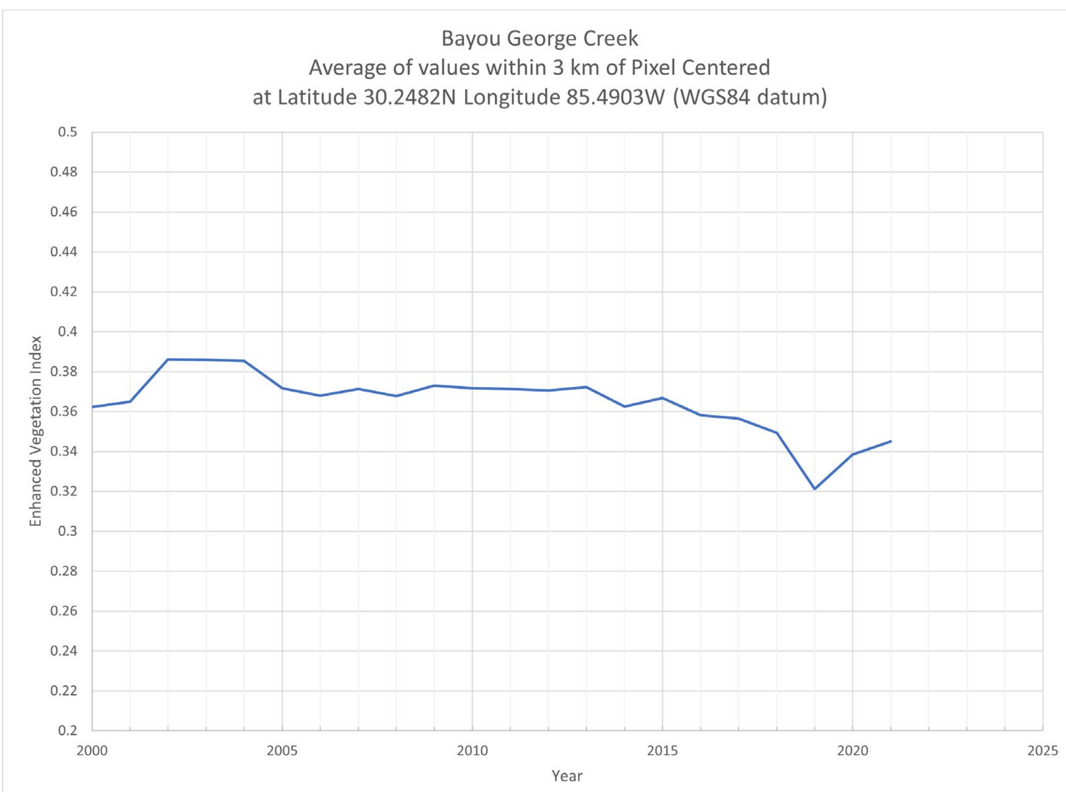

Figure 3-13. Enhanced vegetation index (EVI) values for the Bayou George Creek watershed, 2000 - 2021

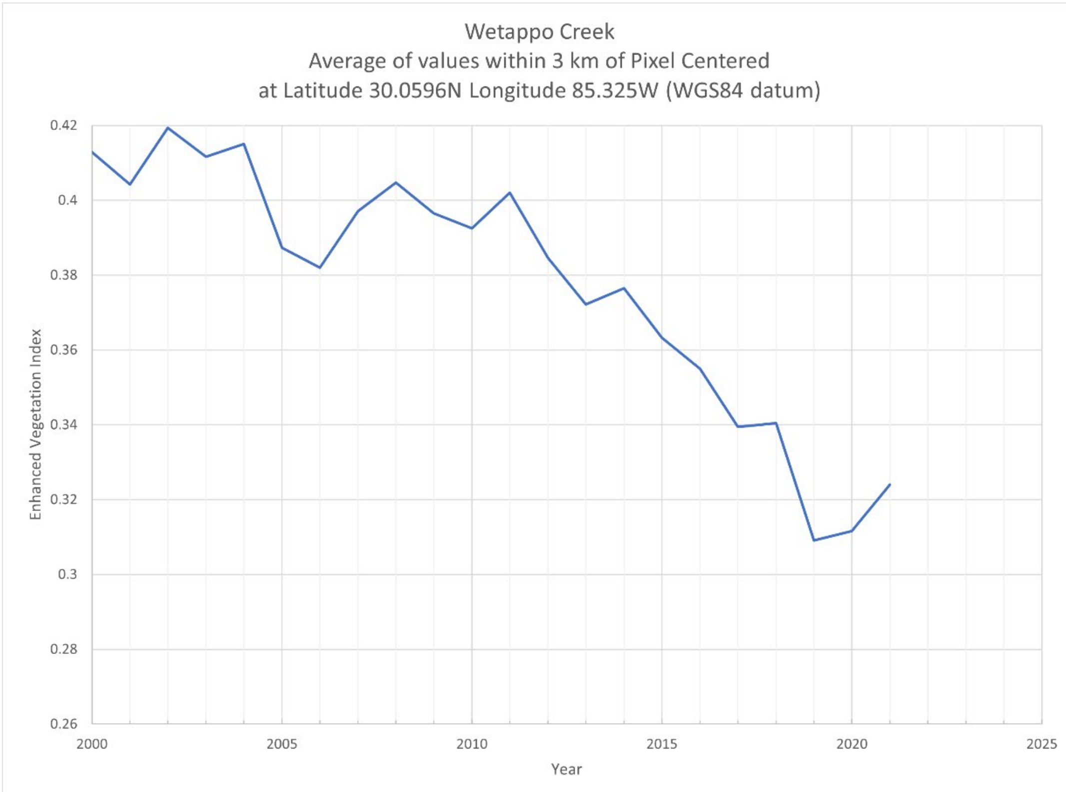

Figure 3-14. Enhanced vegetation index (EVI) values for the Wetappo Creek watershed, 2000 – 2021

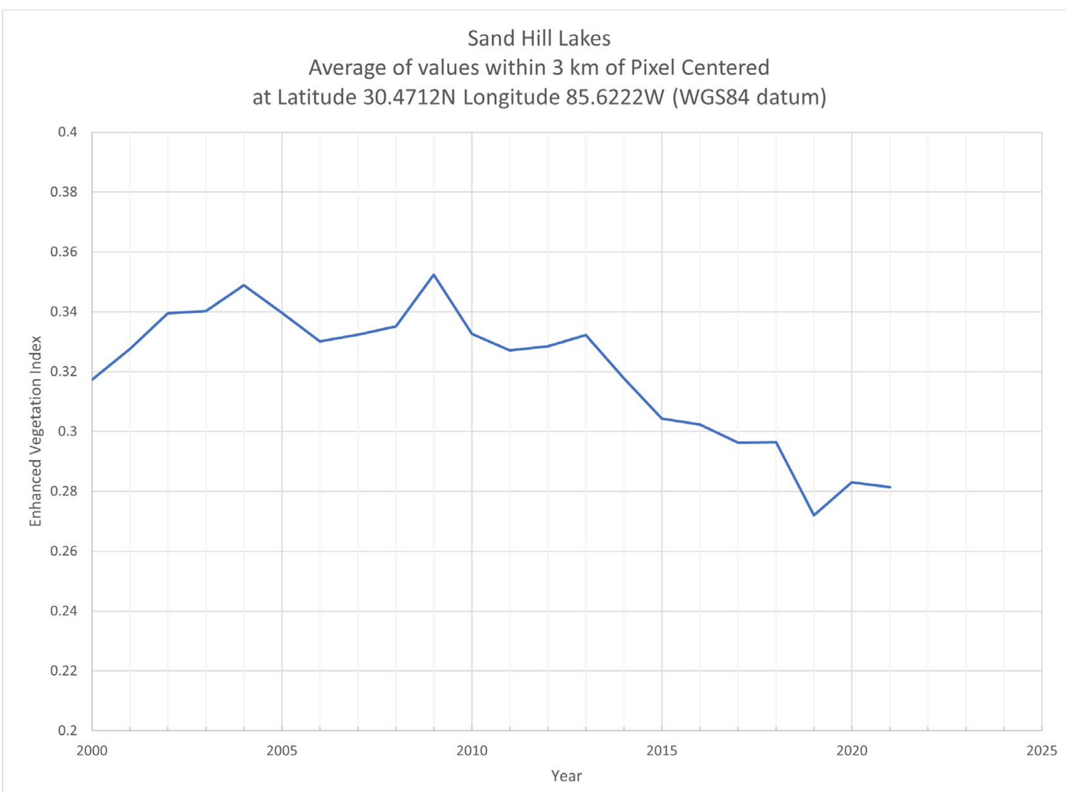

Figure 3-15. Enhanced vegetation index (EVI) values for the Sand Hill Lakes region watersheds, 2000 - 2021

4 Hydrogeology, Groundwater Levels, and Lake-Groundwater Interactions

Three primary hydrogeologic units underly the study area of southern Washington, Bay, and western Gulf counties: the shallow surficial aquifer system (SAS), the intermediate confining unit or intermediate aquifer system (ICU/IAS), and the Upper Floridan aquifer (UFA). The SAS is the shallowest of these three units and generally consists of unconsolidated deposits of sands and sandy clayey sands of the Pliocene age Citronelle Formation or more recent deposits in the areas of interest in Bay, western Gulf, and southern Washington counties (Rupert and Means, 2009; Schmidt and Clark, 1980). In the Sand Hill Lakes region of southern Washington and northern Bay counties, the SAS generally ranges from 50 to 75 ft in thickness (Figure 4-1 and Figure 4-2; Kwader, 2011; Florida Geological Survey Borehole Sample database, accessed June 1, 2022; Schmidt and Clark, 1980). The Pliocene and more recent deposits of the SAS increase in thickness with proximity to the Gulf of Mexico, reaching a thickness of 150 ft or more in some coastal areas of Bay County (Schmidt and Clark, 1980) and in the area of central Gulf County that includes Wetappo Creek (Williams and Kuniansky, 2016, Figure 20). The ICU/IAS consists of low-permeability clays and interbedded carbonates (Rupert and Means, 2009). Although the ICU/IAS may be a source of groundwater at local scales, regionally the ICU/IAS acts as an upper confining unit to the UFA. The thickness of the ICU/IAS ranges from 50 ft or less to around 100 ft in the Sand Hill Lakes region and increases in thickness towards the coastal areas of southeastern Bay and southwestern Gulf counties, where it is more than 350 ft thick. Underlying the ICU is the UFA, which consists of a sequence of carbonate rocks of Miocene to Eocene age that are the primary source of groundwater in the study area. The UFA is generally 200 to 400 ft thick in this area (Williams and Kuniansky, 2016, Figure 25).

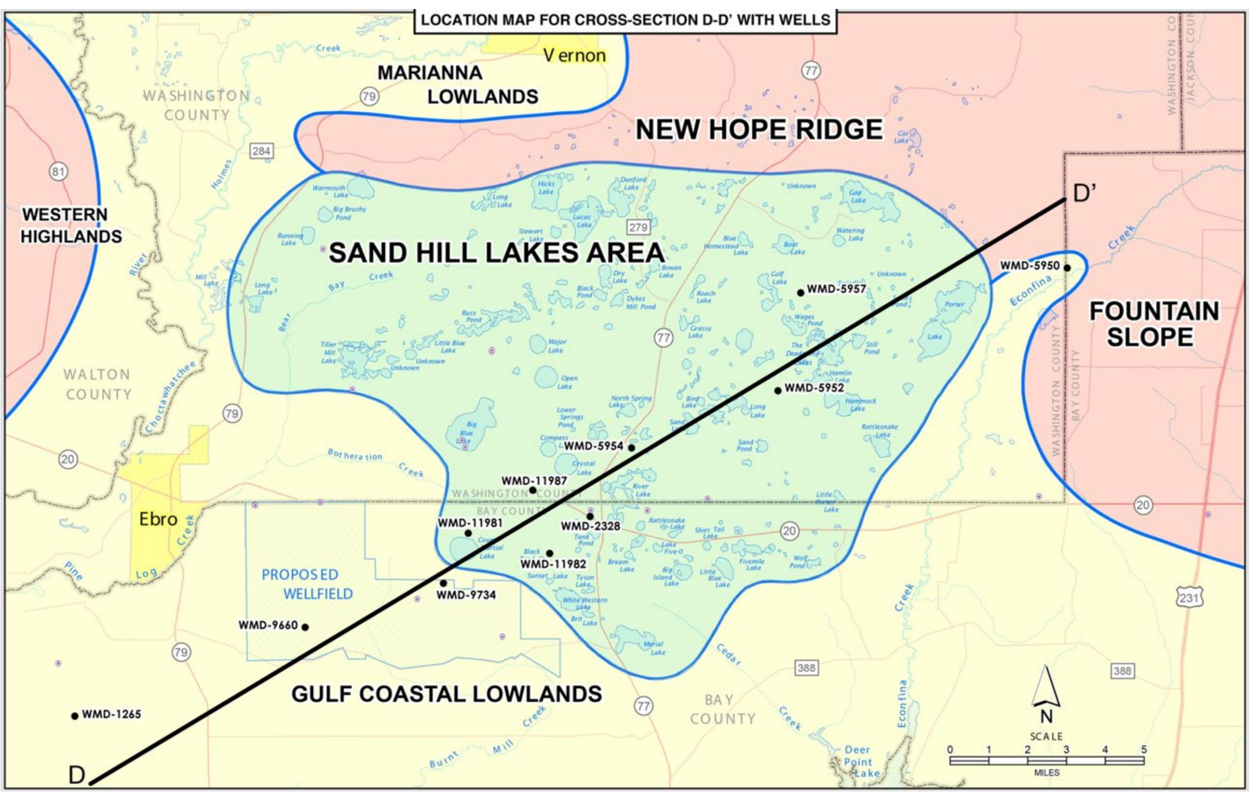

Figure 4-1. Location of Sand Hill Lakes area in Bay and Washington Counties, and Geologic Cross Section D-D' (Kwader, 2011)

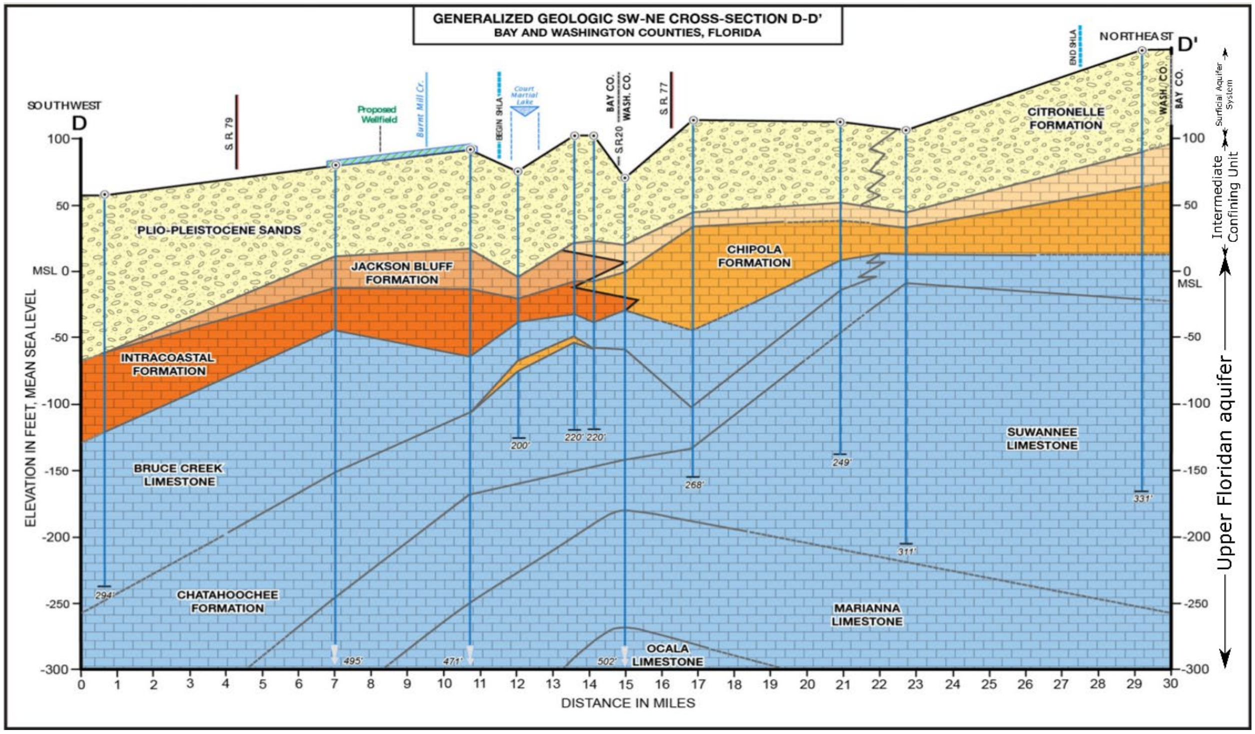

Figure 4-2. Generalized geologic cross section D-D' through southern Washington and northern Bay counties (Kwader, 2011)

A key aspect of the hydrogeology in the Sand Hill Lakes region of northern Bay and southern Washington counties is that the carbonate rocks of the UFA have undergone extensive dissolution over geologic time. In this process, small, preferential pathways for groundwater flow, such as fractures in the rocks and contacts between sedimentary bedding planes, widen over time as infiltrating, weakly acidic water that recharges the aquifer dissolves the rock along these preferred pathways. The increased porosity greatly increases the hydraulic conductivity of the rocks and transmissivity of the aquifer, which allows large quantities of groundwater to flow under moderate hydraulic head gradients. It also accounts for the presence of karst features, such as the large springs along the middle reaches of the Econfina Creek and sinkhole lakes and closed depressions found in the Sand Hill Lakes region.

The SAS and ICU/IAS are thicker in the area underlying Bayou George Creek and the Wetappo Creek drainage basins than they are in the Sand Hill Lakes region. This is particularly the case for the Wetappo Creek basin where the combined thickness of the SAS and ICU can exceed 400 ft. The UFA is therefore more effectively confined under these basins, which limits the exchange of water between the SAS and UFA. It may also explain, at least in part, why these areas do not exhibit the karst features like sinkhole lakes and other closed depressions that are evident in the Sand Hill Lakes region. The transmissivity of the UFA in the areas of Bay and Gulf counties drained by Bayou George Creek and Wetappo Creek may also be lower because of the increased UFA confinement in these areas.

Some additional description of the hydrogeologic characteristics unique to the Sand Hill Lakes region are provided in the text that follows. This is followed by a description of regional patterns of groundwater flow, historical groundwater levels and their relation to historical patterns of rainfall and recent flooding.

4.1 Hydrogeology of Sand Hill Lakes Region

The previously described process of dissolution of the carbonate rocks in the UFA by weakly acidic groundwater from the overlying SAS has resulted in the karst topography in the Sand Hill Lakes region (Figure 4-3). The topography is generally devoid of channelized surface drainage (stream networks) and is relatively flat except near the numerous closed depressions and sinkhole lakes (Figure 4-4 and Figure 4-5). This region has some of the highest densities of closed topographic depressions within the extent of the Floridan aquifer system (Figure 4-6). These closed depressions and sinkhole lakes have formed over time as the carbonate rocks of the UFA have dissolved, leaving large voids in the UFA that are incapable of supporting the overlying ICU and SAS sediments during dry conditions. Under such conditions, the ICU and SAS sediments collapse into these voids, forming closed topographic depressions that can become lakes. The sandy sediments of the SAS can be quite permeable and form high conductance connections between the sinkhole lakes, SAS, and UFA when they fill the sub-lake breaches in the ICU (Figure 4-7). The frequency and extent of these closed depressions indicates the volume and degree to which the carbonate rocks of the UFA have been dissolved and the extensive nature of secondary porosity that contributes to the transmissivity of the UFA in the Sand Hill Lakes region.

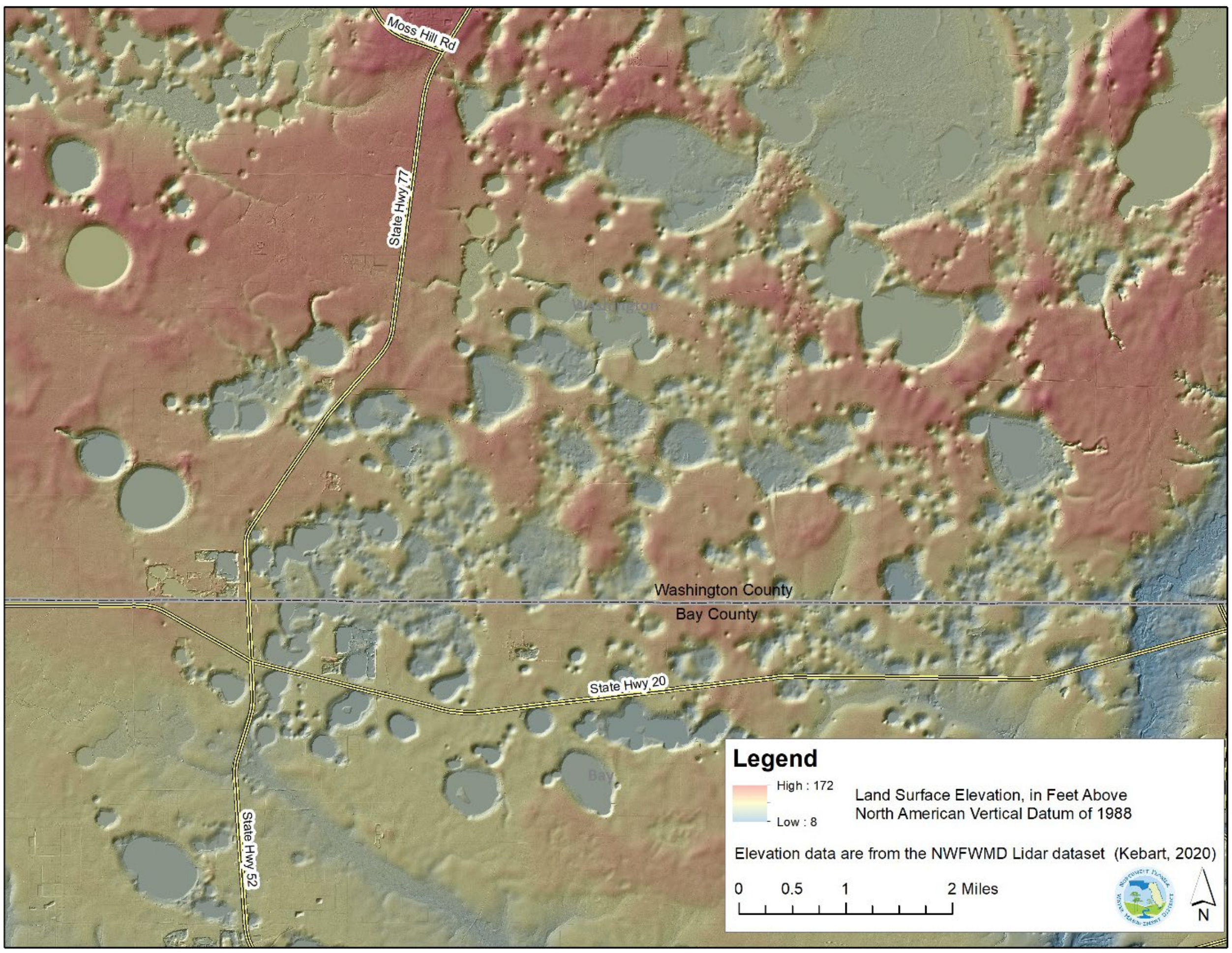

Figure 4-3. Topography of the Sand Hill Lakes region in southern Washington and Northern Bay counties

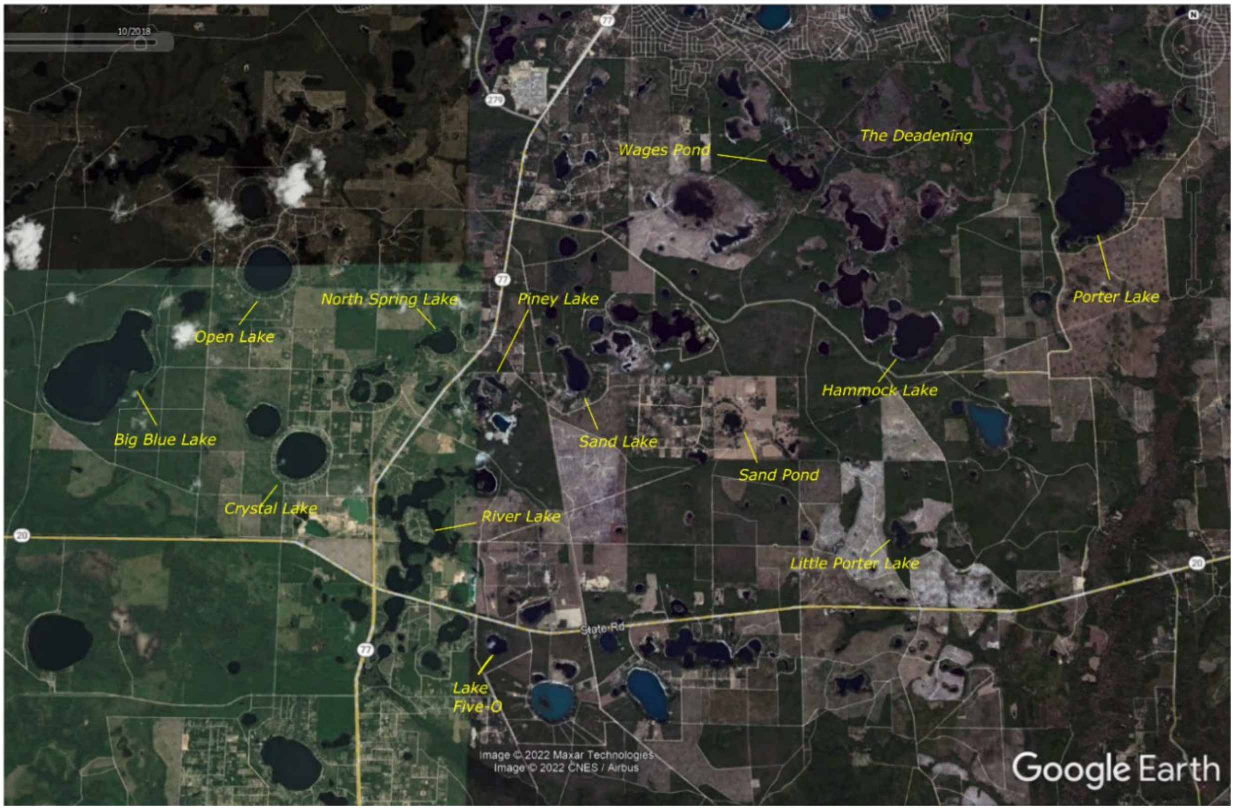

Figure 4-4 Aerial image of Sand Hill Lakes region on October 11, 2018, immediately following the passage of Hurricane Michael

Figure 4-5. Aerial image of Sand Hill Lakes region during December 2012, a period of extremely dry conditions

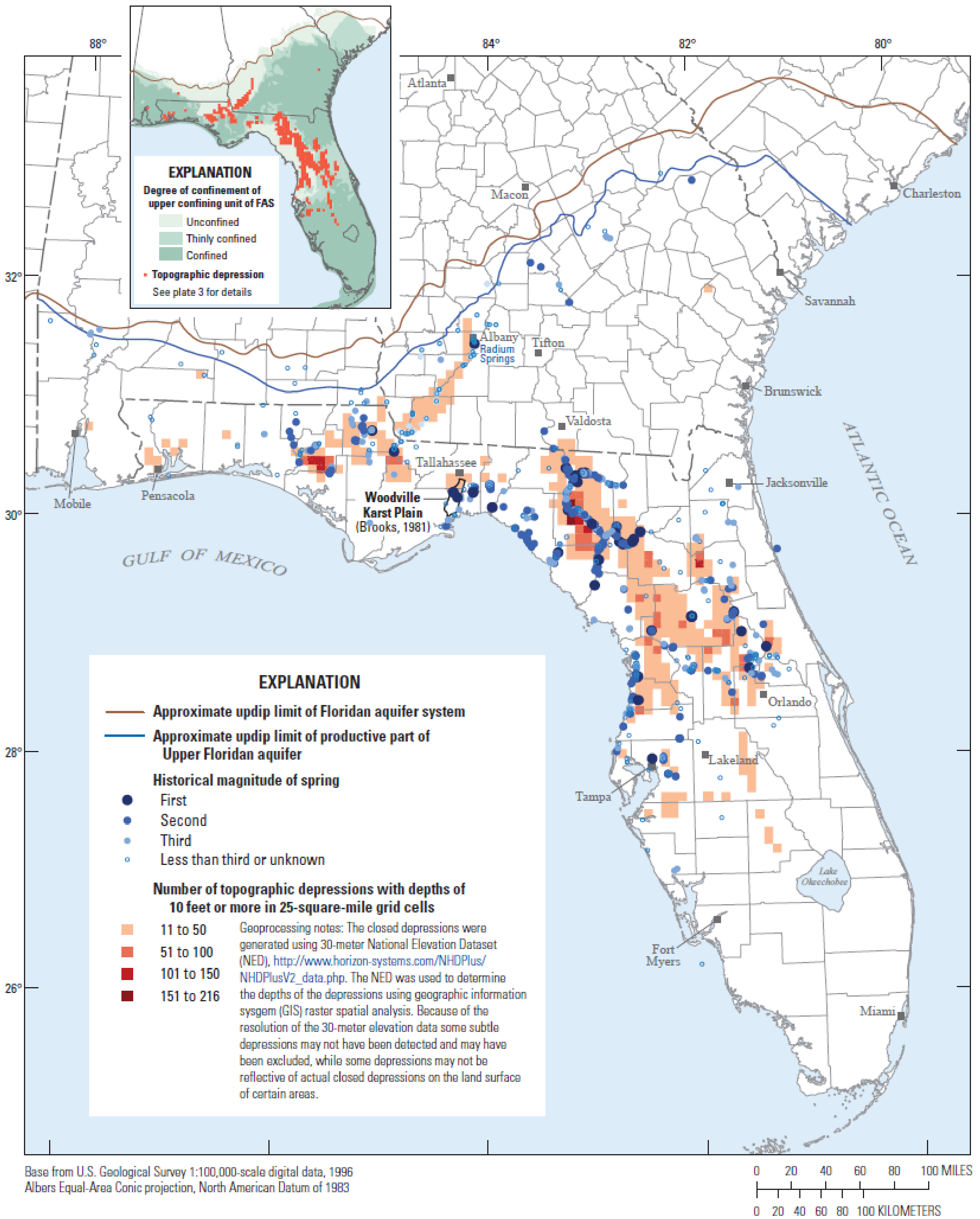

Figure 4-6. Density of closed topographic depressions in the area underlain by the Floridan aquifer system (Williams and Kuniansky, 2016)

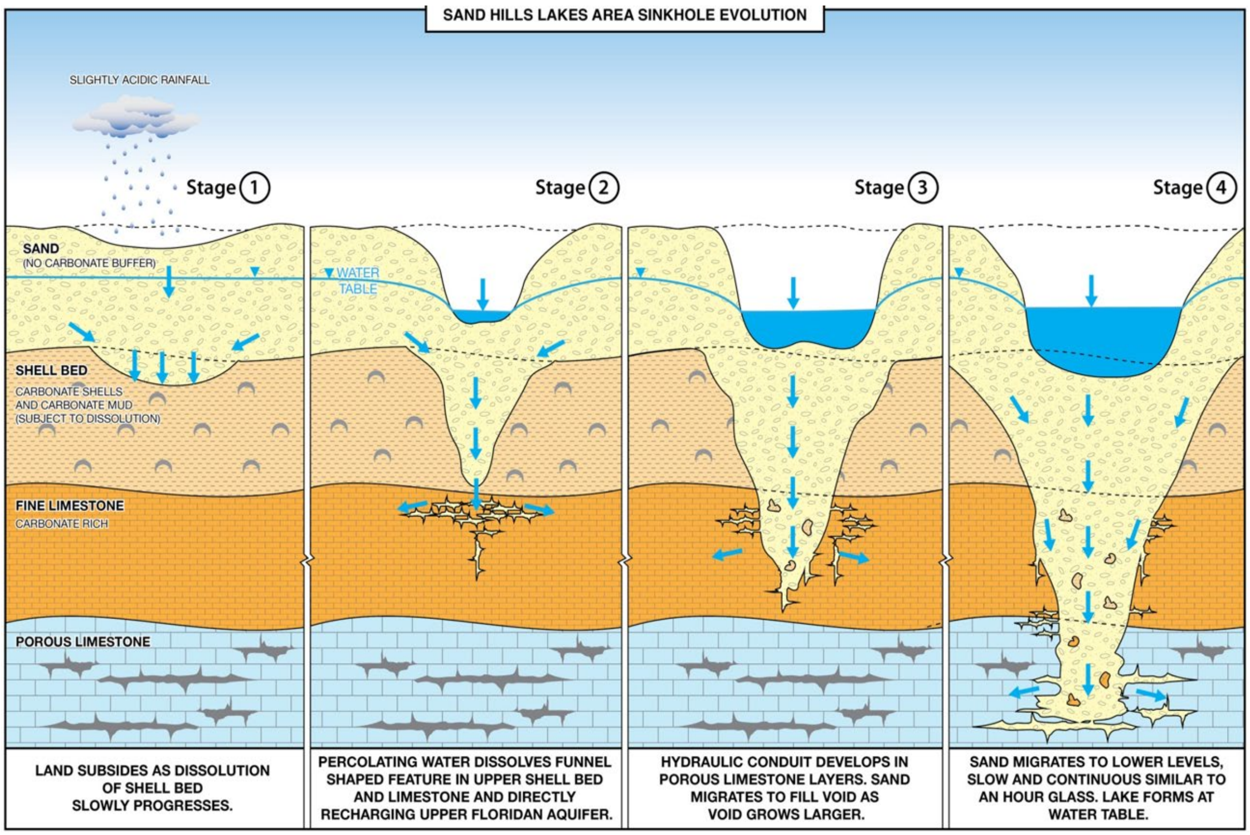

Figure 4-7. Sinkhole and lake formation in the Sand Hill Lakes region in southern Washington and northern Bay counties (Kwader, 2011)

The Sand Hill Lakes region is generally drained internally, so excess rainfall (rainfall that exceeds the evaporation and transpiration losses) moves downward through the SAS and ICU into the UFA, from where it can move laterally towards the Gulf of Mexico (Figure 4-8). Internally drained areas such as this are often referred to as closed basins because water doesn't exit the basin through a well-defined stream channel, but instead exits as groundwater flow. There are some areas in the western and southern portions of the Sand Hill Lakes region that do have streams that discharge outside of the basin. These areas are adjacent to Pine Log, Bear Bay, and Cedar creeks (Figure 4-9). Most of the areas with reported flooding in Washington County are topographically low areas within internally drained, closed basin areas.

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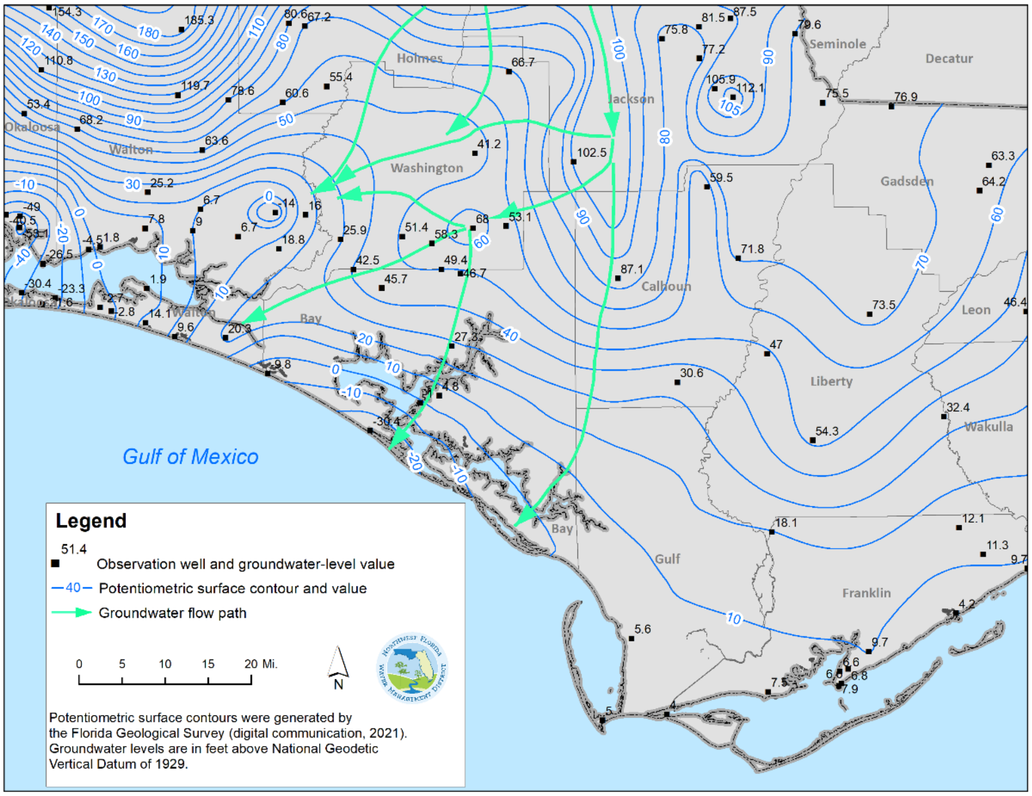

Figure 4-8. Potentiometric surface of the Upper Floridan aquifer during May 2019 with groundwater flow paths (green)

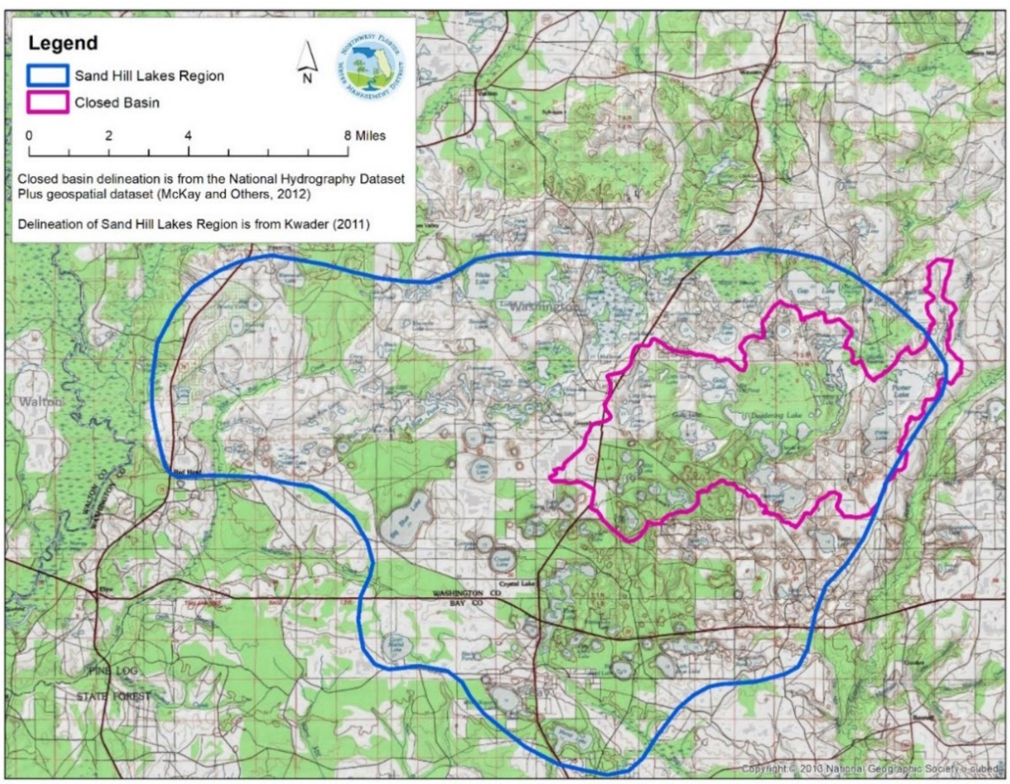

Figure 4-9. Location of White Oak Creek closed basin and Sand Hill Lakes region

The internally drained, closed-basin nature of the Sand Hill Lakes region has developed due to several factors. Soils in this area are typically excessively drained, highly permeable sands, which, along with the generally flat topography, minimizes the potential for direct (storm) runoff and the creation of channelized stream networks. A higher potential for direct runoff exists in localized areas, such as steeply sloped areas adjacent to lakes or depressions, near wetlands, or in disturbed areas such as roadways, residential developments, or sand mines where the soil is compacted or covered with less pervious or impervious material. However, even where localized direct runoff does occur, it is typically directed to adjacent, closed-depression features such as lakes or wetlands and then leaks downward to the UFA. The sandy soils in this area also typically have a low cation-exchange capacity. The likely presence of similar sandy, low cation-exchange capacity sediments within the SAS and the SAS-infilled breaches in the ICU accounts for the weakly acidic nature of the groundwater recharging the UFA in this area, creating the potential for additional dissolution of UFA rocks and enlargement of existing karst features or creation of new karst features.

4.2 Groundwater Levels in Relation to Flooding

Groundwater levels in the UFA in the study area generally range from about 70 ft NAVD88 in southern Washington County and decline with proximity to the Gulf of Mexico, where levels are about 5 to 10 ft NAVD88 in western Gulf County, -20 to 0 ft NAVD88 in southern Bay County (Figure 4-8). Accordingly, groundwater in the UFA generally flows towards the Gulf Coast, although pumping-induced depressions in the potentiometric surface of the UFA in coastal areas of Okaloosa and Walton counties have induced southwesterly groundwater flow towards these depressions from some portions of the study area (Figure 4-8).

Flooding can occur when groundwater levels approach or rise above land surface. This typically occurs in low-lying areas after sustained periods of above-normal rainfall extending a few months or longer. It can also occur over much shorter periods in areas where groundwater levels are particularly shallow, and the area lacks good surface drainage. Both conditions appear to be the case where flooding has occurred in the Sand Hill Lakes region. These conditions may have also led or contributed to flooding in other parts of the study area.

As noted previously, PRISM rainfall data for the Sand Hill Lakes region indicate the 24-month rainfall total for the period ending in October 2018 was higher than approximately 98 percent of the other 24-month totals for the January 1895 to April 2022 period spanned by the PRISM dataset. For the 43-month period after Hurricane Michael (October 2018 to April 2022), the total rainfall for this same grid cell was higher than approximately 98 percent of other 43-month periods over the 1895-2022 period of record. Some of the largest departures from typical monthly rainfall totals also occurred at this location during the period from August to December 2018 and during the fall of 2021. For example, the rainfall totals for August, November, and December of 2018, were approximately 12, 10, and 12 inches above the 30-year rainfall normals for these months. Similarly, the cumulative rainfall for the months of August through October of 2021 was about 29 inches higher than the corresponding cumulative 30-year rainfall normals for these months. Notably, the timing of flooding in the Sand Hill Lakes region from late 2018 to 2021 coincides with wetter than normal conditions and occurred following a period of higher-than-normal rainfall. The cumulative rainfall total from the PRISM data set for the years from 2013-2021 was about 128 inches higher than the 1991-2020 rainfall normal for this same 9-year period, which is equivalent to an average departure of about 14 inches per year during this period.

Groundwater levels are generally correlated with prior accumulations of rainfall (antecedent rainfall). The historically high rainfall totals observed in the years prior to and following Hurricane Michael are reflected in the groundwater levels observed in the SAS and UFA at the two long-term groundwater level monitoring wells near Greenhead, Florida (Figure 4-10 through Figure 4-12). The periods of record for these two wells are the longest in the study area, extending back to September 1962. In the SAS well (District Well ID 003217), groundwater levels rose by about 8 ft from January 2018 to December 2018, when they reached highest levels recorded during the nearly 60-year period of record. Groundwater levels were already higher than normal prior to the arrival of Hurricane Michael. The median groundwater level at the Greenhead UFA well was 61.89 ft NAVD88 for the month of September 2018 (prior to the landfall of Hurricane Michael on October 8, 2018), which was higher than approximately 70 percent of the other monthly median groundwater levels at this site. Peak groundwater levels occurred four months later in February 2018, following a very high rainfall total of more than 30 inches during the final three months of 2018 based on the PRISM rainfall dataset.

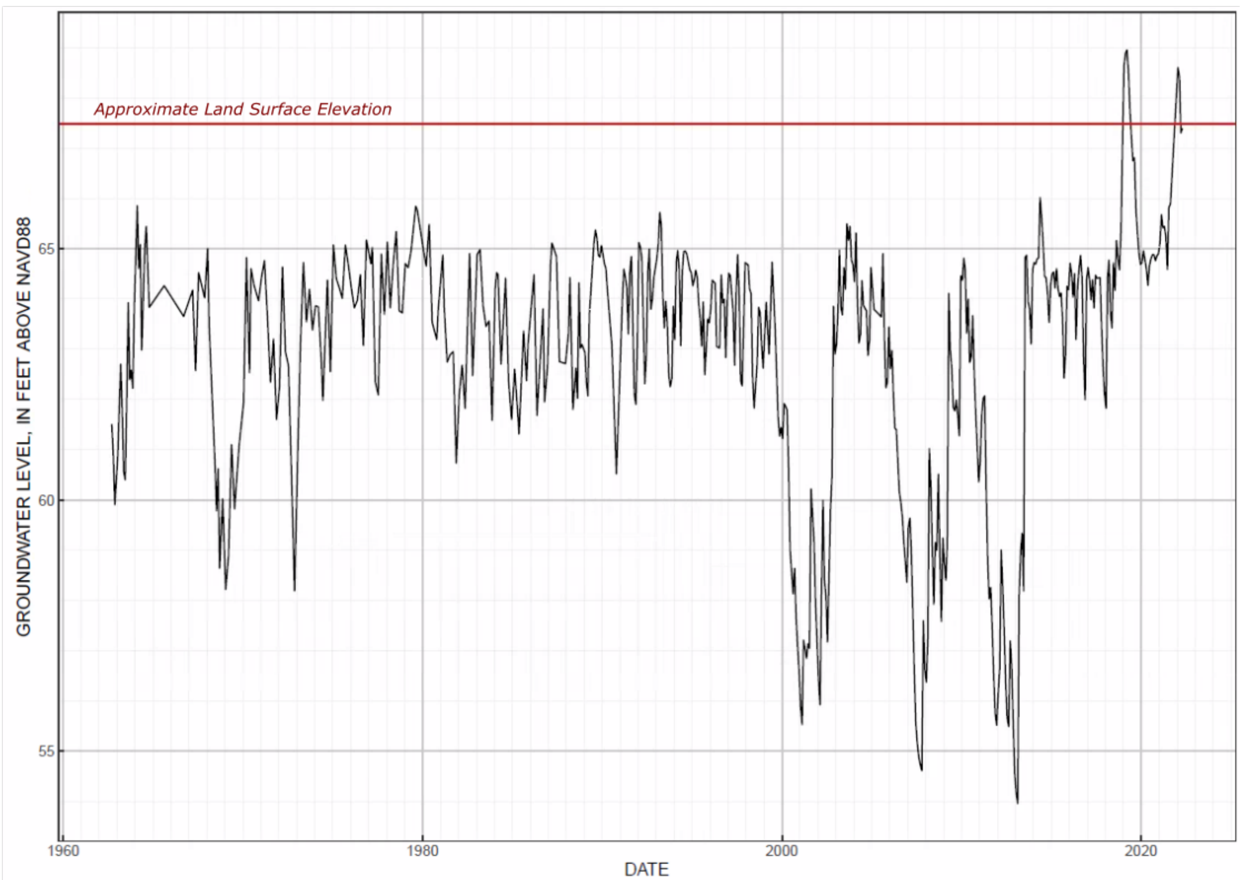

Figure 4-10. Median monthly groundwater levels in the surficial aquifer system well near Greenhead, Florida (District Well ID 3217) for the period of record

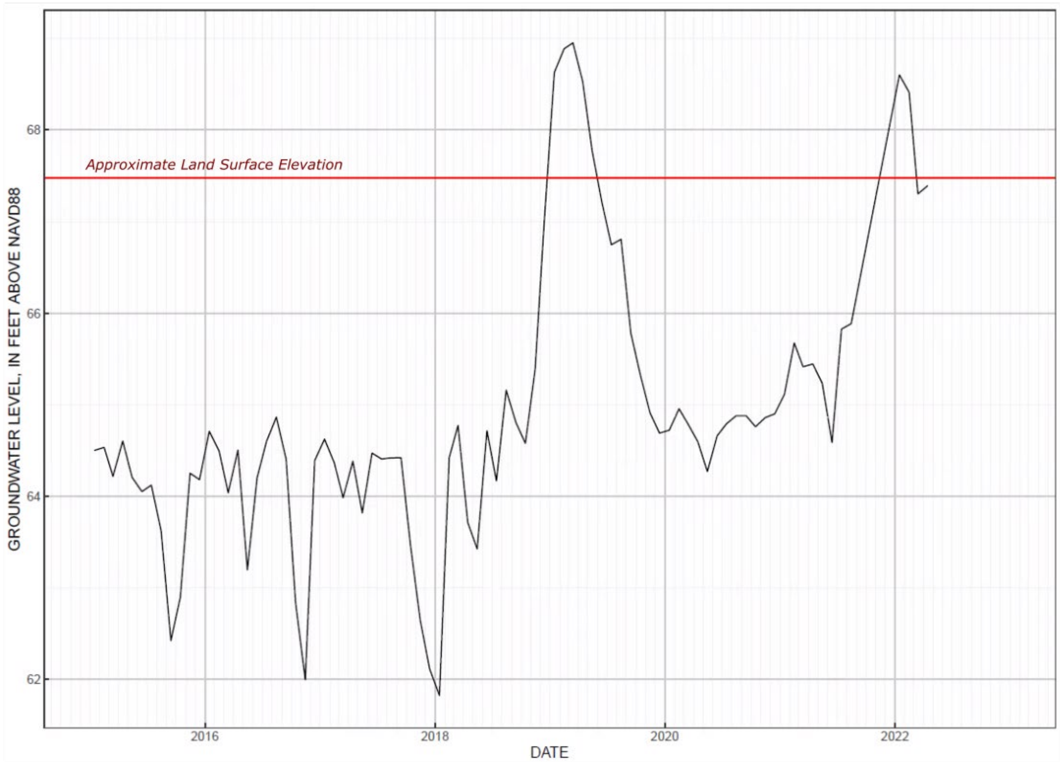

Figure 4-11. Median monthly groundwater levels in the surficial aquifer system well near Greenhead, Florida (District Well ID 3217) for the period since January 2015

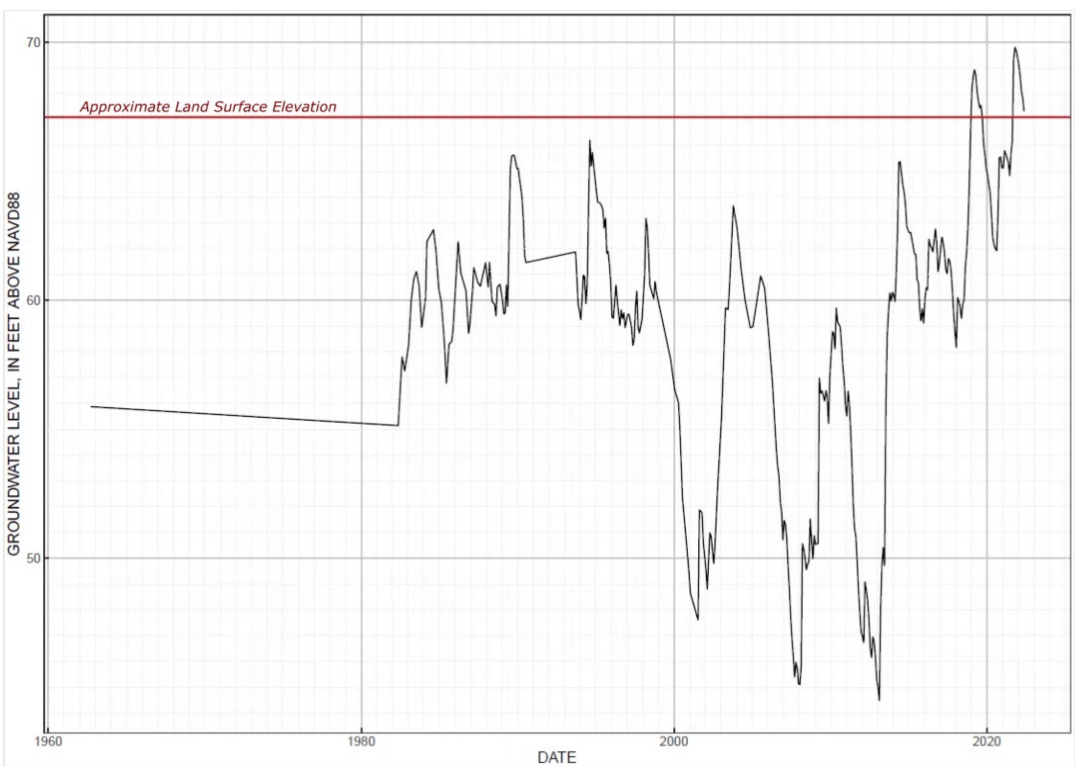

Figure 4-12. Groundwater levels in the Upper Floridan aquifer well near Greenhead, Florida (District Well ID 3216) for the period of record

Table 4-1. Observation wells cited in this report

Map Index Number	District Well ID	Well Name	County	Well Use	Hydrogeologic Unit	Measurement Method
12	5950	NWFWMD-TRAPP POND FLORIDAN	Bay	Monitor	Floridan Aquifer	Recorder
13	5958	NWFWMD-GEORGE'S 40 FLORIDAN	Bay	Monitor	Floridan Aquifer	Recorder
35	3216	USGS-422A NEAR GREENHEAD/S834	Washington	Monitor	Floridan Aquifer	Recorder
35	3217	USGS-422B NEAR GREENHEAD	Washington	Monitor	Surficial Aquifer	Recorder
40	5953	NWFWMD-POWER LINE/S731	Washington	Monitor	Floridan Aquifer	Recorder
41	5960	NWFWMD-PORTER POND EAST	Washington	Monitor	Floridan Aquifer	Recorder
42	5961	NWFWMD-SECTION 20	Washington	Monitor	Floridan Aquifer	Recorder

Because of the wetter than normal conditions prior to and during the latter part of 2018, groundwater levels rose above land surface in December 2018 at the Greenhead monitoring wells (map ID 35) and flooded the site for the first time in the period of record. Flooded conditions persisted at this site through late May 2019, and then resumed in the fall of 2021. Monthly rainfall totals from the PRISM dataset during May 2018 through December 2018 were extremely high, with totals from these months exceeding 70 percent of months in the 127-year period of record. Totals for six of the eight months approached or exceeded 90 percent of the months in the 127-year period.

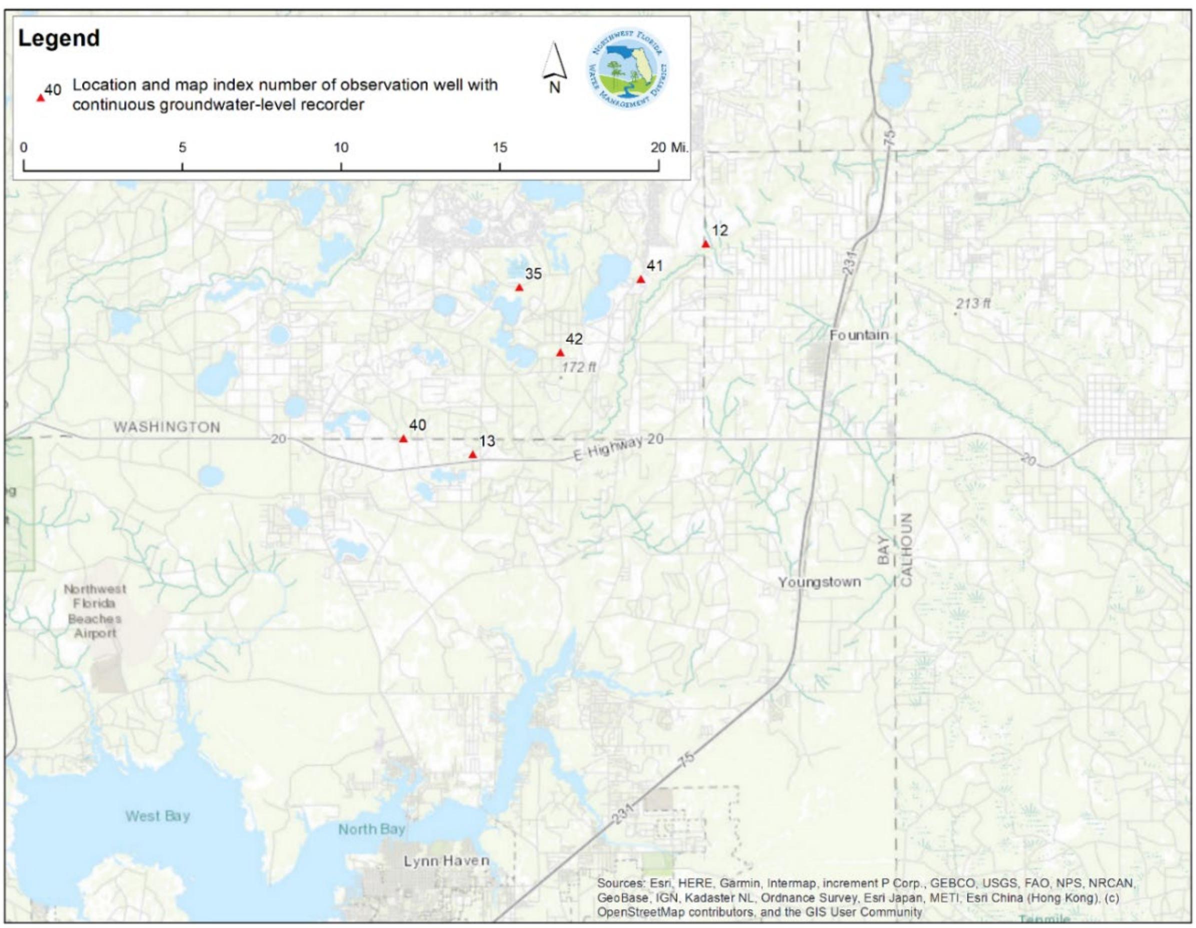

Figure 4-13. Locations of observation wells listed in Table 4-1

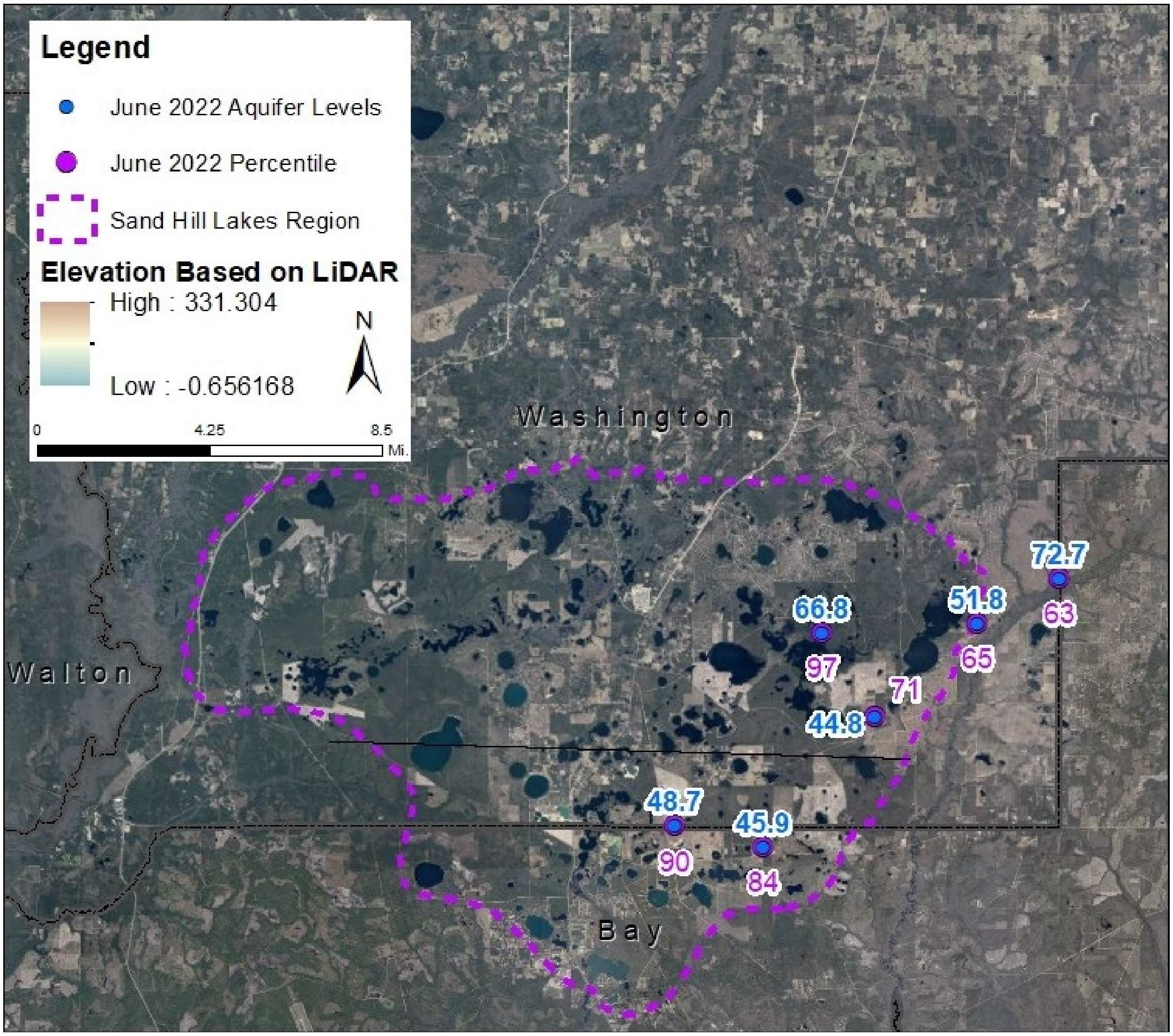

Figure 4-14. Groundwater levels and associated period of record percentiles for wells in the Sand Hill Lakes region, June 2022

The temporal pattern of flooding at the Greenhead site (Figure 4-10, Figure 4-11, and Figure 4-12) also illustrates the important roles that surface drainage and hydrogeology can play in groundwater-related flooding. The Greenhead site is within an extensive, topographically low area of Washington County known as the Deadening lakes area (Musgrove et al., 1965). Because of the topography and location within an internally drained closed basin, the Deadening lakes are prone to flooding because they receive surface and groundwater discharge from adjacent, topographically higher areas, which manifests as lakes and broad wetland features. The closed nature of the drainage basin means that the water that collects in these low-lying areas during or following wet conditions can only drain out through the subsurface, and at rates that are typically much slower than areas with surface drainage outlets. This problem is compounded in the Deadening lakes area because, unlike most areas of the Sand Hill Lakes region, lakes in this area can receive large quantities of surface water runoff. During wet periods, flow from White Oak Creek that doesn't flow to Porter Lake or Gap Pond flows to this area through Blackwater Slough, to Howard Swamp, Sill and Wages ponds, and Gully, Hamlin, and Hammock lakes, and other connected, topographically low areas. The internally drained nature of the area, surface water inputs, and low and flat topography of this area are all factors that have contributed to the flooding reported at residential properties along Wages Pond following recent periods of high rainfall.

The water table at the Greenhead wells is very shallow, generally fluctuating within about two to six feet below land surface. This increases the potential for flooding at the site. This potential for flooding is mitigated by the land surface elevation at these wells, which is a few feet higher than the surrounding Deadening lakes area, the large surface storage of the Deadening lakes area (owing to its breadth and flat topography), and because the wells are within an area that drains southward to Hamlin and Hammock lakes. Despite these mitigating factors, the historically high rainfall rates since 2018 have been sufficient to cause flooding at the Greenhead wells and nearby areas such as Wages Pond. Musgrove and others (1965) noted that the topography of the area "… shows that Deadening lakes to be completely covered with water at an elevation of 69 ft" and "Based on flood marks, about 70 ft is the highest elevations that the lakes have reached." Therefore, flooded conditions may have also occurred historically at the Deadening lakes in extremely wet periods prior to the earliest groundwater level measurements at the SAS Greenhead well.

Shallow groundwater conditions can also be associated with flooding in basins that are not internally drained and may have contributed to flooding in areas near Bayou George Creek, Bear Creek, and Wetappo Creek in Bay and western Gulf counties. The water table in these areas occurs at shallow depths because of the generally flat topography and proximity to the coast. The potentiometric surface in the Upper Floridan aquifer in this area is generally within 10 to 15 ft of land surface and the aquifer is well-confined, which limits the potential for shallow groundwater to move downward into the Floridan aquifer system and away from flooded areas. These conditions contribute to shallow water table conditions that increase the potential for flooding in low-lying areas during extended periods of higher-than-normal rainfall.

4.3 Factors Affecting Lake Levels, Lake-Groundwater Interactions, and Flooding near Lakes and Wetlands

Flooding has been reported on properties adjacent to Piney Lake, Sand Lake, Wages Pond, Spring Pond, Gap Lake, and Watering Lake. Flooding-related complaints have also been reported at Porter Lake, Little Porter Lake, Sparkleberry Lake, and Hammock Lake in the Sand Hill Lakes region. This section describes key factors that affect lake levels, exchanges of water between and aquifers, and flooding near lakes, wetlands, and topographically low areas.

As noted previously, a lower permeability ICU is generally present between the SAS and UFA. Lakes and topographic depressions in the Sand Hill Lakes region typically coincide with breaches in the ICU. The vertical hydraulic conductivity of the ICU strongly affects lake and water table levels in the region. This is illustrated in Figure 4-15 and Figure 4-16. The sediments of the overlying SAS are typically much more permeable than those of the ICU, so water from the lake and groundwater from the SAS can leak downward into the UFA much more readily when the ICU is breached. Lake levels and water table levels near the lake will also be much more similar to the level of the UFA potentiometric surface because of this breaching. The downward rate of leakage of water from the lake and SAS to the UFA and the similarity of lake levels and UFA groundwater levels will be higher when the breach in the ICU beneath a lake is filled with more permeable SAS sediments (Figure 4-15a) than they would be if this breach were filled less permeable ICU sediments (Figure 4-15b).

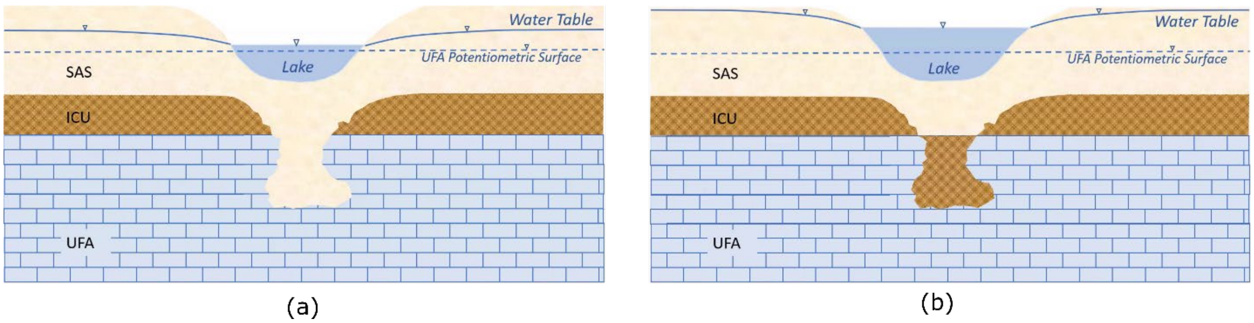

Figure 4-15. Water table and lake levels where confining unit breaches are filled with (a) more permeable sediments and (b) less permeable sediments

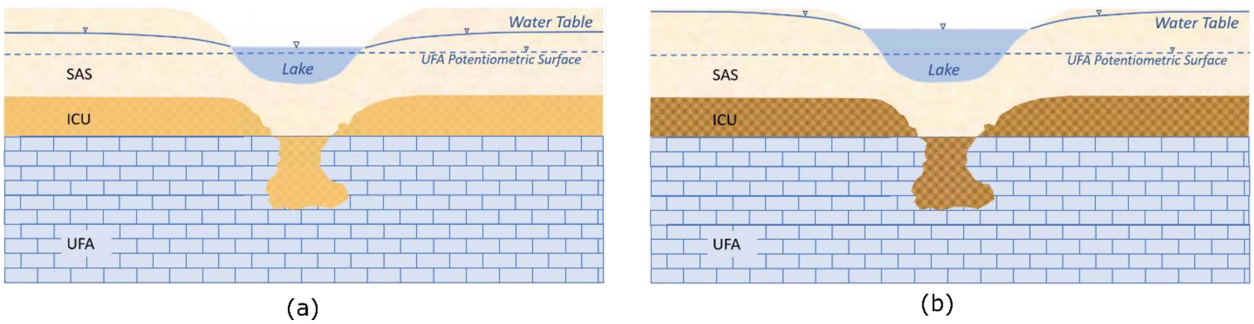

Figure 4-16. Water table and lake levels where the hydraulic conductivity of the intermediate confining unit is (a) high and (b) low

The degree of this hydraulic connection between UFA and overlying lakes and the SAS is expressed quantitatively as hydraulic conductance, a term in Darcy's law, which is an equation that describes the movement of groundwater:

$$Q = KA\frac{dh}{dl} = Cdh$$

where: Q represents the rate of groundwater flow,
K represents the hydraulic conductivity along the path of groundwater flow,
A represents the area through which the flow is occurring,
dh represents groundwater level (head) difference along the path of groundwater flow,
dl represents distance along the path of groundwater flow, and
C represents the hydraulic conductance of the groundwater flow path, which is equal to KA/dl.

In the equation above, the head difference term (dh) is an expression of the potential energy difference available for moving groundwater along a flow path. In effect, it represents the driving force for groundwater flow and the equation essentially states that for less conductive (lower C) flow paths, there must be a larger head difference (dh) to move water at a given volumetric rate.

Rainfall that is not returned to the atmosphere as evapotranspiration must generally flow downward through the SAS and into the UFA before it can move out of this area. Therefore, over time, the average rate of groundwater flow from the SAS to the UFA will be approximately equal to the difference between rainfall and ET (less the small amount of direct runoff that occurs to a few streams that drain the area). Groundwater moves through the SAS to the UFA at this average rate because the head difference between the SAS (and lakes) and the UFA is higher in areas where groundwater flow paths from the SAS to the UFA are less conductive, and lower in areas with more conductive flow paths.

Lake levels rise whenever the difference between rainfall and ET (net precipitation) exceeds the rate at which water can leak from the lake into the aquifer and fall whenever this difference is less than the leakage rate. Rainfall is typically much more variable than ET, so extreme hydrologic conditions such as floods and droughts are typically associated with extremes in rainfall. ET can be a contributing factor, and lower than normal ET rates can exacerbate flooding conditions caused by higher-than-normal rainfall. Variations in lake levels are also affected by the spatial differences in the hydraulic conductivity of groundwater flow paths between the SAS and UFA. Lake level variations will mimic variations in the UFA potentiometric surface level much more closely in areas where the hydraulic conductivity between the SAS and UFA is high (Figure 4-16).

Figure 4-17 which depicts the relation between water level declines from 2004 to 2007 in the Sand Hill lakes and the differences between lake and Floridan aquifer groundwater levels (Kwader, 2011). The data in this figure indicates that lake level declines due to below average rainfall were generally smaller for lakes where the differences between lake and UFA groundwater levels were larger, and where the conductance of the groundwater flow path between the SAS (and lake) and UFA was presumably less. This is also consistent with the inference that lake levels are more sensitive to variations in the head in the UFA for lakes that have high-permeability connections to the UFA.

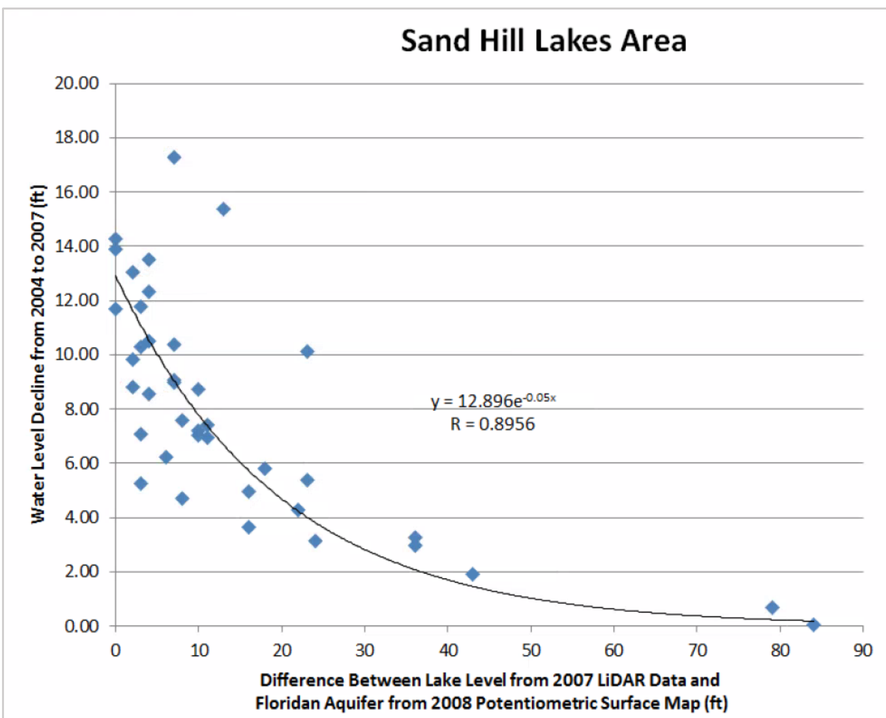

Figure 4-17. Relation between lake water-level declines and the differences between lake and Floridan aquifer levels (Kwader, 2011)

Lake level data for Piney Lake were reviewed for the period from December 17, 2021, through early August 2022 (Figure 4-18). The level of Piney Lake approached elevations that caused flooding at the lowest lying, lakefront properties during late 2021. Large pumps were transported to the lake and used to withdraw water from the lake during the period from December 18, 2021, through February 20, 2022, and transport it through a temporary pipeline to a location on District property east of the lake. The lake level data appear to show some effects from this pumping because the lake-level recession rate was a little more than twice the recession rate of the groundwater levels in underlying Upper Floridan aquifer during that pumping period. A second pumping period occurred from October 5 to November 2, 2022, while this report was in preparation.

Available data indicate that lake levels rose by about 0.2 ft from March 23 through April 25, 2022, while groundwater levels in the UFA (e.g., Power Line and Section 20 wells on Figure 4-18) declined by approximately 0.5 ft. Although groundwater levels in the UFA probably influence Piney Lake levels to some degree, the temporal patterns of lake and groundwater levels suggest that the breaching of the ICU under Piney Lake may be less conductive than some of the deep sinkhole lakes in the region, and that Piney Lake levels may be more sensitive to local rainfall conditions and exchanges of groundwater with the SAS. The high levels of Piney Lake observed during 2021 and 2022 are likely caused by the extremely high rainfall total during the summer through fall of 2021 and higher-than-normal rainfall amounts in January and March of 2022. Historical aerial imagery indicates that Piney Lake can experience large variations in lake levels and surface area and can almost completely dry out under drought conditions, as described below.

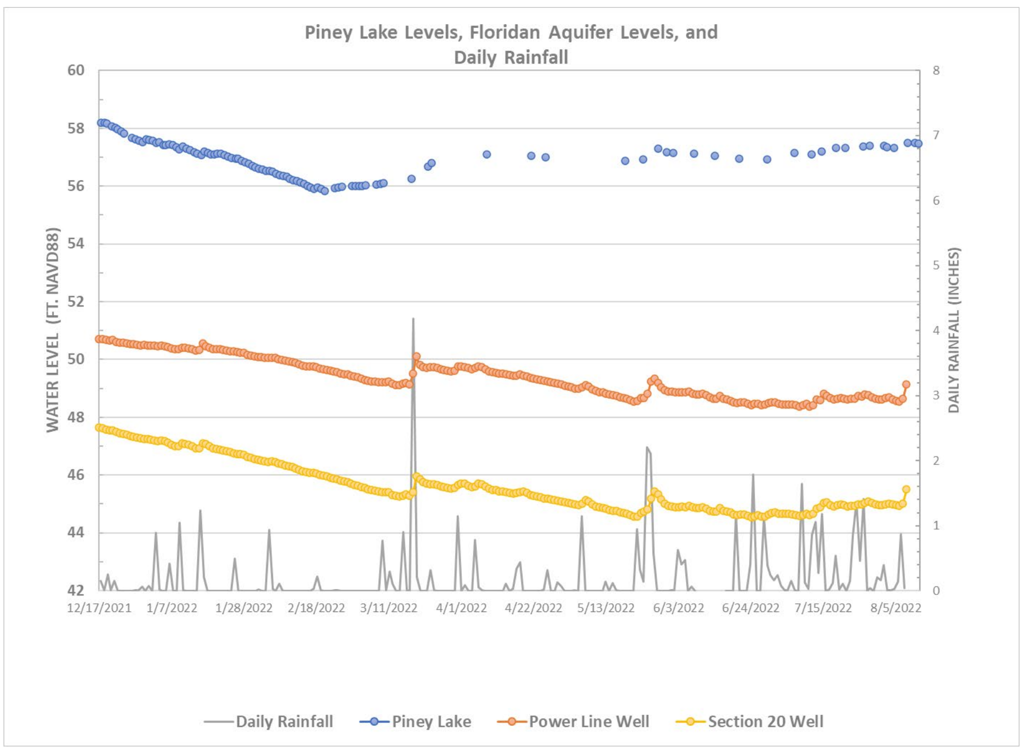

Figure 4-18. Piney Lake levels, Floridan aquifer levels, and daily rainfall, December 17, 2021 to August 11, 2022

Lake level and lake surface area variations are also a function of changes in the volume of water stored in the lake and the bathymetric characteristics of the lake. For example, the surface area of a shallow lake located in a gently sloping topographic depression will increase much more rapidly (for a given change in lake level) than that of a deep lake located in a more steeply sloped depression. Shallow lakes will also be more likely to dry out during drought periods, or flood areas near the shoreline during wetter than normal periods. This is illustrated by Figure 4-19, which depicts the relation between lake surface area and depth for two hypothetical lakes with conical cross sections that are identical except for the slope of the lakebed. This is particularly relevant to flooding of properties along the shorelines of lakes. Lakeside properties in steeply sloped depressional areas will generally be less likely to flood than lakeside properties at a similar distance from the shore of a lake in a less steeply sloped area because the former property will be at a lower elevation that is much closer to the typical elevation of the lake.

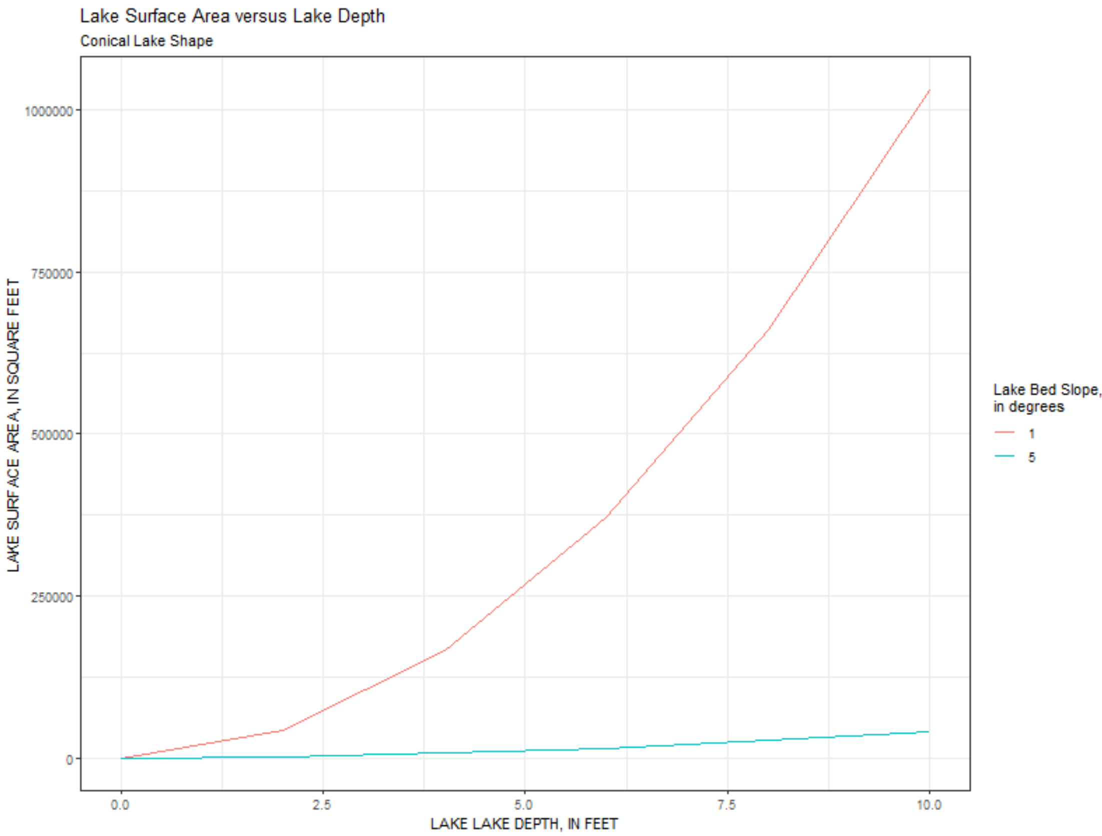

Figure 4-19. Relationship between lake area and lake depth for a hypothetical, conically shaped lake with lakebed slopes of 1 and 5 degrees.

Although a limited amount of historical lake level data is available for the region, aerial imagery can be used to assess the degree to which lake levels and inundated areas have varied over time. Historical imagery shows that the inundated area of some lakes in this region vary considerably as hydrologic conditions change from wet to dry, while the inundated area of other nearby lakes show much less variability (Figure 4-4 and Figure 4-5). For example, bathymetric data are available for Lake Five-O, Big Blue, and Crystal Lake and indicate that these lakes are very deep. The maximum depth of Lake Five-O is about 50 ft (Grubbs, 1995), and the maximum depths of Big Blue and Crystal Lakes are at least 75 ft (Upchurch, 2011). The areas inundated by these lakes changed by a relatively small amount from the dry conditions in December 2012 to the wet conditions in October 2018 (Figure 4-4 and Figure 4-5).

Aerial images of Big Blue Lake (Figure 4-20 and Figure 4-21) and Piney Lake (Figure 4-22 and Figure 4-24) also provide useful illustrations of variations in historical lake levels and inundated areas. Like other lakes in the region, both lakes are karst lakes with hydraulic conductances to the Upper Floridan aquifer that have been enhanced through breaches in the ICU beneath the lakes. Historical imagery indicates that the water surface elevation at Big Blue Lake has varied by at least 17 ft (Cantrell, 2011), and by 20 ft or more at Piney Lake. Imagery from an extremely dry condition in December 2012 (Figure 4-22 ; Google Earth and

Maxar Technologies © 2022) indicates that the level of Piney Lake was at least as low as 36 ft[1] above sea level[2] at that time, and that the lake was essentially dry except for a few isolated pools. This contrasts with much higher lake level of approximately 58 ft above sea level that was measured in December 2021. LiDAR-derived elevation estimates (Figure 4-23) also indicate that the level of Piney Lake was approximately 47.7 ft NAVD88 during April-May 2017 LiDAR data collection period, which is about 10 ft lower than the high level measured during December 2021.

Historical imagery of Piney Lake from May 8, 1949 (Figure 4-24a[3]; University of Florida aerial imagery collection) indicates that flooding conditions have occurred at this lake during past periods of sustained, higher than normal rainfall accumulations. The May 1949 image date indicates that what is usually a low-elevation peninsula in the center of Piney Lake became an island during the extremely wet conditions in 1949. The area inundated by Piney Lake during the May 1949 high water conditions appears to be greater than the area inundated in the high-water conditions images from October 2018 image ((b), Google Earth), December 2018 (Google Earth and Maxar Technologies © 2022), and February 2020 (Google Earth, CNES/Airbus © 2023; Maxar Technologies © 2023). PRISM estimates of historical rainfall indicate that the 24-month antecedent rainfall total for May 1949 was slightly lower, but comparable to the 24-month antecedent rainfall totals for October 2018, December 2018, and February 2020 (Figure 2-6).

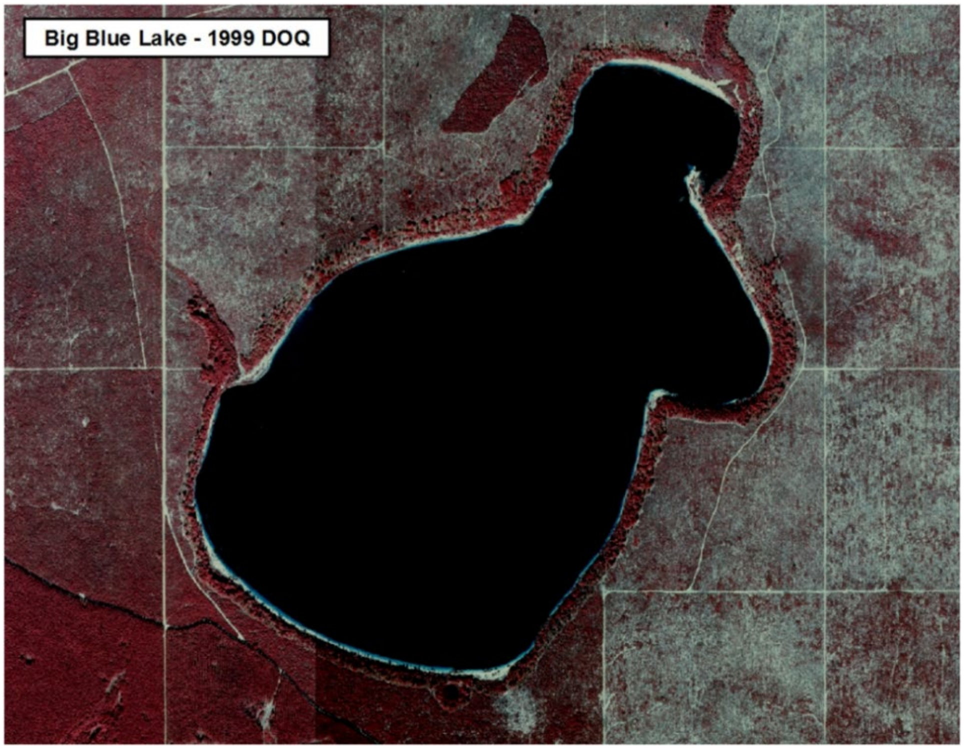

Figure 4-20. Color infrared, aerial image of Big Blue Lake in 1999 (Cantrell, 2011; image from U.S. Geological Survey EROS Archive of Digital Orthophoto Quadrangle images, https://doi.org/10.5066/F7125QVD)

[1] This estimate is also consistent with extrapolation of the near-shore topographic slope at Piney Lake, which indicated that the dry lakebed may be five to ten ft lower than the LiDAR estimated lake level of 47.7 during April-May 2017.

[2] In this context, the North American Vertical Datum of 1988 (NAVD88) is used as a proxy for sea level.

[3] This historical image was from the NWFWMD collection of geo-referenced images from University of Florida aerial imagery collection (https://original-ufdc.uflib.ufl.edu/UF00071792/00050/4j, photo CPJ-2F-169, taken May 8, 1949).

Figure 4-21. Aerial image of Big Blue Lake in 2010 (Cantrell, 2011; image from the U.S. Geological Survey National Aerial Photography Program Digital Orthophoto Quadrangle collection)

Figure 4-22. Aerial image of Piney Lake during December 2012, a period of extremely dry conditions

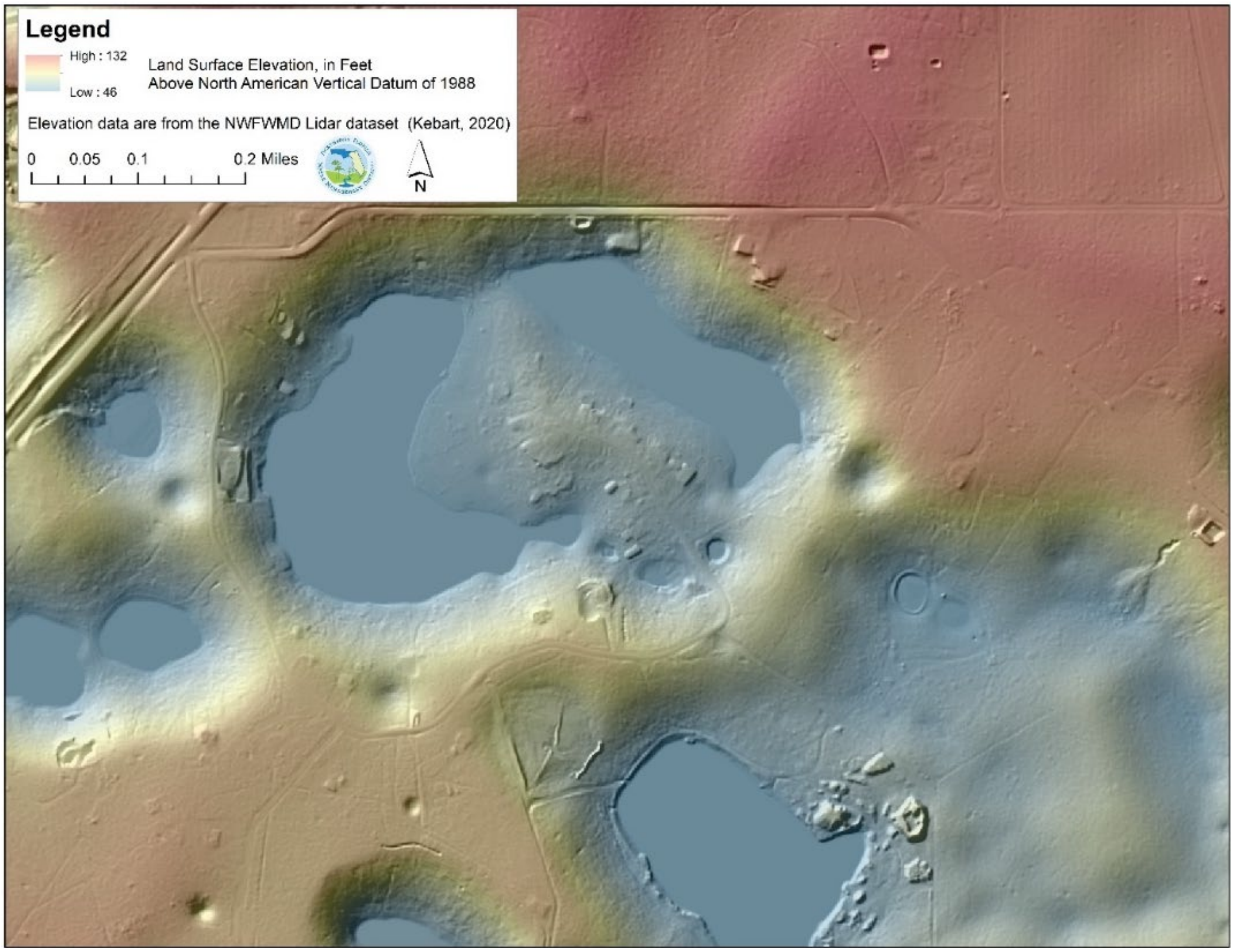

Figure 4-23. Lidar-based topography of area near Piney Lake. LiDAR data were acquired April 9 through May 17, 2017

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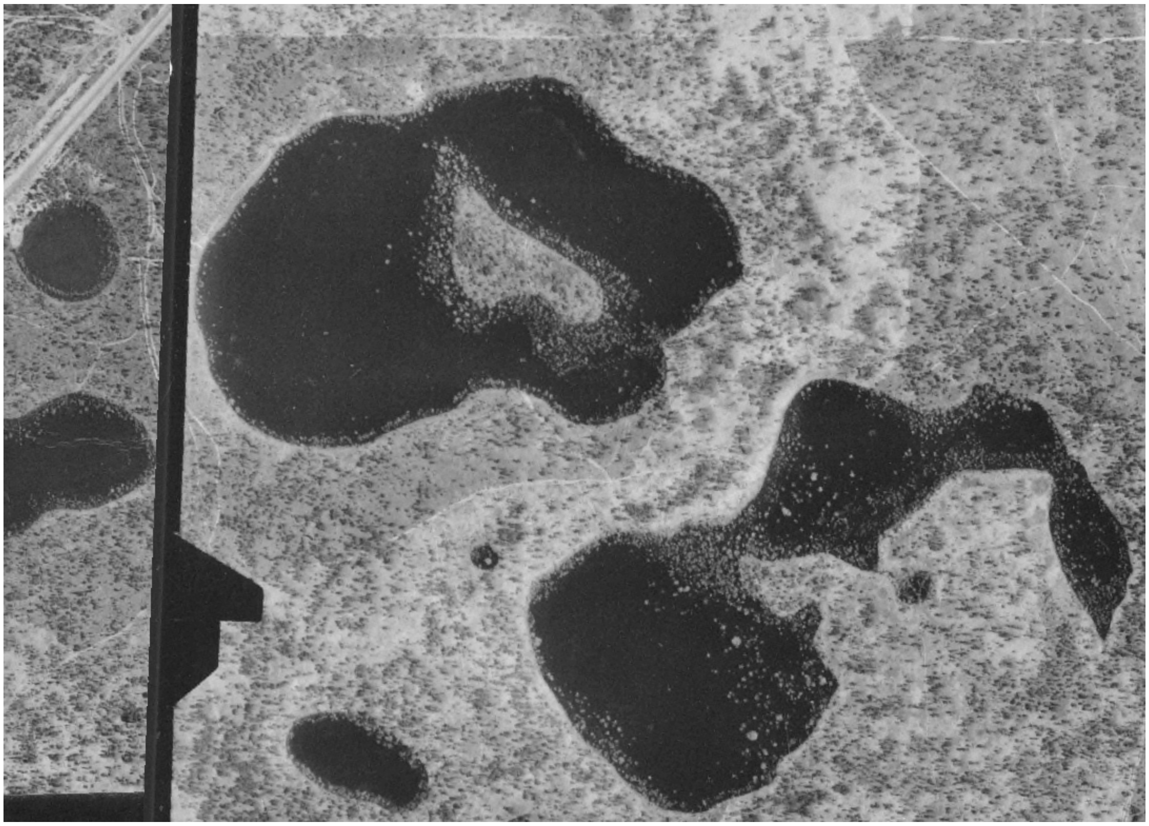

(a)

(b)

Figure 4-24. Aerial images of Piney Lake from (a) May 8, 1949 and (b) October 11, 2018, immediately following the passage of Hurricane Michael, which was preceded by a period of wetter than normal conditions

Kwader (2011) produced a map of the water level differences between lakes and the Upper Floridan aquifer in the Sand Hill Lakes region (Figure 4-25). Big Blue Lake lies in the area that was mapped as having a separation of greater than 16 ft, which suggests that the hydraulic connection between Big Blue Lake and the UFA is lower than the high recharge areas shown in this map. No data were shown for Piney Lake on Kwader's map. Piney Lake lies within one of the high recharge areas that Kwader mapped where the difference between lake and Upper Floridan aquifer levels is generally seven feet or less and where lakes generally have a better hydraulic connection to the underlying UFA. However, recent lake and Upper Floridan aquifer levels (Figure 4-25) indicate that the hydraulic connection between Piney Lake and the UFA may not be quite as high as other lakes within Kwader's (2011) high recharge areas (Figure 4-25).

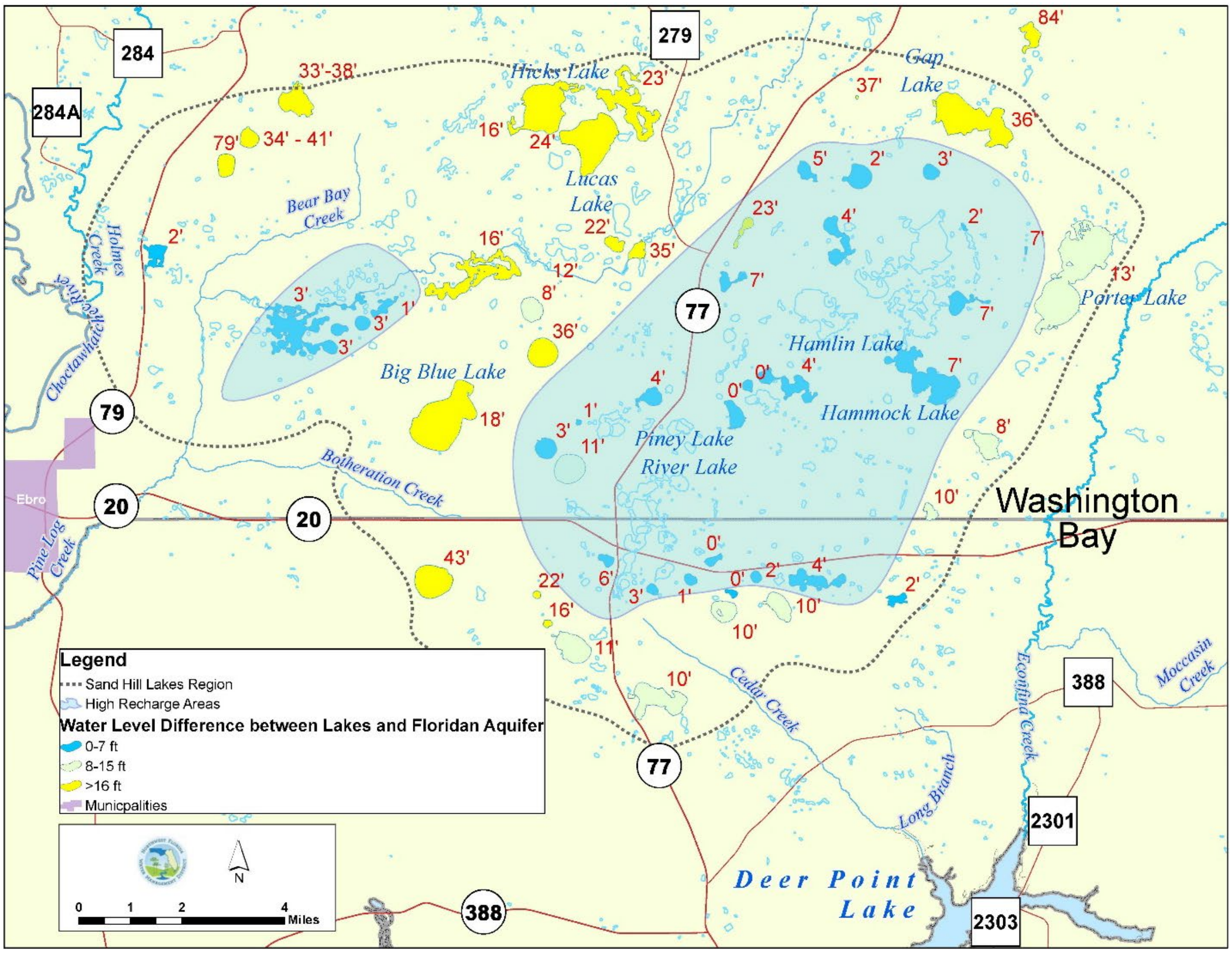

Figure 4-25. Difference in lake and Floridan aquifer groundwater levels in the Sand Hill Lakes region (based on Kwader, 2011)

Flood risks are highest for the lowest lying properties adjacent to a waterbody. Most of the properties reporting flooding concerns were lakefront properties or properties on or adjacent to wetlands at the lowest topographic elevations relative to the typical level of adjacent waterbodies. The elevation of properties relative to adjacent water levels, lake bathymetry, the topographic slope near a lake's shoreline, and the proximity of areas of concern to the typical shoreline location may be the most important variables for predicting flooding in the Sand Hill Lakes region. Differences in the bathymetric and hydrogeologic characteristics of lakes likely explain why some lakes in the Sand Hill Lakes region dry out completely or nearly so, while others retained much of their average lake area, even under drought conditions. For example, Big Blue Lake, Crystal Lake, and Lake Five-O are deep lakes with bathymetric profiles that likely slope much more steeply towards their lake bottoms than lakes such as Piney Lake, Sand Pond, Lower Spring Ponds, River Lake, Long Lake, and Wages Pond that dried out during the prolonged drought periods that occurred during late 1998 through 2012. Piney Lake, Sand Pond, Lower Spring Ponds, River Lake, Long Lake, and Wages Pond are therefore probably shallower and have more gradually sloping bathymetric profiles than lakes such as Big Blue Lake, Crystal Lake, and Lake Five-O, which are known to be very deep and did not go dry (or nearly so) in 2012. Shallower lakes are therefore more likely to experience dry or nearly dry lakebed conditions. They are also more prone to flooding near the shoreline during very wet periods, such as the wet period that occurred prior to and after the landfall of Hurricane Michael. Many of the lakes that were dry in December 2012 and, therefore likely to be significantly shallower, are also lakes like Piney Lake, Sand Pond, Lower Spring Ponds, River Lake, Long Lake, and Wages Pond where properties adjacent to these lakes reported flooding concerns in the period beginning in 2019. These properties were typically in locations that were topographically low, adjacent to lake shorelines or wetlands and at elevations that were not much higher than typical lake elevations (given the range of possible lake level variation), and with gradually-sloping near shore topographies, such as peninsular features within lakes, areas near wetlands, or low areas connecting lakes.

Lakes that have a better hydraulic connection to the UFA will also be more sensitive to regional fluctuations in UFA groundwater levels and antecedent rainfall conditions. Therefore, if regional rainfall conditions have been much wetter or drier than normal, the levels of lakes with better hydraulic connections to the UFA will more closely reflect these regional conditions. Such lakes will still be sensitive to local conditions such as locally higher water tables from localized rainfall events. However, such sensitivity will likely be more short-lived because lake water or groundwater in the SAS can readily drain downward to the UFA through high-conductance breaches in the ICU. Flooding of low-lying, lakefront properties in the Sand Hill Lakes region has probably been exacerbated by high groundwater levels in both the SAS and UFA. The UFA levels in the region have been at historically high levels in response to the historically high rainfall totals in the region in the months prior to the recent flooding.

Porter Lake may be an example of a lake that is particularly sensitive to both local and regional hydrologic conditions. The aerial image during December 2012 (Figure 4-26) and data from Musgrove et al. (1965) indicate that the level of Porter Lake can vary from about 57 ft above sea level, during periods when the lake could be almost completely dry, to about 70 ft above sea level during wet conditions. Like other lakes in the Deadening lakes area, Porter Lake receives inflows from White Oak Creek. Therefore, the level and inundated area of Porter Lake are affected by hydrologic conditions that influence the streamflow from the White Oak Creek and Sand Mountain Branch, local conditions in the SAS, and regional conditions and groundwater levels in the UFA.

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Figure 4-26. Aerial Image of Porter Lake during December 2012, a period of extremely dry conditions

Figure 4-27. Aerial image of Porter Lake on October 11, 2018, immediately following the passage of Hurricane Michael, which was preceded by a period of wetter than normal conditions. Imagery from Google Earth.

5 Stream Hydrology and Riverine Flooding

Stream or riverine flooding occurs when the flow exceeds the conveyance capacity of a stream causing water to flow overbank and into or beyond the adjacent floodplain. The water level or stage sufficient to inundate areas not normally covered by water is defined as the flood stage. A stream will have multiple flood stages, each of which is associated with a particular return interval or frequency. Typically, out-of-bank flows occur at a frequency of roughly a 2-year to 5-year return interval (Amec Foster Wheeler, 2016). However, severe damage caused by riverine flooding often occurs at lower frequencies, such as a 50- or 100-year flood, meaning a flood of a certain magnitude has a 1-in-50 or 1-in-100 probability of occurring within a given year. These flood events are defined by an evaluation of historical streamflow data to determine the expected peak level or flow for a certain return interval.

Several factors can contribute to the occurrence of a flooding event including prolonged above average rainfall over days, weeks, or months, or intense rainfall over a short duration. Additionally, downed trees in the channel and floodplain can cause elevated stream stages for a given flow, reducing conveyance capacity and increasing the flooding risk. Changes in topography, soil conditions, and land cover can also affect the amount and intensity of surface water runoff which ultimately becomes streamflow, and potentially contribute to flooding. Elevated groundwater levels caused by extended periods of above average rainfall can also contribute to increased stream baseflow and therefore exacerbate flooding risk.

This section presents a detailed evaluation of the factors contributing to observed flooding along Econfina Creek and Bear Creek. It also includes a description of factors associated with recent flooding in the upper reaches of Cedar Creek.

5.1 Econfina Creek

Baseflow derived primarily from spring discharge in the middle reaches of Econfina Creek accounts for most of the streamflow under low to moderate flow conditions. Average estimated baseflow at USGS 2359500 Econfina Creek Near Bennett, FL is 445 cfs, which represents 83% of the long-term average streamflow. Small intermittent streams, including Cat Creek and Moccasin Creek located north of CR 388 contribute surface water runoff during high flow periods. Other inputs to Econfina Creek include direct precipitation, spring inflows, and diffuse groundwater inflow.

The primary groundwater contribution area for the springs discharging into Econfina Creek encompasses approximately 129,000 acres within southern Washington and northern Bay counties. The Sand Hill Lakes region comprises the portion of the contribution area immediately west of the middle Econfina Creek, including southern Washington and northern Bay counties. This area provides for significant groundwater recharge which directly contributes to Econfina Creek spring discharge.

To determine potential causes of recent flooding in Bay County, an evaluation of current and historical hydrologic conditions along Econfina Creek was conducted. The USGS Station 2359500 Econfina Creek Near Bennett, Florida (Econfina Creek @ CR 388) was used for this evaluation since daily flows at this station are available from 1935 to present, allowing for an evaluation of long-term trends. Monthly precipitation is available for 1913 to present at the National Weather Service (NWS) station USC00086842 located in Panama City, Florida, and was used to evaluate trends. Trends in regional groundwater levels were assessed using the Greenhead Floridan aquifer monitoring well (District Well ID 3216). As discussed in Section 4, the Greenhead well is located within the Sand Hill Lakes region.

The primary hypothesis tested was whether recent flooding events are consistent with observed climatic conditions, or if physical impacts to streams and the associated watersheds caused by Hurricane Michael resulted in more streamflow or higher stages than expected from changes in precipitation alone. Historical relationships were compared to those during recent periods, including post Hurricane Michael, to determine if regional hydrology was altered by the hurricane, potentially affecting flooding frequency.

5.1.1 Trends in Baseflow and Climatic Conditions

Daily average flow at the USGS station 2359500 Econfina Creek Near Bennett, Florida is shown on Figure 5-1. Flows at this location have been relatively stable over time, with no long-term increasing or decreasing trends although short-term fluctuations occur due to climatic variability. Average flow at this location over the 1935 to April 2022 period was 535 cfs with annual average flows ranging between 343 cfs (2012) and 741 cfs (1948).

To determine baseflow at Econfina Creek, the baseflow separation technique referred to as the "USF Method" (Perry 1995) was utilized. This is a low-pass filter technique applied for a specified time window. This method is a modified version of the USGS HYSEP baseflow separation technique allowing for modified window lengths to better represent baseflow processes typical of Florida streams. A moving, 61-day averaging period was chosen to best represent average baseflow processes in Econfina Creek. This 61-day averaging period ('window') represents the period 30 days before and after a given date, and a 61-day minimum flow is calculated on a daily basis moving forward one day at a time. After the minimum flow has been calculated for each day, a second 61-day moving window averages the previously calculated minimum flows, resulting in a smoothed time series that is assumed to represent baseflow. Baseflow at Econfina Creek Near Bennett, Florida, computed using the USF method with a 61-day window is shown in Figure 5-1.

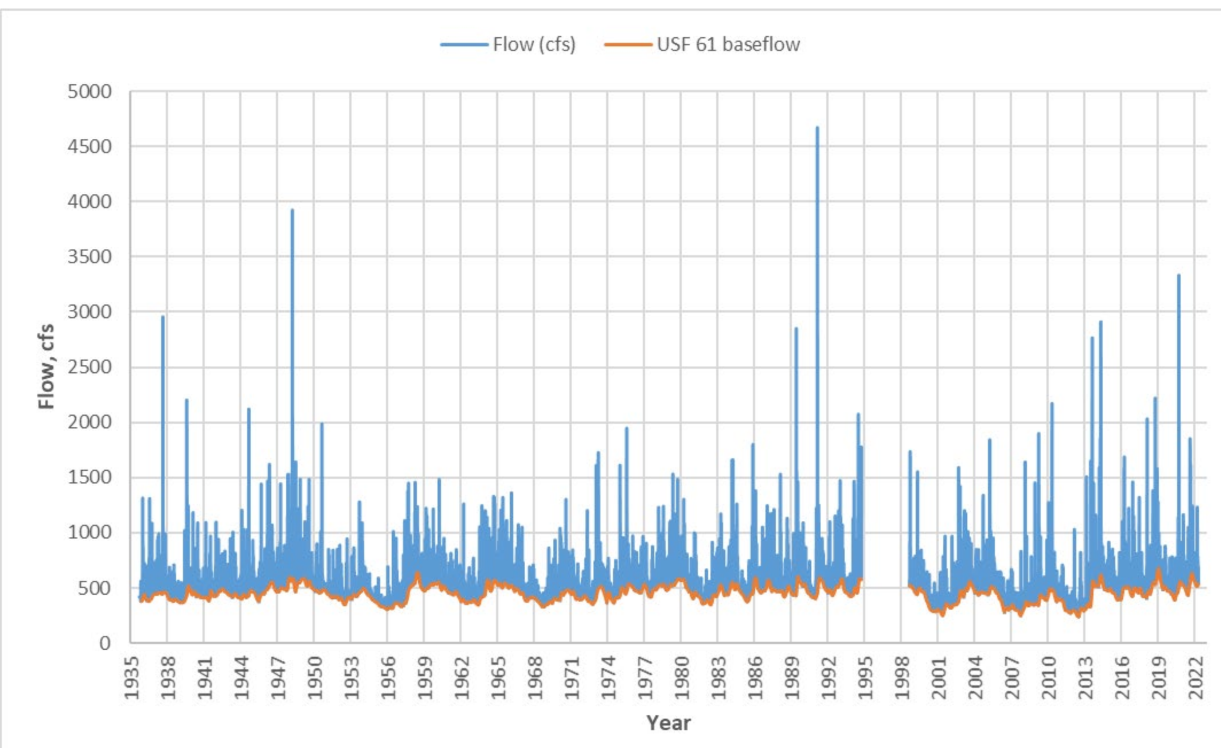

Figure 5-1. Daily flow and baseflow at the USGS station 2359500 Econfina Creek Near Bennett, Florida

A careful examination of Figure 5-1 shows an increase in both baseflow and total flow in Econfina Creek from January 2013 to April 2022 compared to previous time periods, particularly the mid-2000s when several years of below average flow occurred. The average baseflow from January 2013 to April 2022 (484 cfs) was significantly higher than average baseflow from August 1998 to December 2012 (381 cfs). To determine if increased baseflow correlates to climatic variability, baseflow was compared to historical cumulative precipitation and groundwater levels. Baseflow at Econfina Creek was compared to the preceding two-year moving average monthly total rainfall from the Panama City NWS station (Figure 5-2). A two-year moving average was utilized to account for the effect of antecedent rainfall conditions on baseflow. As demonstrated in Figure 5-2, fluctuations in baseflow are consistent with fluctuations in cumulative rainfall, although some variability is present likely due to uncertainty in computed baseflow and differences in recharge rates and time of travel within the watershed, which may not correspond directly to a two-year moving average rainfall.

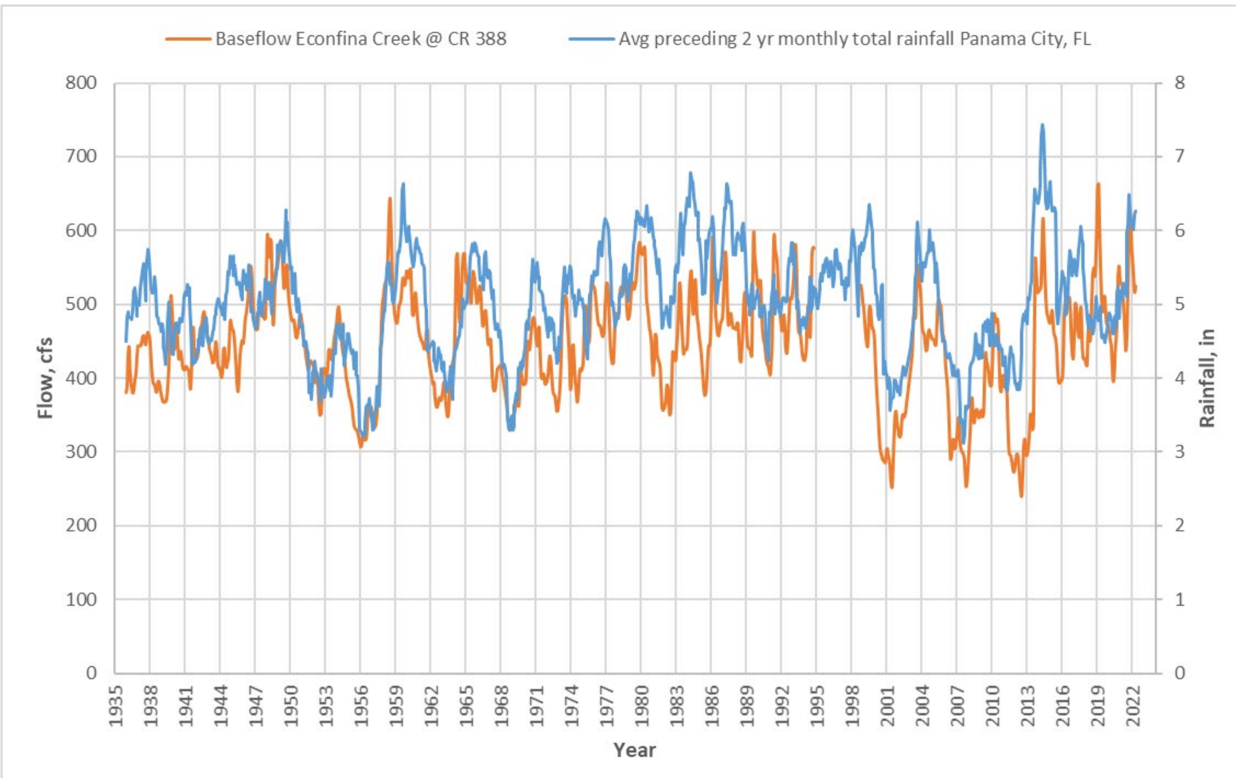

Figure 5-2. Baseflow at the USGS station 2359500 Econfina Creek Near Bennett, Florida and the preceding two-year moving average monthly total rainfall from National Weather Service station USC00086842 in Panama City, Florida

In addition to precipitation, baseflow at Econfina Creek @ CR 388 was compared to groundwater levels from the Greenhead Floridan aquifer monitoring well (District Well ID 3216) from 1998 to 2022 (Figure 5-3). Similar to cumulative rainfall, fluctuations in baseflow are consistent with fluctuations in groundwater levels. A linear regression between baseflow and groundwater levels showed a consistent relationship between the two variables from 1998 to 2022, with an R^2 value of 0.8213 (Figure 5-4).

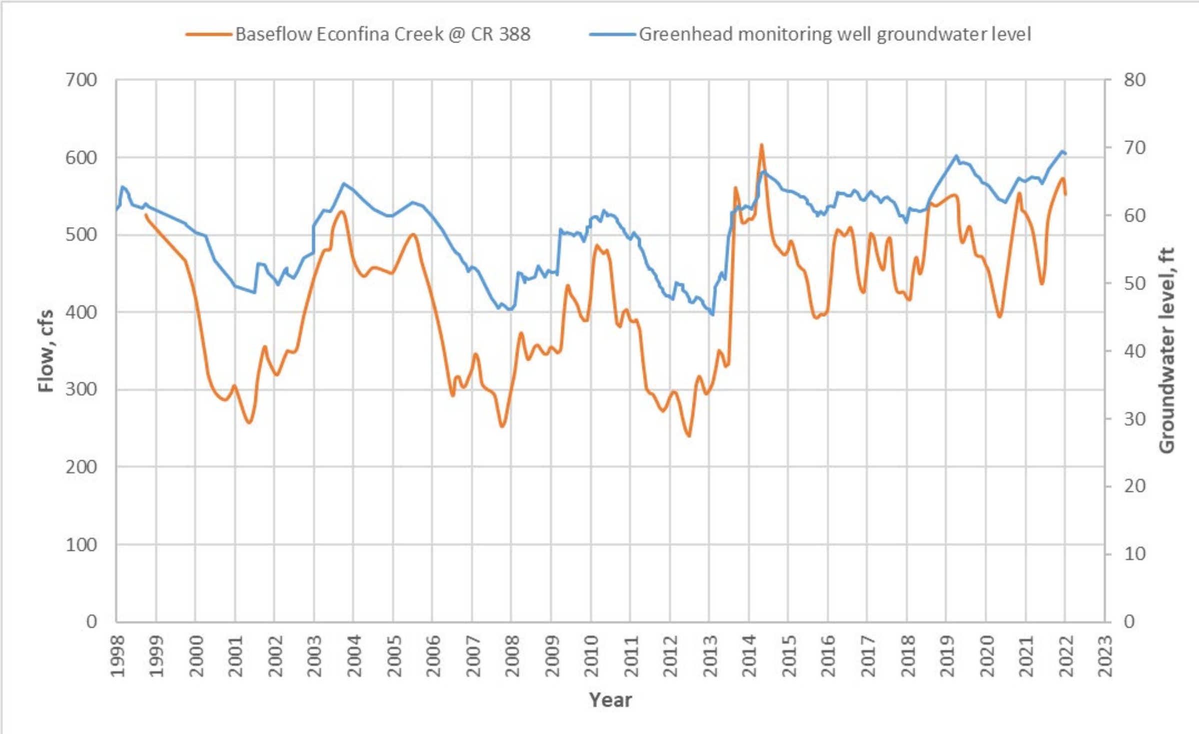

Figure 5-3. Average daily baseflow at the USGS station 2359500 Econfina Creek Near Bennett, Florida, and groundwater levels at Greenhead Floridan aquifer monitoring well, 1998 to 2022

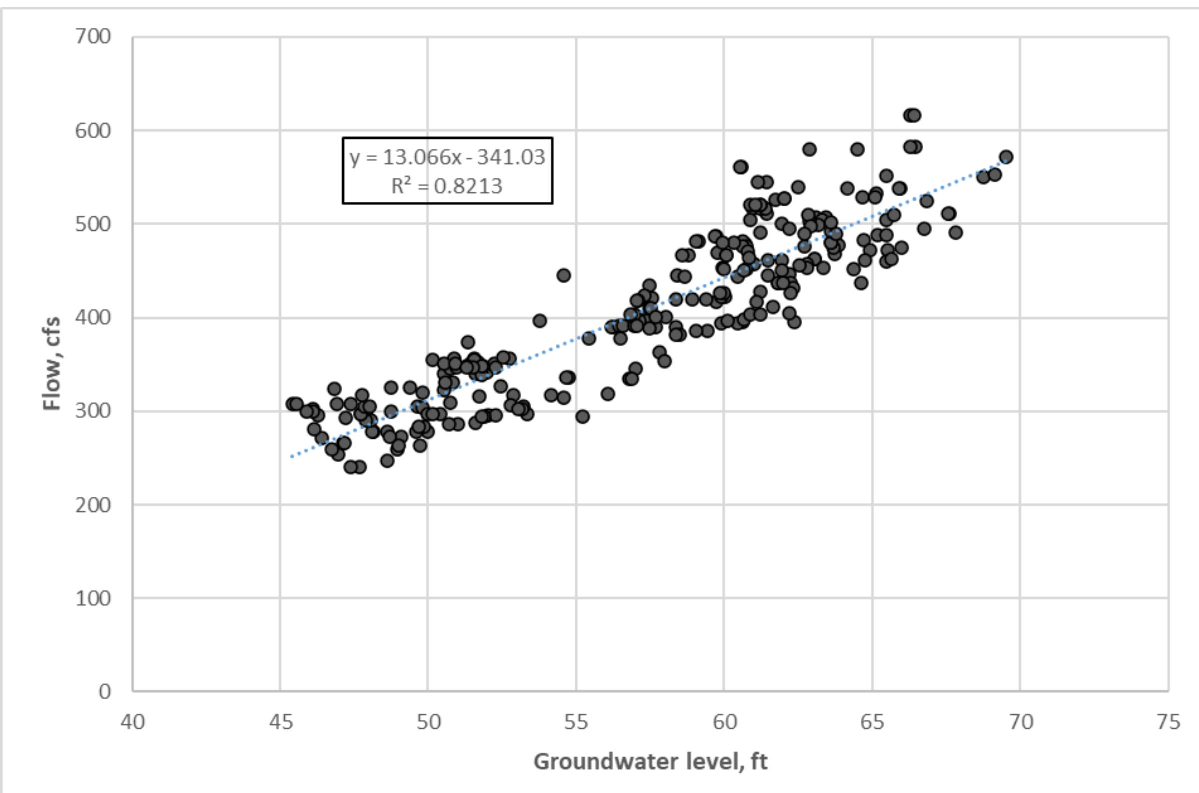

Figure 5-4. Linear regression between baseflow at the USGS station 2359500 Econfina Creek Near Bennett, Florida, and groundwater levels at Greenhead Floridan aquifer monitoring well (ft NAVD88), 1998 to 2022

Analysis of baseflow, cumulative rainfall, and groundwater levels at the Greenhead monitoring well shows consistent increases in all three variables from January 2013 to present compared to the period of 1998 to 2013. Annual rainfall in 2013 totaled 87 inches which is the highest annual total on record for the Panama City NWS station. The average annual rainfall for this station is 59 inches. This high rainfall during 2013 contributed to an increase in both groundwater levels and corresponding baseflow from January 2013 to April 2022. In recent years, rainfall has been well above average, with observed annual rainfall of 69 inches during 2020 and 74 inches during 2021. Total rainfall for August 2021 was 20 inches compared to the long-term average of 7.9 inches during August for this station. As a result, groundwater levels and baseflow have remained elevated.

5.1.2 Econfina Creek Flow Frequencies Post Hurricane Michael

Flow frequency curves were developed for Econfina Creek Near Bennett, FL to compare pre- and post-Hurricane Michael flows. Figure 5-5 shows flows have been higher across all flow percentiles post Hurricane Michael (October 10, 2018 to April 26, 2022) compared to the historical period of record. Increases are on the order of 50 to 100 cfs for most flow percentiles. This is consistent with the analysis previously discussed, indicating that flows have increased from 2013 to 2022 due primarily to above average rainfall and elevated groundwater levels.

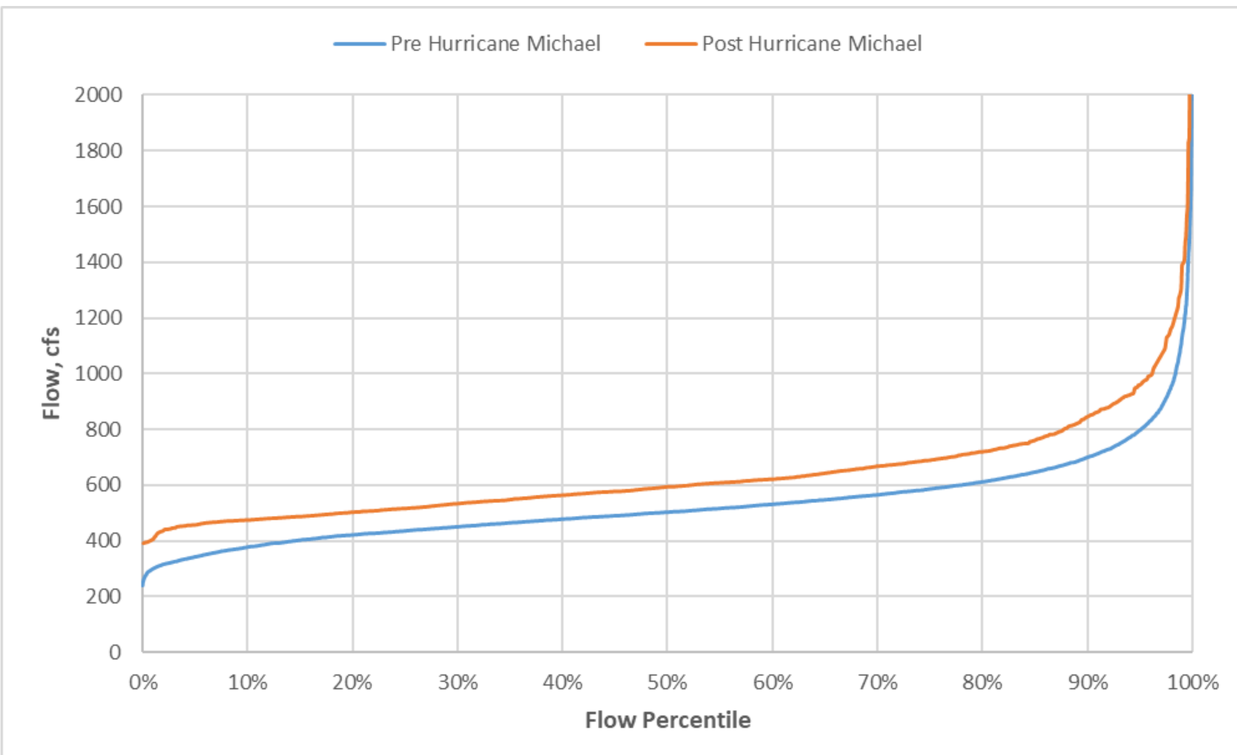

Figure 5-5. Flow frequency curve for the USGS station 2359500 Econfina Creek Near Bennett, Florida

Flow for Econfina Creek can be divided into two components: baseflow derived primarily from spring discharge and surface water runoff derived primarily from stormwater runoff. To further investigate the nature of flow increases post hurricane Michael, frequencies for both components were determined. Surface water runoff was determined as the difference between daily average streamflow and estimated baseflow from the USF 61 methodology described previously. As shown in Figure 5-6, flow frequencies for the surface component of Econfina Creek flows are similar pre and post Hurricane Michael, indicating that increased baseflow is the primary cause of increased streamflow post Hurricane Michael. This indicates that observed increased flows post Hurricane Michael are largely due to climatic factors. Reductions in forest land cover due to Hurricane Michael and associated ET reductions may have also contributed to higher groundwater levels and the increased baseflow in Econfina Creek.

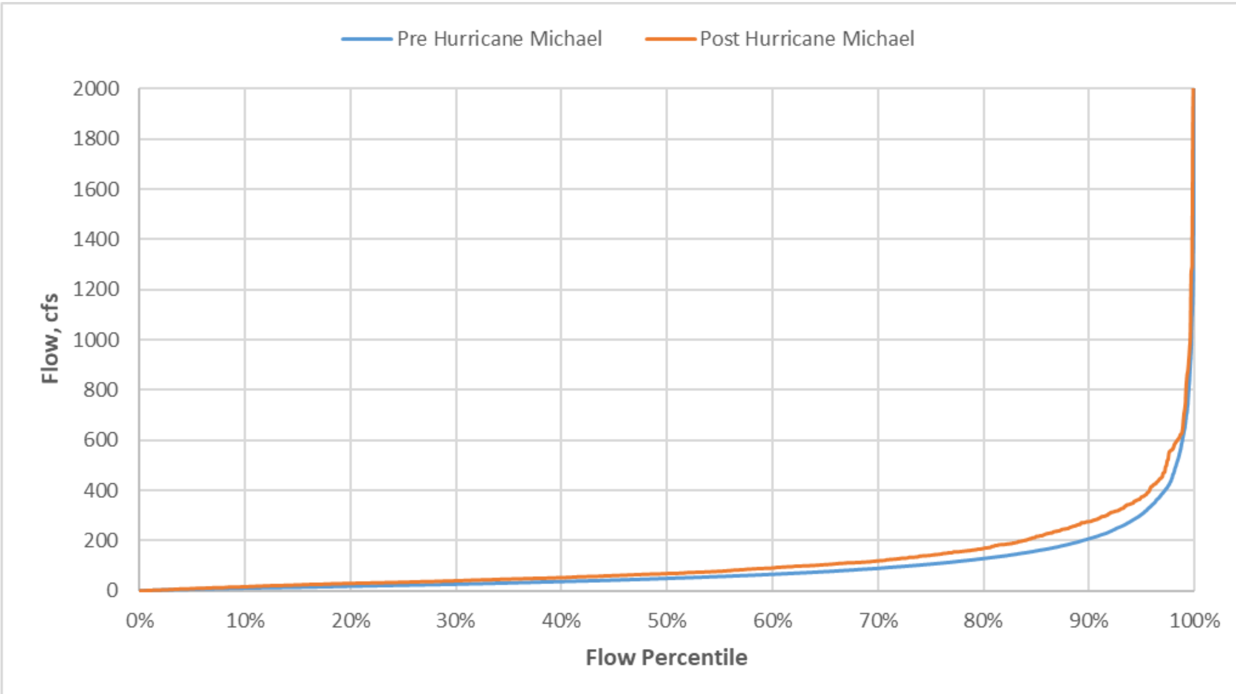

Figure 5-6. Flow frequency curve for surface water inputs at USGS station 2359500 Econfina Creek Near Bennett, Florida

5.1.3 Stage-Discharge Relationships for Econfina Creek

In addition to increased flow frequencies, another potential contributor to increased flooding propensity was reduced hydraulic conveyance in Econfina Creek caused by Hurricane Michael. Large amounts of debris fell into Econfina Creek and surrounding floodplain areas during the passage of Hurricane Michael, causing changes to the hydrology and reducing the conveyance capacity of Econfina Creek. Downed trees in the channel and floodplain resulted in less conveyance area, resulting in slower water velocities and increased stage for a given flow. To restore Econfina Creek, debris was removed from portions of the main channel, including areas upstream of the Econfina Creek Near the Bennett, Florida gaging station. No debris removal was conducted in the floodplains.

Median flow and stage percentiles for several recent periods are summarized in Table 5-1. Median flows post Hurricane Michael as well as seasonal flows during fall 2021, winter 2021, and spring 2022 were well above average and ranged between 587 cfs to 669 cfs compared to the period of record median flow of 505 cfs. Similarly, median stages post Hurricane Michael as well as stages observed during fall 2021, winter 2021, and spring 2022 were well above average, ranging between 7.41 to 7.88 ft NAVD88 compared to the period of record median stage of 6.84 ft NAVD88.

Table 5-1. Flow and stage percentiles for recent conditions at USGS station 2359500 Econfina Creek Near Bennett, Florida

Time Period	Median Flow, cfs	Median Stage, ft NAVD88	Percentile Flow	Percentile Stage
Period of Record (October 1, 1935 to April 26, 2022)	505	6.84	50%	50%
Post Hurricane Michael (October 10, 2018 to April 26, 2022)	594	7.58	75%	86%
Fall 2021 (September 22, 2021 to December 20, 2021)	669	7.88	87%	92%
Winter 2021 (December 21, 2021 to March 19, 2022)	587	7.41	74%	81%
Spring 2022 (March 20, 2022 to April 26, 2022)	617	7.45	80%	82%

Analysis of stage - discharge relationships was conducted for three periods, shown in Figure 5-7:

- Pre-hurricane conditions (prior to October 10, 2018)
- Post-hurricane conditions prior to completion of debris clearing (October 10, 2018 to March 31, 2019)
- Post-hurricane conditions after completion of debris clearing (April 1, 2019 to April 26, 2022)

Review of Figure 5-7 shows substantial increases in stage for a given flow following Hurricane Michael as compared to historical conditions. However, upon completion of debris removal in the Econfina Creek channel, the stage-discharge relationship returned to conditions similar to pre-hurricane conditions, although stages remain slightly elevated likely due to remaining debris. This indicates the benefit of debris removal in restoring historical hydrologic regimes of Econfina Creek and reducing flooding risk proximal to the creek. Similar results were achieved in other sections along Econfina Creek and Chipola River where debris removal efforts occurred (NWFWMD 2020). Likewise, areas where debris removal efforts were not conducted show continued elevated stages relative to historical conditions.

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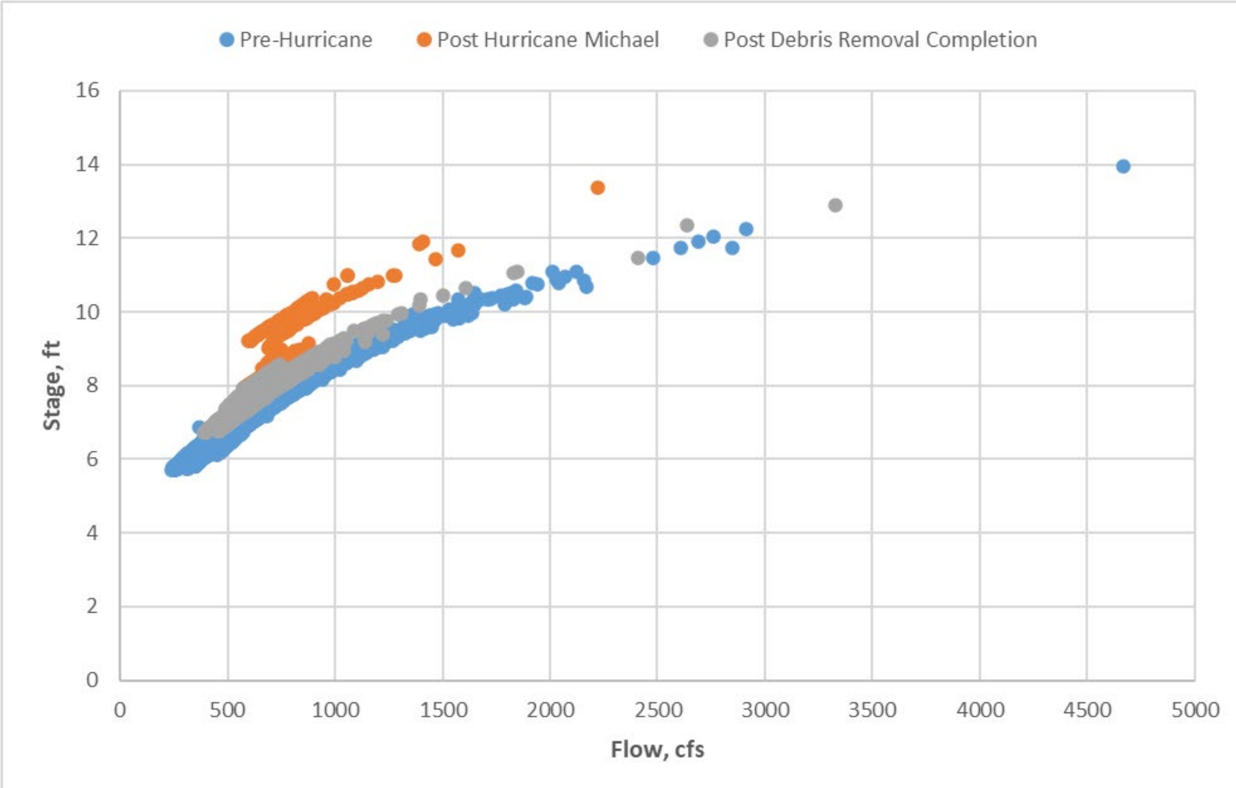

Figure 5-7. Comparison of stage-discharge relationships for the USGS station 2359500 Econfina Creek Near Bennett, Florida

5.1.4 Effects of Hurricane Sally on Hydrologic Conditions Near Econfina Creek

Significant rainfall from Hurricane Sally, which made landfall on September 16, 2020, resulted in extensive flooding impacts throughout the central portion of the Florida panhandle including in the vicinity of Econfina Creek. Stage at Econfina Creek Near Bennett, Florida, was elevated prior to landfall of Hurricane Sally (Figure 5-8), due to 3 inches of rainfall occurring within five days, which contributed to flooding risks. The peak stage at Econfina Creek reached a similar level during both Hurricane Sally and Hurricane Michael. However, the stage dropped more quickly following Hurricane Sally. Seven days after Hurricane Sally, the stage was within one foot of the pre-hurricane level. For a high rainfall event that occurred in 2016, the difference between the peak stage and the lowest stage measured within 30 days after the event was 3.26 ft. For comparison, the peak stage declined by 4.56 ft following Hurricane Michael and 5.73 ft following Hurricane Sally. The stages following both the 2016 event and Hurricane Michael increased at the end of the 30-day period due to additional rainfall. Stages following Hurricane Sally returned to levels below that following Hurricane Michael due to debris clearing post Hurricane Michael in the vicinity of the gage, although the stage remained slightly elevated relative to baseline conditions.

When considering the rainfall associated with Hurricane Sally as well as pre-landfall impacts, the rainfall totals associated with Hurricane Sally are substantially greater than both the 2016 event and Hurricane Michael (Figure 5-9). The severe rainfall intensity associated with Hurricane Sally coupled with elevated stages prior to landfall, downed debris remaining from Hurricane Michael impacts, and a high groundwater table prior to the storm's landfall contributed to widespread flooding and flooding-related damages associated with the storm.

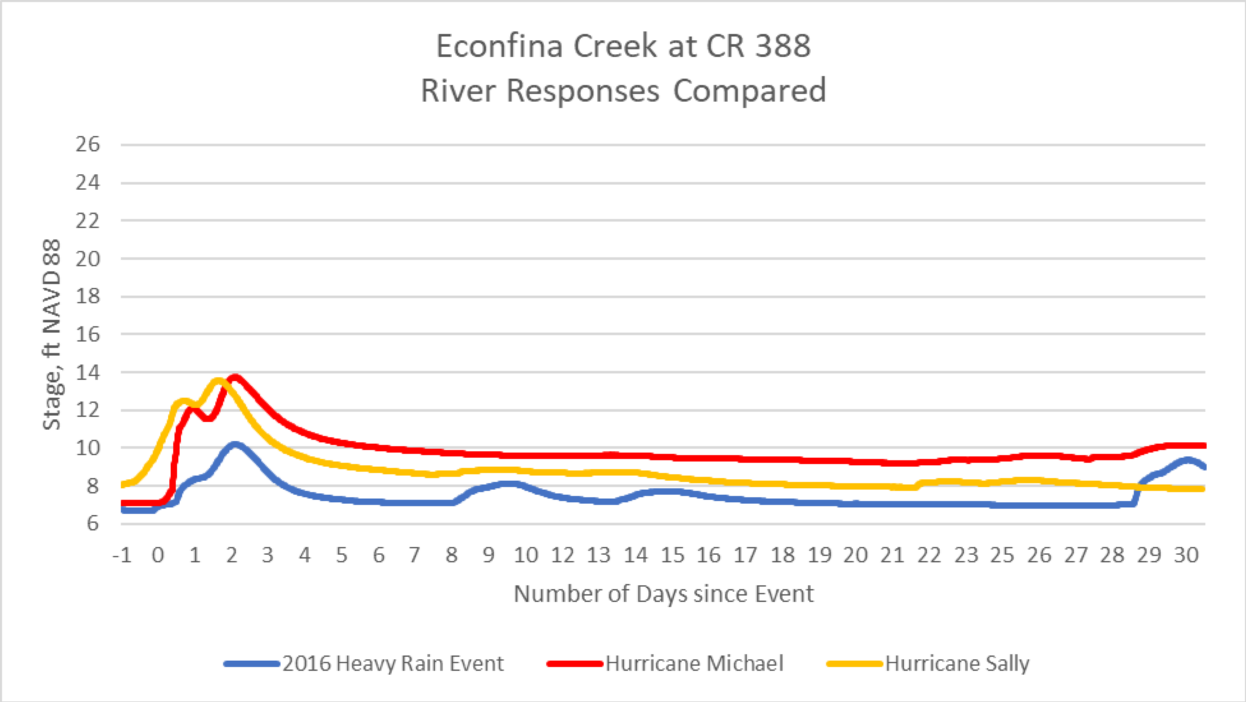

Figure 5-8. Stage recorded at USGS station 2359500 Econfina Creek Near Bennett, Florida from 2016 to 2020 and stage responses to the 2016 rainfall event, Hurricane Sally, and Hurricane Michael

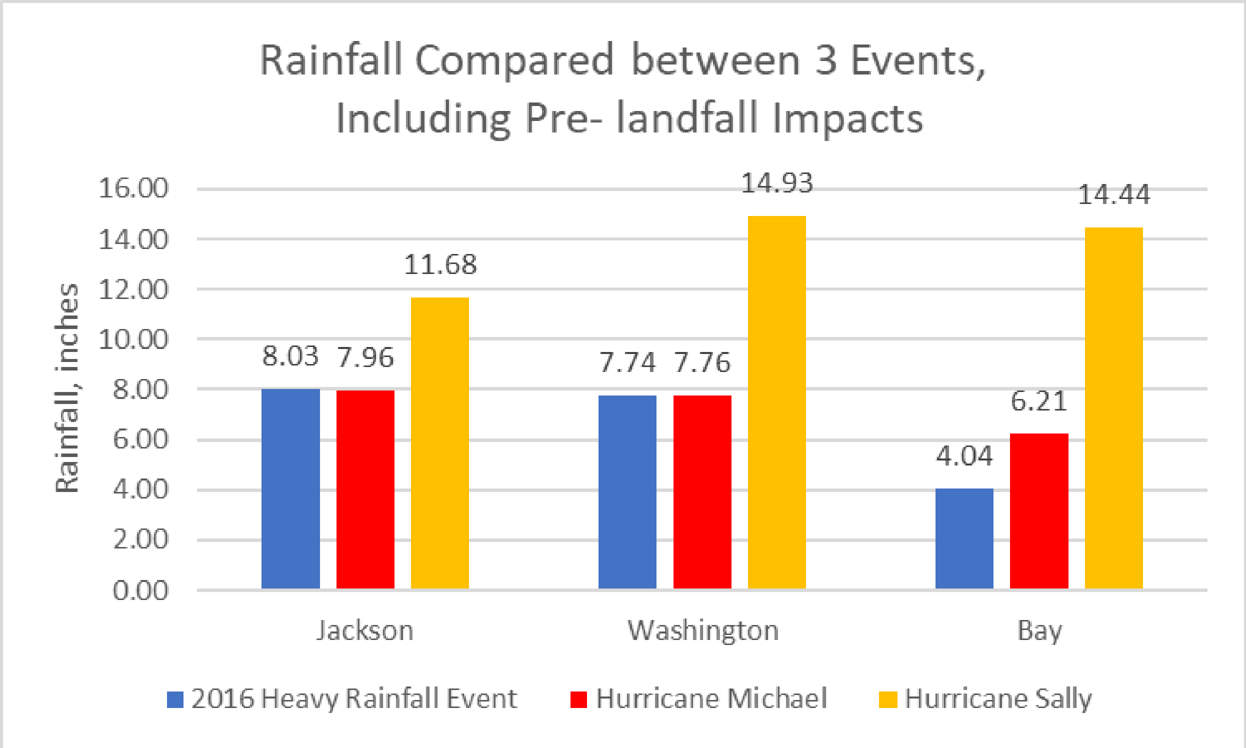

Figure 5-9. Rainfall recorded prior to and during the 2016 rainfall event, Hurricane Michael and Hurricane Sally

5.2 Bear Creek

An analogous assessment to that performed for Econfina Creek was conducted for Bear Creek to assess potential causes of recent flooding events. The Bear Creek watershed comprises approximately 119 square miles in eastern Bay County, Florida, and is a subbasin of the Deer Point Lake watershed. Bear Creek extends 18 miles from its headwaters in northeast Bay County to the Deer Point Lake Reservoir. Bear Creek is a major freshwater source to Deer Point Lake, providing approximately 20 percent of total inflow (Crowe et al. 2008).

Unlike Econfina Creek, Bear Creek derives most of its flow from surface water contributions from several tributaries including Little Bear Creek. Daily average total streamflow at the NWFWMD station 8571 Bear Creek @ US 231 and baseflow computed using the USF method with a 61-day window are shown in Figure 5-10. Flows at this location are more variable than in Econfina Creek due to flow being predominantly driven by surface water inputs. Average flow at this location over the period of record from August 1998 to April 2022 was 113 cfs. Note that this probably underestimates the true average, because flows above 400 cfs could not be estimated at this station for the post Hurricane Michael portion of the period of record.

Similar to Econfina Creek, both total streamflow and baseflow for Bear Creek increased from January 2013 to April 2022 compared to previous time periods due to above average rainfall, including record rainfall during 2013 as well as above average rainfall during 2020 and 2021. Trends in Bear Creek baseflow are consistent with groundwater level trends in the region (Figure 5-11). A two-year moving average was also applied to computed baseflow due to the variable nature of Bear Creek flows, providing for a better comparison to groundwater levels from the Greenhead monitoring well (Figure 5-11).

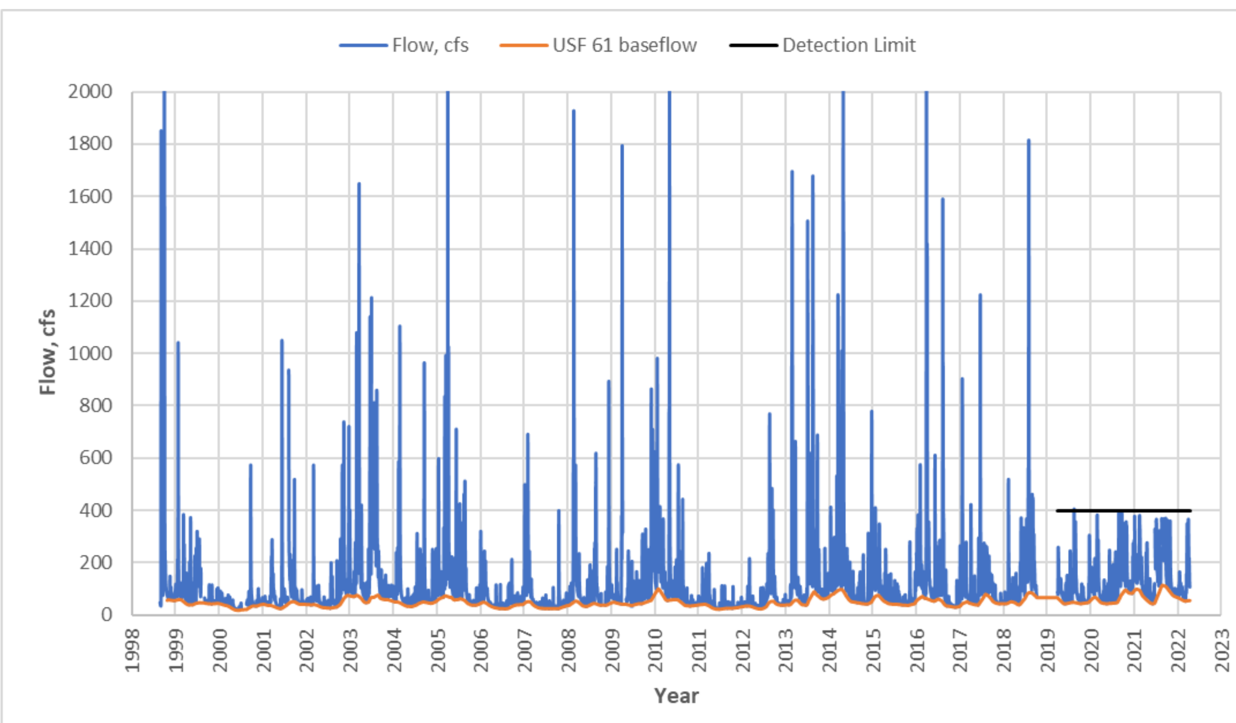

Figure 5-10. Daily flow and baseflow at the NWFWMD station 8571 Bear Creek @ US 231

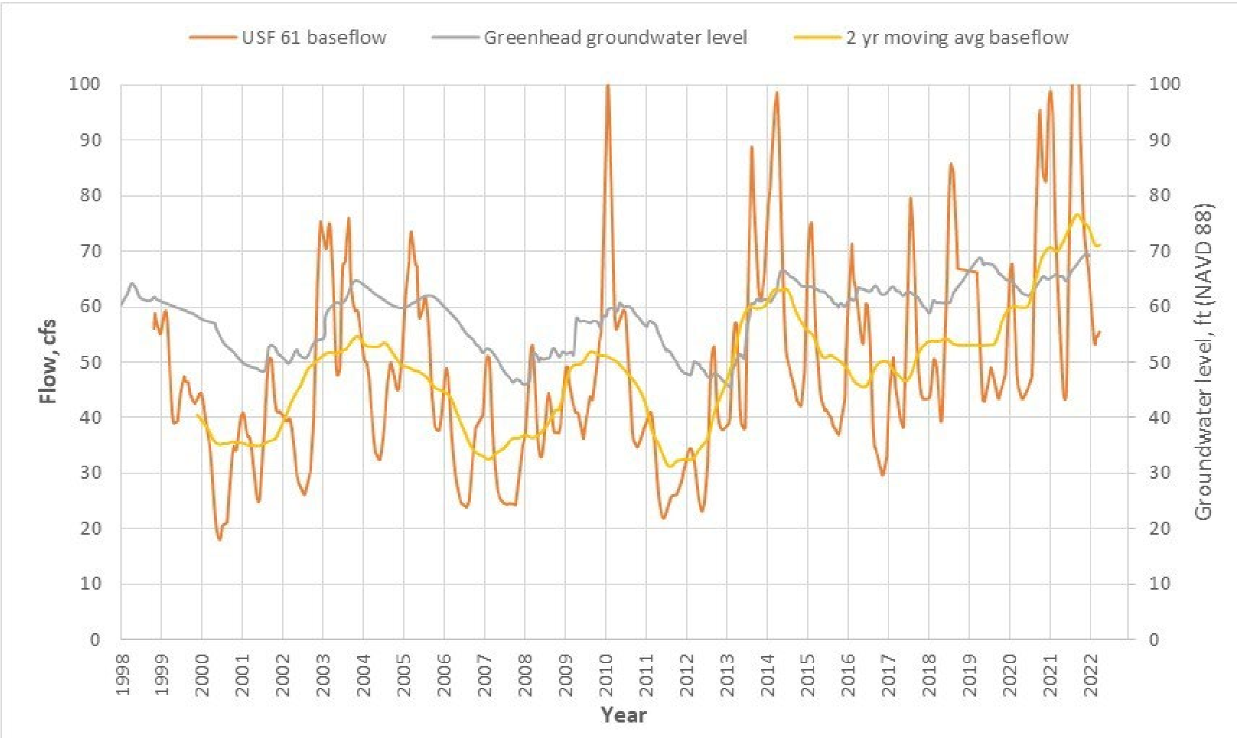

Figure 5-11. Comparison of average daily baseflow at the NWFWMD station 8571 Bear Creek @ US 231 and Floridan aquifer levels at the Greenhead monitoring well

Flow frequency curves were developed for the Bear Creek @ US 231 station to determine the extent and nature of increased flows post Hurricane Michael compared to the historical record prior to the hurricane. Figure 5-12 shows that flows have been higher post Hurricane Michael across all flow percentiles compared to pre-hurricane conditions. Flows above 400 cfs were unable to be estimated at this station post hurricane. To provide for an equivalent comparison, flows above 400 cfs were removed from the dataset. However, flow increases are disproportionally larger for high flow events suggesting that surface runoff in addition to baseflow (Figure 5-12) has increased during this timeframe. This is reasonable since Bear Creek flow is primarily driven by surface water runoff from storm events. The available data indicates that increases in flows are most likely the result of increased precipitation and elevated groundwater levels in the region. The Bear Creek watershed is located mostly within the Severe Impact Zone for Hurricane Michael. Reductions in forest and forested wetland land cover types occurred in this area following Hurricane Michael, resulting in lower ET within the Bear Creek watershed. Reduced ET in the Bear Creek watershed may have contributed to increased storm runoff post Hurricane Michael, although increased precipitation is likely the primary driver of the observed flow increases. Since the hydrologic record for Bear Creek does not extend prior to 1998, it is unknown if similar hydrologic conditions have occurred previously in this watershed.

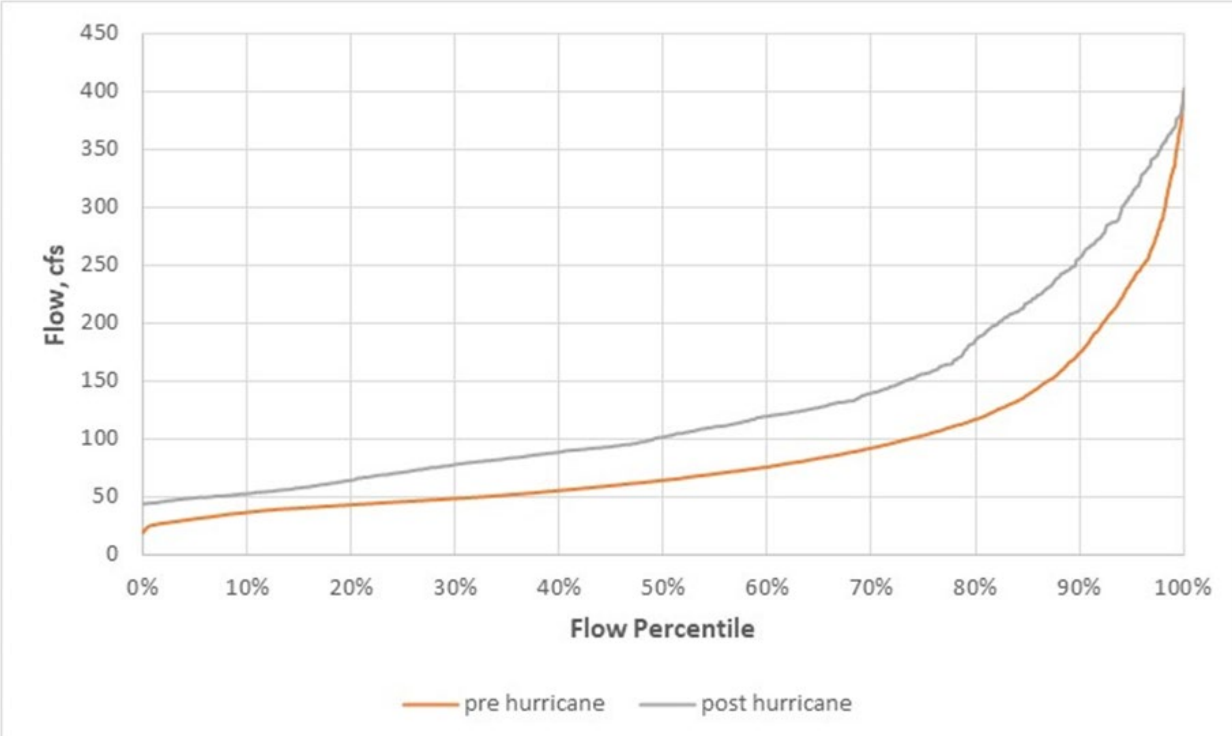

Figure 5-12. Flow frequency curve for NWFWMD station 8571 Bear Creek @ US 231. Only flows less than 400 cfs are included as post-hurricane flows exceeding 400 cfs could not be estimated.

Median flow and stage percentiles for several recent periods are shown in Table 5-2. Median annual flows post Hurricane Michael as well as median flows during fall 2021, winter 2021, and spring 2022 were above average ranging between 89 cfs to 107 cfs compared to the period of record median flow of 68 cfs (flows ≤ 400 cfs). Similarly, median stream stages post Hurricane Michael as well as median stages during fall 2021, winter 2021 and spring 2022 were well above average ranging between 17.04 and 17.53 ft NAVD88 compared to the period of record median stage of 15.37 ft NAVD88.

Table 5-2. Flow and stage percentiles for recent and period of record conditions at NWFWMD station 8571 Bear Creek @ US 231

Time Period	Median Flow, cfs	Median Stage, ft NAVD88	Percentile Flow	Percentile Stage
Period of Record (flows ≤ 400 cfs) (October 1, 1935 to April 26, 2022)	68	15.37	50%	50%
Post Hurricane Michael (October 10, 2018 to April 26, 2022)	101	17.35	71%	83%
Fall 2021 (September 22, 2021 to December 20, 2021)	107	17.53	74%	84%
Winter/Spring 2021/2022 (December 21, 2021 to April 13, 2022)	89	17.04	65%	80%

In addition to increased flow frequencies, another potential contributor toward increased flooding propensity is elevated stages in Bear Creek caused from downed trees in the channel and floodplain from Hurricane Michael. Large amounts of debris fell into Bear Creek and surrounding floodplain areas from

Hurricane Michael, causing changes to the hydrology of Bear Creek. Unlike Econfina Creek, no debris removal efforts took place following Hurricane Michael on Bear Creek.

Analysis of stage - discharge relationships for Bear Creek was conducted for two periods, shown in Figure 5-13:

- Pre-hurricane conditions (pre-October 10, 2018, flows ≤ 400 cfs)
- Post-hurricane conditions (March 30, 2019 to April 26, 2022)

Flow data from October 10, 2018 through March 29, 2019 was unavailable at this station. Based on Figure 5-13, stages remain elevated in Bear Creek post Hurricane Michael through April 2022 with stages being approximately 1 to 2 ft higher for a given flow than pre-hurricane stages. Based on similar assessment of stage-discharge relationships for Econfina Creek and Chipola River, the likely cause of elevated stages in Bear Creek is remaining debris left from Hurricane Michael, creating less conveyance area for a given flow, resulting in slower water velocities and increased river stage. Debris clearing in portions of Econfina Creek and Chipola River succeeded in restoring historical hydrologic regimes and reducing flooding risks for adjacent properties. Debris removal efforts in reaches of Bear Creek affected by Hurricane Michael would similarly be anticipated to restore historical hydrologic regimes of Bear Creek and potentially reduce flooding risk in the vicinity of the creek.

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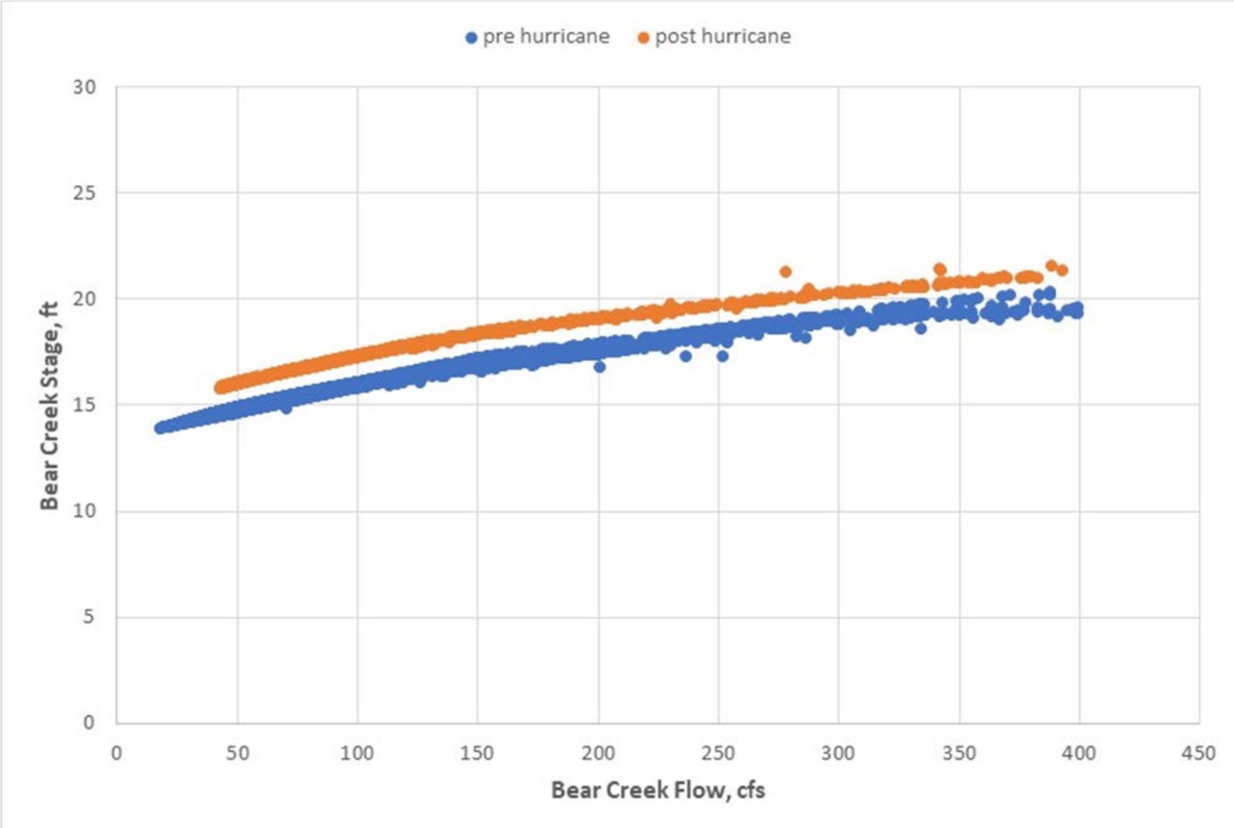

Figure 5-13. Comparison of stage-discharge relationships for NWFWMD station 8571 Bear Creek @ US 231. Note that flows above 400 cfs could not be computed for the post-hurricane period.

5.2.1 Effects of Hurricane Sally on Hydrologic Conditions along Bear Creek

Significant rainfall from Hurricane Sally resulted in extensive flooding impacts to Bear Creek and surrounding areas. The stage at Bear Creek @ US 231 was elevated prior to landfall of Hurricane Sally, due to 3 inches of rainfall occurring within five days of landfall as well as remaining debris post Hurricane Michael (Figure 5-14). The median stage after Hurricane Michael was more than 1.5 ft higher than the median stage from December 2016 to October 2018, despite this watershed receiving rainfall similar to Econfina Creek where stages have returned to near pre-Michael levels. The peak stage in Bear Creek was more than 5 ft higher during Hurricane Sally compared to Hurricane Michael. Following the high rainfall event that occurred during 2016, the peak stage dropped a total of 2.56 ft, the Hurricane Michael stage dropped at total of 5.67 ft, and the Hurricane Sally stage dropped a total of 11.66 ft. All three events had an increase in stage at the end of the 30-day period due to additional rainfall. Compared to the larger Chipola River and the nearby Econfina Creek, Bear Creek water levels respond much more quickly to rainfall. As with Econfina Creek, the severe rainfall intensity associated with Hurricane Sally coupled with elevated stages prior to landfall, downed debris remaining from Hurricane Michael impacts, and a high groundwater table prior to Hurricane Sally landfall contributed to widespread flooding and flooding related damages along Bear Creek that were associated with the storm.

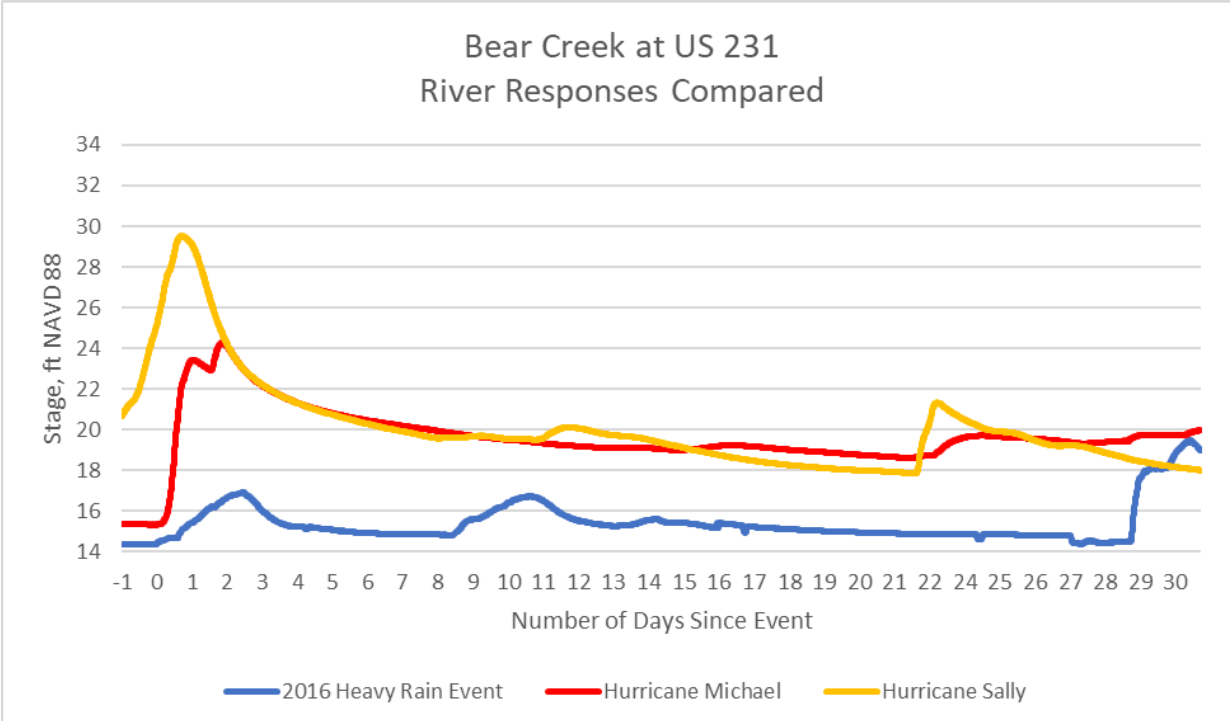

Figure 5-14. Stage recorded at Bear Creek at US 231 from 2016 to 2020 and stage responses to the 2016 rainfall event, Hurricane Sally, and Hurricane Michael

5.3 Cedar Creek

Cedar Creek traverses a distance of about 14 river miles, from its upstream limit at the southern end of River Lake in northern Bay County to its mouth in southern Bay County, where it discharges into Deer Point Lake. The creek drains an area of approximately 48 square miles[4]. Limited hydrologic data are available for Cedar Creek. However, 20 field measurements of stage and discharge were made during March 9, 1962 through October 4, 1964 at USGS station 02359650 Big Cedar Creek Near Bennett, Florida[5], where the creek passes under Highway 388. Discharge values from these measurements ranged from 3.5 to 598 cfs, with median, 25th, and 75th percentile values of 9.5 cfs, 7.3 cfs, and 17.4 cfs, respectively. Water surface elevation values ranged from about 19.3 ft to 24.8 ft NAVD88, with a median value of 20.0 ft NAVD88.

Aerial images indicate that the reaches of Cedar Creek upstream of Spikes Road are completely dry during periods of lower-than-normal rainfall. LiDAR-based topographic data, aerial imagery, survey data, and field visits indicate that a topographically high and relatively flat reach of Cedar Creek controls the water-surface elevation of the creek upstream of Spikes Road under flooding conditions. This reach extends from the dirt road above Spikes Road (about 0.4 miles upstream from Spikes Road) to a little over one mile downstream of Spikes Road (Figure 5-15).

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[4] This drainage area is based on summing the areas of subwatersheds with Hydrologic Unit Codes 031401010501 and 031401010502, in the Deer Point Watershed (Hydrologic Unit Code 0314010105).

[5] Note the drainage area assigned to this site was 95 square miles, which is about twice that of Hydrologic Unit Codes 031401010501 and 031401010502. This suggests that some non-contributing areas were probably included in the calculation of the drainage area of station 02359650.

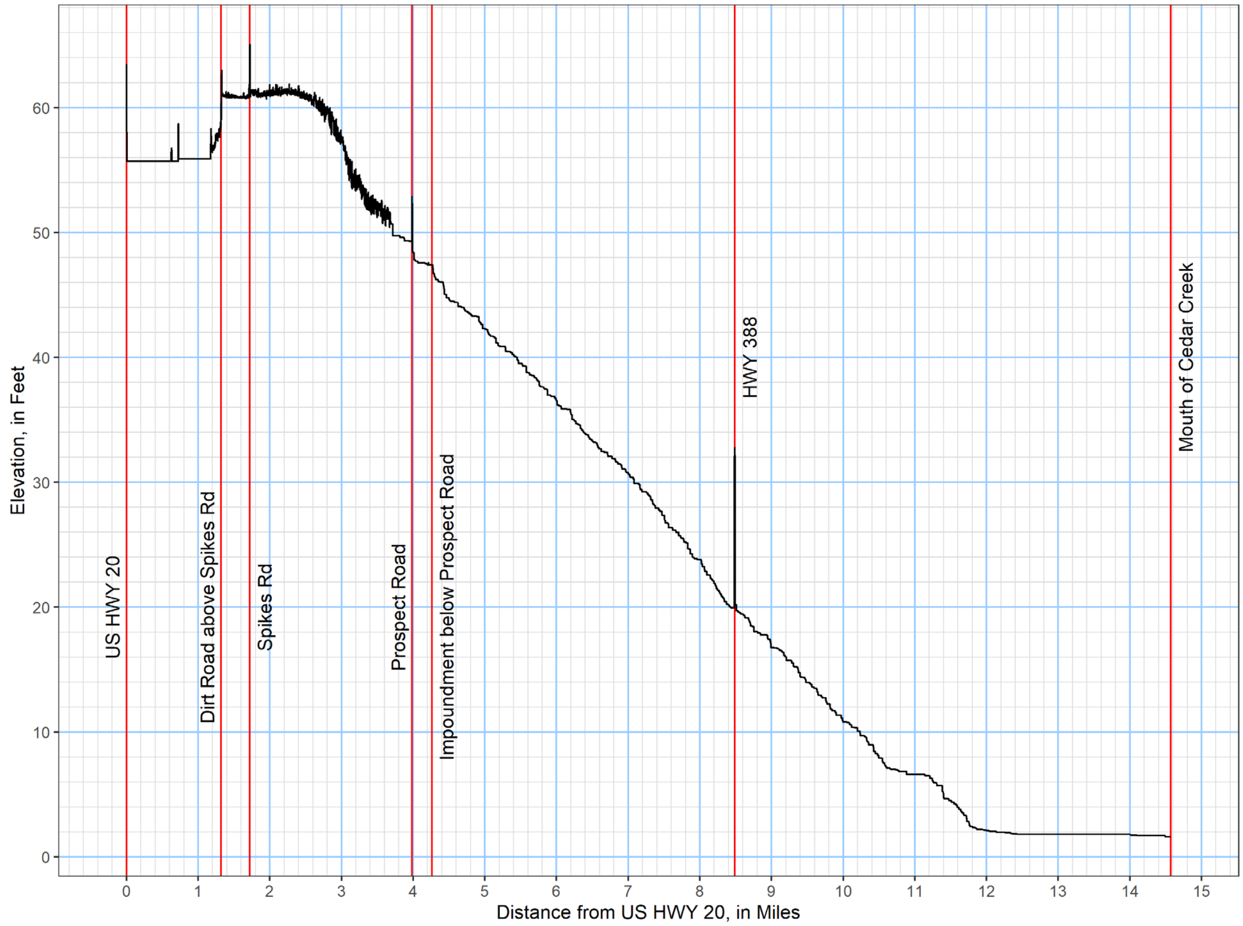

Figure 5-15. LiDAR-estimated water-surface elevation profile along Cedar Creek[6]

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[6] The profile shown in this figure is based on LiDAR data collected during the period from February 8 through February 23, 2020, and are an interim dataset that may be updated once review of the dataset is completed.

6 Conclusions

An evaluation of recent and historical hydrologic conditions was performed to determine causes of flooding events that occurred in Bay, Gulf, and Washington counties, Florida during the fall of 2018 through the fall of 2022. The analyses examined the Sand Hill Lakes, Econfina Creek, Bear Creek, and Bayou George Creek watersheds and limited data for Wetappo Creek and other watersheds. Conclusions drawn regarding the causes of flooding in these are likely applicable to many other areas within the central panhandle counties (Bay, Gulf, Washington, Calhoun, Liberty, Gadsden, Jackson) that have experienced flooding during this timeframe. Conclusions from this evaluation include the following:

Rainfall

- Multiple years of above average rainfall are the primary driver of the flooding that has occurred across the panhandle during the period extending from the fall of 2018 through the fall of 2022.
- Most counties within the central panhandle have received above average rainfall since 2013. During eight of the last ten years, annual precipitation totals have exceeded the 30-year (1991-2021) precipitation normals in at least one of these counties. Bay and Washington counties received their highest rainfall over the past thirty years during 2018. Total rainfall in Washington County was 52 percent higher than its 30-year normal during 2018, and total rainfall in Bay County was 42 percent higher than its 30-year normal. Total rainfall in Gulf County in 2021 was 37 percent higher than its 30-year normal, and higher than any other annual total for the past three decades.
- The above average rainfall is due to a combination of hurricanes, tropical storms, and extended periods of higher-than-normal rainfall. These events included Hurricane Michael, Hurricane Sally, Tropical Storm Fred, and the period from 2013 through 2021, which included multiple months with particularly high rainfall amounts, such as late December 2016 to early January 2016, June 2017, and December 2018 to January 2019.
- Flooding from late 2018 through the fall of 2022 within the Sand Hill Lakes Region and in some areas of Bay and Gulf counties was preceded by and coincides with extremely wet conditions. For example, monthly rainfall totals from May 2018 through December 2018 were extremely high, with totals from all months in this period exceeding 70 percent of months in the 127-year period of record. In addition, monthly rainfall totals for six of the eight months were close to or exceeded the totals of 90 percent of the months in this 127-year period.

Changes in Evapotranspiration and Land Cover

- National Land Cover Data indicate that Hurricane Michael caused the loss of nearly 80,000 acres of evergreen forest and 28,000 acres of woody wetlands. Although nearly all of these losses were offset by similar increases in herbaceous and shrub/scrub land cover types, the changes resulted in lower evapotranspiration (ET) rates immediately following Hurricane Michael, particularly during 2019 and 2020. The ET reductions were the largest in the areas most impacted by Hurricane Michael. During 2019, annual ET rates in the catastrophic, severe, and moderate impact zones were approximately 8.9 inches, 4.8 inches, and 0.8 inches, further below average, respectively, than the average ET rates for unimpacted counties within the District.
- Average ET rates in the Bear Creek, Bayou George Creek, and Wetappo Creek watersheds from 2019 to 2021 were approximately 4 to 10 inches below their respective averages for the 2000 to 2021 period of record. In comparison, average precipitation totals during 2019 to 2021 in these watersheds were approximately 7 to 17 inches higher than their respective 1991-2020 rainfall normals, indicating that above average rainfall is the primary cause of the observed flooding.

- Reduced ET contributed to higher groundwater levels, particularly during 2019, and likely exacerbated the flooding caused by excessive rainfall in areas impacted by Hurricane Michael.
- The ET rates in the severe and catastrophic impact zones remained below average during 2021 but increased from the period of record lows that occurred during 2019. The 2021 ET rates in the moderate impact zone were similar to pre-Hurricane Michael values.
- A pattern of generally declining ET values in the Bear Creek, Bayou George Creek, Lower Wetappo Creek, and Sand Hill Lakes region watersheds has been evident since 2014 suggesting that long-term changes in ET may have also occurred.
- Average ET rates for the period from 2015 through 2021 were about 3 to 10 inches lower than average ET rates for the period from 2000 through 2014 for the study area watersheds. In comparison, average precipitation departures (based on 1991-2020 normals) for the 2015 to 2021 period were about 8 to 12 inches above normal. These data suggest that changes in ET rates since 2014 may have exacerbated the effects of flooding from excessive rainfall during this period.

Hydrogeology, Groundwater Levels, and Lake-Groundwater Interactions

- Flood risks are highest for the lowest lying properties adjacent to a waterbody, such as lakefront properties or properties on or adjacent to wetlands or streams. Most of the properties reporting flooding concerns were such properties. High rainfall accumulations raise groundwater levels in the shallow surficial aquifer system and deeper Upper Floridan Aquifer (UFA), which raises lake and wetland levels as well. Shallower water tables also increase the potential for storm runoff adjacent to water bodies, increasing surface inflows to lakes and streams and the flood risk from such waterbodies.
- Historically high rainfall totals are reflected in the groundwater levels. For example, groundwater levels rose above land surface in December 2018 at the Greenhead monitoring wells because of wetter than normal conditions prior to and during the latter part of 2018. Flooded conditions persisted at this site through late May 2019, subsequently declined, and then resumed in the fall of 2021. Prior to the recent period of flooding, measured groundwater levels at this site had never risen above land surface, and the period of groundwater level records for these two wells are the longest in the study area, extending back to September 1962.
- The Sand Hill Lakes region is an internally drained, closed basin area with numerous closed depressions and sinkhole lakes that are generally well-connected hydraulically with the surficial aquifer system (SAS) and underlying, highly transmissive Upper Floridan aquifer. As such, lake levels in the region are affected by groundwater levels in the SAS and UFA. The historically high groundwater levels in the UFA and SAS have coincided with the flooding conditions that have occurred on low lying, lakefront or wetland properties in the Sand Hill Lakes region.
- Lakes that are more well connected hydraulically to the underlying UFA because of a leakier intermediate confining unit (ICU) will be much more sensitive to changes in UFA groundwater levels and regional hydrologic conditions. Conversely, lakes underlain by a less leaky ICU will be more sensitive to more local hydrologic conditions and local water table levels.
- The bathymetric characteristics of a given lake, such as the relation between lake area and depth, also affect flooding risk to lakeside properties. Low-lying properties along the shorelines of shallow lakes and wetlands are particularly vulnerable to flooding during very wet conditions because the inundated area of shallow lakes and wetlands changes more rapidly as lake and wetland levels rise in response to increased rainfall and rising groundwater levels. Conversely, shallow lakes are much more likely to become dry or nearly so than deep lakes during extended drought periods.

- High groundwater levels in the surficial aquifer system and UFA may have also contributed to flooding in areas near Bayou George, Bear, and Wetappo creeks in Bay and western Gulf counties, respectively. The water table in these areas may generally occur at shallow depths because of poor surface drainage, and because groundwater levels in the Upper Floridan aquifer may be near land surface or similar to water table elevations, which prevents or limits the ability of groundwater to move downward and through the SAS and away from flooded areas. The downward movement of groundwater can also be restricted in these areas because confinement of the Upper Floridan aquifer also increases with proximity to the Gulf of Mexico. These conditions contribute to shallow water table conditions and increase the potential for flooding in low-lying areas following extended periods of higher-than-normal rainfall or periods with high rainfall rates.

Stream Hydrology

- The variability of Econfina Creek and Bear Creek streamflow and baseflow can be attributed to fluctuations in climatic conditions, including changes in cumulative precipitation and regional groundwater levels.
- Periods of above average rainfall, particularly record rainfall in 2013, and above average rainfall during 2020 and 2021, have led to increased Econfina Creek and Bear Creek flows which may have contributed to recent increases in flooding propensity near these streams.
- Flow increases in Econfina Creek are primarily the result of increased baseflow resulting from periods of above average rainfall. This is likely due to the karst topography and sandy soils characteristic of the recharge area to Econfina Creek.
- For Bear Creek, flow increases post Hurricane Michael are disproportionally larger during high flow events suggesting that surface runoff in addition to baseflow has increased during this timeframe. This is reasonable since Bear Creek is primarily driven by surface water runoff from storm events. Increases in flow are the result of increased precipitation and elevated groundwater levels in the region.
- Topographic and hydrogeologic data, aerial imagery, and field observations indicate that a topographically high and relatively flat reach of Cedar Creek controls the water levels in Cedar Creek upstream of Spikes Road and of River Lake under flooding conditions, rather than the culverts at Spikes Road.
- Cedar Creek flows into Deer Point Lake Reservoir. The elevation of Deer Point Lake is about 60 ft lower than Cedar Creek at the Spikes Road crossing. Therefore, fluctuations in the level of Deer Point Lake Reservoir do not influence or contribute to flooding in the Sand Hill Lakes area.
- The effect of Hurricane Michael on changes to Econfina Creek and Bear Creek hydrology appears to be primarily due to decreased flow convenance resulting from significant downed tree debris in both the channel and floodplain.
- Debris removal efforts in portions of the Econfina Creek channel resulted in the stage-discharge relationship returning to conditions similar to pre-hurricane, although stages remain slightly elevated, likely due to remaining debris in the floodplain. Similar results were achieved in other sections along Econfina Creek and Chipola River where debris removal efforts commenced. Likewise, areas where debris efforts were not conducted show continued elevated stages relative to historical conditions. This includes Bear Creek, where stages continued to be elevated during 2022. Therefore, continued debris removal efforts in affected areas by Hurricane Michael including Bear Creek would be anticipated to further restore historical hydrologic regimes and potentially reduce flooding risk near streams.

6. Conclusions

- Hurricane Sally is the first event after Hurricane Michael to generate large amounts of rainfall in a short time, more than twice as much rainfall as Hurricane Michael in some locations. After Hurricane Sally, water levels on the Chipola River and Econfina Creek reached stages nearly as high or higher than stages reached during Hurricane Michael. Stages receded following Hurricane Sally and returned to near normal but slightly elevated water levels in Econfina Creek where debris removal occurred but were elevated in Bear Creek.
- While more rain was directly associated with Hurricane Sally than Hurricane Michael, Hurricane Michael illustrates that subsequent weather conditions can have as much of an impact as the rain event itself. After Hurricane Michael, there was subsequent sustained rainfall several weeks after the storm that kept water levels high. Additionally, reduced evapotranspiration from widespread loss of trees as well as reduced infiltration capacity due to high groundwater levels likely contributed to higher stream stages.

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