Recommended Minimum Flows for Wakulla and Sally Ward Springs

Wakulla County, Florida

Final

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List of Acronyms

AMO	Atlantic Multidecadal Oscillation	OSTDS	Onsite Sewage Treatment and Disposal Systems
ATM	Applied Technology and Management, Inc.	PBIAS	Percent Bias
FT	Federally Threatened	PFA	Primary Focus Area
FT(SA)	Federally Threatened due to Similarity of Appearance to Another Species	PHABSIM	Physical Habitat Simulation
FNAI	Florida Natural Areas Inventory	ppt	Parts per thousand
FWC	Florida Fish and Wildlife Conservation Commission	QSE	Quinine Sulfate Equivalent
FWCISMP	FWC Imperiled Species Management Plan	RMSE	Root Mean Square Error
FWRI	Fish and Wildlife Research Institute (FWC)	RSR	RMSE Ratio
gpm	Gallons per Minute	SAV	Submerged Aquatic Vegetation
HEC-RAS	Hydraulic Engineering Centers River Analysis System	SE	State Endangered (Florida)
in	Inches	SEFA	System for Environmental Flows Analysis
LOWESS	Locally Weighted Scatterplot Smoothing	SJRWMD	St. Johns River Water Management District
m	Meters	SPI	Standard Precipitation Index
MAE	Mean Absolute Error	SRWMD	Suwannee River Water Management District
ME	Mean Error	ST	State Threatened (Florida)
MFL	Minimum flows and levels	SWFWMD	Southwest Florida Water Management District
mgd	million gallons per day (United States Liquid)	TMDL	Total Maximum Daily Load
mg/L	milligrams per liter	TPS	Thomas P. Smith Reclamation Facility
NAVD88	North American Vertical Datum of 1988	µg/L	Microgram per Liter
N	Nitrogen	µS/cm	Microsiemens per centimeter
NL	Not Listed by the State of Florida	USFWS	United States Fish and Wildlife Service
NOAA	National Oceanographic and Atmospheric Association	USGS	United States Geological Survey
NTU	National Turbidity Units	WRV	Water Resource Value
NWFWMD	Northwest Florida Water Management District	yr	Year
NWI	National Wetlands Inventory	α	alpha, significance level

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Executive Summary

Section 373.042 (1), Florida Statutes, provides that "The minimum flow for a given water body is defined as the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area." As such, this minimum flow evaluation focuses solely on the effects of reduced spring flows from surface water and groundwater extraction to the ecology of with Wakulla River and Sally Ward Spring run. This MFL is not used for offsetting the effects of sea level rise, changes in precipitation patterns, changes in river hydraulics, natural changes in conduit networks, changes in water quality not related to withdrawal impacts, etc.

The Northwest Florida Water Management District (NWFWMD or District) is establishing minimum flows and minimum water levels (MFLs) for priority waterbodies located within its boundaries in accordance with Section 373.042(1), Florida Statutes. Wakulla Spring is one of three Outstanding Florida Springs within the NWFWMD. Minimum flows are required to be established for the District's three Outstanding Florida Springs by July 1, 2026. Minimum flows are also required to be established for second magnitude springs located on state-owned lands purchased for conservation purposes. Wakulla Spring (first magnitude) and Sally Ward Spring (second magnitude) are both located within the boundaries of Edward Ball Wakulla Springs State Park in Wakulla County, Florida.

MFLs are defined as the limit beyond which further withdrawals would be significantly harmful to the water resources or the ecology of the area. This report presents the technical assessment to determine recommended minimum flows for Wakulla Spring and Sally Ward Spring located in Wakulla County, Florida.

The Wakulla River and Sally Ward spring run are the focus of this MFL assessment. The majority of the Wakulla River and Sally Ward spring run, in addition to their respective floodplains, remains in a relatively natural condition as development along much of the system is relatively limited compared to other rivers, especially within the boundaries of the Edward Ball Wakulla Springs State Park. Despite the lack of development, Wakulla Spring, Sally Ward Spring and their respective spring runs have experienced changes during the past several decades including the excavation of portions of the Wakulla River and Sally Ward Spring Run, an invasion of hydrilla (*Hydrilla verticillata*), numerous subsequent herbicide treatments, historical fluctuations in water clarity, and periodic short-term increases in specific conductivity associated with spring flow reversals from the coastal Spring Creek Spring Group. The Wakulla River and Sally Ward spring run are home to numerous wildlife species and are extensively utilized for recreation.

Wakulla Spring is one of the largest freshwater springs in Florida with a median daily discharge of 586 cubic feet per second (cfs) (equivalent to 379 million gallons per day (mgd), and an average discharge of 575 cfs (372 mgd) between October 23, 2004, and December 31, 2019, making it a first magnitude spring. Sally Ward Spring is considerably smaller and discharges an average of 23 cfs daily (15 mgd), making it a second magnitude spring. Both springs are unique among Florida springs in that discharge has increased significantly during recent years. Both springs are connected to numerous other springs, sinkholes, and swallets by an extensive network of underground conduits. The Sally Ward spring run flows approximately

0.7 miles to the southeast where it joins the Wakulla River just downstream of the main spring pool. The combined discharge from both springs then flows downstream approximately nine miles to the southeast where it discharges to the St. Marks River at the City of St. Marks, Florida. The lower St. Marks River then flows south and discharges into Apalachee Bay and the Gulf of Mexico. Research into the possible reasons for increasing flows at Wakulla Spring has identified two mechanisms contributing to the increased flows that are supported by the available data. Lower river and spring pool stages resulting from changes in the Wakulla River channel have resulted in additional spring discharge by increasing the gradient between the upper river and spring pool and the Floridan aquifer. In addition, increases in coastal sea levels are likely increasing the equivalent freshwater head at the Spring Creek Spring group resulting in intermittent diversions of water from the Spring Creek Spring group to Wakulla Spring.

Some coastal groundwater monitor wells located south of Wakulla Spring exhibit increasing trends in aquifer levels, consistent with sea level rise (see Appendix A). Long-term aquifer level data at a monitor well pair located near the Wakulla Spring pool date back to year 2000. Available data indicates that the aquifer levels near Wakulla Spring, while varying with climatic conditions, exhibit no apparent trends during the available year 2000 to present period of record. Groundwater withdrawals by the City of Tallahassee, the largest permitted use within the groundwater contribution area, have remained relatively unchanged since 1995. Total withdrawals are a small fraction of the water budget; therefore, groundwater withdrawals are not the cause of changes observed at Wakulla Spring during the past two decades.

Rule 62-40.473, Florida Administrative Code, and Section 373.0421, Florida Statutes, requires consideration be given to natural seasonal fluctuations in water flows, non-consumptive uses, structural alterations, and ten environmental values when establishing minimum flows. The ten environmental values listed in Rule 62-40.731, Florida Administrative Code, are referred to herein as Water Resource Values (WRVs). WRVs were assessed within the Wakulla and Sally Ward systems study area, which extends from Wakulla and Sally Ward springs, downstream to the confluence with the St. Marks River. The District has carefully considered all ten WRVs and determined that four are most relevant to the Wakulla River, have the potential to be adversely affected by spring flow reductions, and have sufficient data for assessment:

1- Recreation in and on the Water (Recreation)

2- Fish and Wildlife Habitats and the Passage of Fish (Fish and Wildlife Resources)

3- Estuarine Resources

4- Water Quality

The remaining WRVs were all considered for MFL analysis but were not utilized directly to quantify minimum flows for Wakulla and Sally Ward Springs. These WRVs were determined to have a low potential for impacts resulting from spring flow reduction, were not applicable to the Wakulla River, and/or sufficient data was unavailable to quantify the WRV.

For each WRV used in MFL analysis, quantitative metrics were utilized to relate WRVs to spring flows and to assess potential effects of reductions in flows from Wakulla and Sally Ward springs. Recreation was evaluated in terms of the frequency of sufficient water depths for recreational motorized boat and canoe/kayak passage in the Wakulla River below the Shadeville Road bridge. In addition, boat passage was evaluated within the State Park at transects located along the established tour boat route. Metrics for Fish and Wildlife Resources were designed to protect sufficient water depths and frequencies for the passage of fish and manatees and the availability of adequate thermal refuge for manatees (during winter months). Metrics for Estuarine Resources were designed to protect the volume, bottom surface area, and shoreline length of multiple low-salinity habitats. Several water quality parameters were evaluated to ensure that potential reductions in spring flow would not cause significant harm to Wakulla and Sally Ward spring water quality. For Sally Ward Spring, safe fish passage from the Wakulla River to the Sally Ward Spring (Fish and Wildlife Resources) were also evaluated as the quantifiable metrics.

To determine the effects of springflow reductions on WRV metrics, reference or "baseline" spring flow time series for Wakulla and Sally Ward springs were developed. The Wakulla Spring baseline time series was developed using the best available data from multiple sources. The District collected direct spring discharge data using a sensor located within the spring vent. When discharge data from the vent was unavailable, spring discharge was estimated using relationships developed between Wakulla Spring vent discharge and flow in the Wakulla River near Crawfordville, FL (USGS station 02327022). Discharge from both Wakulla Spring and the Sally Ward Spring has increased over time. At Wakulla Spring, the median discharge has increased from 209 cfs during 1998 to 686 cfs in 2019. No measurable effects of consumptive uses are discernible in the spring discharge time series, and baseline conditions were defined as the period of record extending from October 23, 2004 to December 31, 2019.

The baseline time series for Sally Ward Spring also was developed using the best available data. The District collected spring discharge data from a station located on the spring run approximately 0.5 miles downstream of the Sally Ward Spring vent and 0.2 miles upstream of the confluence with the Wakulla River. Similar to Wakulla Spring, discharge from Sally Ward Spring exhibits an increasing trend. No discernible effects of consumptive uses are present in the data, and the baseline flows for Sally Ward Spring includes all manual discharge measurements made between October 23, 2004 and December 31, 2019.

Seasonal fluctuations in spring flow from Wakulla and Sally Ward springs were examined and determined to be small, particularly relative to other Florida rivers. Because seasonal variations are relatively small and the metrics utilized in MFL determination are relevant throughout the year, period of record flows rather than seasonal flow blocks, were used to develop the proposed minimum flows. Structural alterations were considered, such as the use of dynamite to deepen the Sally Ward spring run and the Wakulla River to allow tour boat passage, and the subsequent deposition of material along the streambanks in the late 1960s. However, data are limited regarding the magnitude of potential effects of these alterations on spring flows or floodplain communities.

Potential effects of spring flow reductions were assessed using a hydraulic model (Hydrologic Engineering Centers River Analysis System, “HEC-RAS”) for water depth-based metrics associated with Recreation and

Fish and Wildlife Resources). Hydrodynamic models (Environmental Fluid Dynamics Code, "EFDC") were utilized to assess the effects of spring flow reductions on salinity and temperature to evaluate Estuarine Resources habitat metrics and manatee thermal refuge, respectively. To allow for reasonable model run times for the EFDC models, a smaller subset of the baseline flows period was required. The period of December 1, 2007 through October 4, 2010, which is representative of the range of flows within the entire baseline period of record, was selected and used to evaluate potential spring flow reductions on estuarine habitats. Four separate baseline periods were used to evaluate manatee thermal refuge at Wakulla Spring (February 9, 2013 through March 31, 2013, November 13, 2014 through March 31, 2015, November 6, 2017 through March 31, 2018, and November 1, 2018 through March 31, 2019). The entire baseline period for each spring was used for the HEC-RAS modeling. Physical habitat models such as Physical Habitat Simulation (PHABSIM) and the System for Environmental Flows Analysis (SEFA) were considered; however, tidal fluctuations and changes in vegetation density throughout the Wakulla River precluded the development of reliable relationships among channel profiles, velocities, and substrates (Gore 2015). Additional models and tools which are used to assess instream habitats are continually being refined and updated. While not available at the time of this technical assessment's preparation, additional tools are now available which may be capable of modeling instream habitats in systems like the Wakulla River. As part of the District's adaptive management policy for MFLs, instream models will be reconsidered during the Wakulla and Sally Ward Springs MFL future reevaluations. To ensure within bank flows are protected, other instream habitat metrics, including riparian wetland habitats, woody habitats, and fish passage, were investigated to determine minimum flows.

Hydraulic (HEC-RAS) and hydrodynamic (EFDC) models were used to determine the flow regime needed to prevent significant harm from withdrawals. Although significant harm is not specifically defined in statute, a maximum of 15 percent reduction in Water Resource Value metrics is used in this MFL evaluation. This definition has been implemented as the protection standard for numerous MFLs throughout Florida and has been accepted by more than a dozen MFL peer review panels (Gore et al. 1992, SRWMD 2016, SWFWMD 2017a, SWFWMD 2017b, NWFWMD 2019). The implementation of the MFL for Wakulla and Sally Ward springs will follow an adaptive management approach, with MFLs periodically reviewed and revised by the District as needed, to incorporate new data and information.

<u>Results of Minimum Flows Evaluations</u>

The results of minimum flows evaluations for the Wakulla and Sally Ward springs are shown in the table below. Safe Manatee Passage was evaluated at all transects along the Wakulla River. At River Station 41707.76, Wakulla River flows of 560 cfs or more are needed to maintain a water depth of 3.8 ft at the shallowest transect during a mean daily high tide. This corresponds to a combined Wakulla Spring and Sally Ward Spring flow of 520 cfs. For manatee passage, a depth of 3.8 ft across a continuous width of 3.8 ft, as reported by Rouhani et al. 2007 as the volume of water needed for a single manatee for thermal refuge, was used; however, conversations with the FWC (FWC 2020b) indicated that water depths above 2.5 ft are adequate. A flow reduction of 59 cfs was modeled to reduce the water depths on average by 1.7 inches, which would not adversely affect manatee passage at this transect. All other transects contained more than 3.8 ft of water during all flow conditions.

Four metrics (Safe Public Boat Passage, Safe Canoe/Kayak Passage, Safe Tour Boat Passage, and Safe Fish Passage) were shown to be insensitive to spring flow reductions as the river/spring run conditions required were met under all observed and modeled spring flows. Additional metrics including inundation of floodplain vegetation communities and shoreline woody habitat (live roots and dead woody debris) were considered. However, the available data and modeling results indicate that floodplain communities are maintained largely by direct precipitation and high water-table conditions rather than spring flow (Section 5.1.2). Significant portions (>50%) of the floodplain along the Wakulla River were only inundated when Wakulla River flows were extremely high (average 5 percent exceedance) which are typically associated with high rainfall events. In addition, low sample sizes and concerns with the randomness of data collection precluded the use of shoreline woody habitat. Due to these concerns and with the recommendation from scientific peer reviewers from the St. Marks River Rise MFL Technical Assessment, floodplain communities were not used as MFL metrics.

Low salinity (oligohaline) habitats in the downstream portion of the Wakulla River were shown to be relatively insensitive to Wakulla and Sally Ward spring flow reductions. A 36 percent modeled spring flow reduction resulted in a 15 percent reduction in available volume and bottom surface area of the zone of less than one part per thousand (ppt) salinity. The less than 0.5 ppt salinity zone was not included as this was the oligohaline zone considered to be fresh water, and the EFDC model did not extend upstream to the spring vents to include the entire freshwater portion of the Wakulla River and Sally Ward Spring run. This makes estimates of available freshwater habitats greatly underestimated.

Manatee thermal refuge was evaluated near the Wakulla Spring pool under two criteria assumed to be detrimental to manatee health, acute (<15 °C for more than four consecutive hours) and chronic (<20° C for more than three consecutive days). Under baseline conditions and an extreme Wakulla Spring flow reduction scenario of 30 percent the acute temperature criteria were never observed in the model domain. Under the chronic stress criteria with a 30 percent Wakulla Spring flow reduction, the amount of available thermal habitat could support 1900 manatees, which far exceeded the maximum number of manatees observed at Wakulla Spring (n=43). As a result, the manatee acute and thermal stress thermal criteria were determined to not be a limiting factor in the determination of minimum flows for Wakulla Spring.

Results of Minimum Flow Determination for All Metrics

Water Resource Value	Metric	Allowable Flow Reduction (cfs)
Recreation	Safe Public Boat Passage	Limiting Depth Never Obtained
	Safe Canoe Passage	Limiting Depth Never Obtained
	Safe Tour Boat Passage	Limiting Depth Never Obtained
Fish and Wildlife Resources	Safe Fish Passage	Limiting Depth Never Obtained
	Floodplain Habitat Inundation	Maintained by direct precipitation and high water-table conditions
	Live Root Habitat Inundation	Only Inundated at Extremely High Flows
	Dead Woody Debris Inundation	Only Inundated at Extremely High Flows
	Safe Manatee Passage Transect 41707.76	59 cfs
	Manatee Acute Thermal Refuge Habitat	Acute Temperature (<15°C) Never Observed or Modeled with 30 Percent Spring Flow Reduction
	Manatee Chronic Thermal Refuge Habitat	Determined to be Not Limiting Due to Large Amount of Habitat Available with a 30 Percent Spring Flow Reduction
Estuarine Resources	Volume of Oligohaline Habitat	Metric Not Limiting
	Surface Area of Oligohaline Habitat	Metric Not Limiting
	Shoreline Length of Oligohaline Habitat	Metric Not Limiting

*Combined Wakulla and Sally Ward Spring Flow at Transect 41707.76 for the critical elevation

As discussed in Section 6, the allowable flow reduction is proposed to be applied to the average daily baseline spring flow of 598 cfs. Based upon the results summarized above, the recommended allowable flow reduction for the combined Wakulla and Sally Ward Springs System is 59 cfs (38 mgd) or a 9.9 percent reduction in spring flows from average daily baseline spring flow (See Table Below).

Proposed Minimum Flow for the Wakulla and Sally Ward Springs Systems. *Represents the combined spring flows of Wakulla Spring and Sally Ward Spring

System	Average Daily Baseline Spring Flow for Baseline Period (October 23, 2004 – December 31, 2019)	Allowable Spring Flow Reduction	Allowable Percent Reduction in Average Daily Baseline Spring Flow (%)
Wakulla and Sally Ward Springs System*	598 cfs (386 mgd)*	59 cfs (38 mgd)	9.9 Percent

1 Introduction

This report provides the technical analysis for determining recommended minimum flows for the Wakulla and Sally Ward springs. Wakulla Spring is a first magnitude spring (>100 cubic feet per second, cfs) and Sally Ward Spring is a second magnitude spring (between 10 cfs and 100 cfs). Both springs are located within the Edward Ball Wakulla Springs State Park in Wakulla County, Florida and comprise the headwaters of the Wakulla River (Figure 1). This assessment focuses on determining the threshold at which additional withdrawals would cause significant harm to ecology and water resources of the area.

Section 1 (Introduction) of this report describes the objective, background, and requirements for establishing minimum flows, as well as a description of the study area. Section 2 (Water Resource Values) describes the ten Water Resource Value (WRVs) defined in Rule 62-40.473, Florida Administrative Code, and the associated metrics used to quantify the potential effects of reduced spring flows. Section 3 (Hydrologic Models) describes the available data, spring flows, and the models utilized to determine minimum flows. Section 4 (Evaluation of Water Resource Values) provides the evaluation of the WRV metrics described in Section 2 and the results. Section 5 (Recommended Minimum Flows) provides the recommended minimum flow regime for Wakulla and Sally Ward springs system.

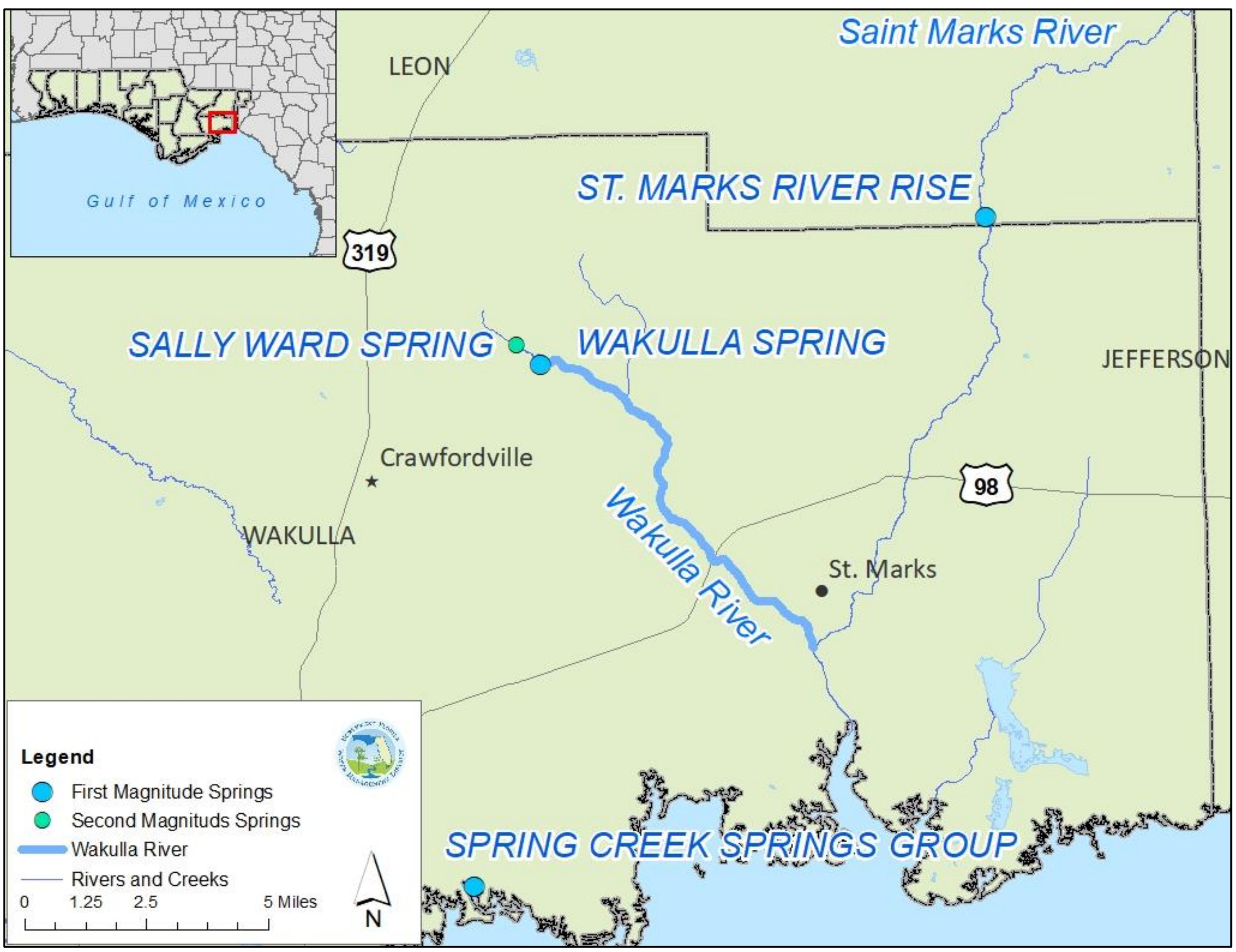

Figure 1: Wakulla River, Wakulla Spring, and Sally Ward Spring Locations.

1.1 Objective

The objective of this Technical Report is to determine recommended minimum flows for spring discharge at the Wakulla and Sally Ward springs to ensure protection of aquatic habitats, recreation, and other water resource values from significant harm due to consumptive uses.

1.2 Background

The Northwest Florida Water Management District (District) is required to establish minimum flows and minimum water levels (MFLs) for specific water bodies located within its boundaries (Section 373.042, Florida Statutes). A map of the NWFWMD's priority water bodies for MFL establishment and MFLs previously established can be found in on the District's website (www.nwfwater.com). Section 373.042 (1), Florida Statutes, provides that "The minimum flow for a given water body is defined as the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area." As such, this minimum flow evaluation focuses solely on the effects of reduced spring flows from surface water and groundwater extraction to the ecology of with Wakulla River and Sally Ward Spring run. This MFL is not used for offsetting the effects of sea level rise, changes in precipitation patterns, changes in river hydraulics, natural changes in conduit networks, changes in water quality not related to withdrawal impacts, etc.

MFLs are to be established using the "best available information." In accordance with Rule 62-40.473, Florida Administrative Code, and Section 373.0421, Florida Statutes, the District must consider natural seasonal fluctuations in water flows or levels (Section 2.4), non-consumptive uses (Section 1.7, Section3), structural alterations (Section 1.7), and multiple environmental values (referred to as Water Resource Values or WRVs, Table 1, Section 3), when developing the minimum flows. Detailed descriptions of the WRVs and their relevance to the Wakulla and Sally Ward springs system are provided in Section 2.

Water management districts are required to develop and implement either a recovery or prevention strategy at the time of rule adoption if the system is currently not meeting or projected to not meet applicable minimum flows. A recovery strategy is required when a system is currently not meeting MFL criteria, while a prevention strategy is required if the MFL is expected to not be met during the following 20 years based on projected withdrawals. Prevention/recovery strategies may include water conservation measures and additional water supply or water resource development projects.

Table 1: Environmental Values (62-40.473, Florida Administrative Code)

Water Resource Value	Description
WRV 1	Recreation In and On the Water
WRV 2	Fish and Wildlife Habitats and the Passage of Fish
WRV 3	Estuarine Resources
WRV 4	Transfer of Detrital Material
WRV 5	Maintenance of Freshwater Storage and Supply
WRV 6	Aesthetic and Scenic Attributes
WRV 7	Filtration and Absorption of Nutrients and Other Pollutants
WRV 8	Sediment Loads
WRV 9	Water Quality
WRV 10	Navigation

1.3 Conceptual Approach

The development of minimum flows for Wakulla and Sally Ward springs builds upon methods applied elsewhere in Florida. The District's approach toward establishing MFLs for Wakulla and Sally Ward springs is that an alternative hydrologic regime exists such that the system's water resource values are protected from significant harm caused from water withdrawals. The approach is based on quantifiable relationships between discharge from the springs (Wakulla and Sally Ward) and multiple physical and ecological features of the spring run, or WRV metrics, as described in Sections 2 and 4. Rule 62-40.473, Florida Administrative Code, outlines requirements regarding specific WRVs which must be considered in setting MFLs (Table 1).

Similar to MFLs established elsewhere in Florida, the District assessed each WRV. Multiple WRVs were considered and evaluated based on the relevancy to the Wakulla River and Sally Ward springs system, the potential to be adversely affected by reductions in spring flow, and whether there are measurable and quantifiable relationships that can be used to develop spring flow thresholds for significant harm. These WRVs in relation to the Wakulla and Sally Ward springs system are described in detail in Section 2.

The results from the evaluation of multiple WRV metrics were used to determine the recommended minimum flows for Wakulla and Sally Ward springs. Although significant harm is not specifically defined in statute, an allowable 15 percent reduction in WRV metrics has been implemented as the protection standard for multiple MFLs throughout Florida. This definition of significant harm was first proposed by Gore et al. (2002) during their review of the upper Peace River MFL report (SWFWMD 2002). The peer review panel stated, "In general, instream flow analysts consider a loss of more than 15 percent habitat, as compared to undisturbed or current conditions, to be a significant impact on that population or assemblage." This definition of significant harm has been subsequently utilized and accepted by more than a dozen MFL peer review panels in the establishment of MFLs for springs and rivers (Munson and Delfino 2007, NWFWMD 2019, SRWMD 2005, SRWMD 2007, SRWMD 2013, SRWMD 2015, SRWMD

2016a, SRWMD 2016b, SWFWMD 2008, SWFWMD 2010, SWFWMD 2011, SWFWMD 2012a. SWFWMD 2012b, SWFWMD 2017a, SWFWMD 2017b). The 15 percent threshold is also used in this assessment, recognizing that additional data collection and long-term research to confirm or refine this threshold for MFL assessments in Florida would be beneficial. MFL implementation will follow an adaptive management approach, with MFLs periodically reviewed and reevaluated by the District to reflect new data and information. As new data and information are developed regarding the definition of or threshold for significant harm, the District will consider this information in future MFL re-evaluations.

To establish minimum flows, a detailed understanding of the hydrology of the Wakulla and Sally Ward springs system is required to quantify effects of spring flow reduction scenarios. Models developed to assess changes in WRV metrics associated with reduced spring discharge include a Hydrologic Engineering Centers River Analysis System (HEC-RAS) model to simulate changes in river depth/inundation and Environmental Fluid Dynamics Code (EFDC) hydrodynamic models to simulate changes in salinity and temperature. These tools are well-vetted and have been applied across a wide range of conditions and places to establish MFLs in Florida (NWFWMD 2019, SRWMD 2015, SRWMD 2016, SWFWMD 2005, SWFWMD 2012).

1.3.1 Study Area

This section describes the Wakulla River surface watershed, physiography, land use, population, and past structural alterations to the Wakulla River and Sally Ward spring run.

1.3.2 Wakulla River Watershed

Wakulla Spring and Sally Ward Spring are located in the Florida panhandle south of the City of Tallahassee. Both springs and the entire Wakulla River are located within Wakulla County, Florida (Figure 1). The Wakulla River originates at the Wakulla Spring main vent and flows approximately 9 miles to the southeast where it discharges into the St. Marks River at the City of St. Marks. The main source of inflow to the Wakulla River is the first magnitude (>100 cfs, 64.6 million U.S. gallons per day) Wakulla Spring, which discharged approximately 575 cfs (372 million gallons per day, mgd US) of water based upon daily average flows between October 23, 2004, and December 31, 2019. The second magnitude (>10 cfs, 6.5 million gallons per day) Sally Ward Spring contributes on average 23 cfs (15 mgd US) of flow to the Wakulla River based upon 96 discrete discharge measurements taken between October 23, 2004, and October 19, 2019. Flow from Sally Ward enters the Wakulla River just downstream from the Wakulla Spring pool. Sally Ward Spring discharge represents approximately 3.6 percent of the inflow to the river at this location. Additionally, numerous smaller springs (described in Sections 1.5 and 2.1) are present along the Wakulla River but provide relatively minor amounts of additional flow. Diffuse groundwater discharge (e.g., baseflow) can also contribute to flow in the river. The Wakulla River has a total surface watershed area of approximately 1,170 mi^2 (748,800 acres) of Wakulla and Leon counties, Florida and includes a substantial portion of the City of Tallahassee and unincorporated lands to the south and west of the city (Figure 2). The groundwater contribution area for Wakulla and Sally Ward springs includes portions of Wakulla, Leon, and Gadsden counties and extends into southern Georgia. Due to the karst geology, surface water runoff is relatively low and most water originating in the river is derived from spring flow.

Several intermittent streams within the watershed discharge into sinkhole type features called swallets, which transmit surface waters into the Floridan aquifer. More detail on the complex hydrogeology of the watershed and groundwater contribution area is provided in section 1.5. The study area for this minimum flow determination extends from the Wakulla and Sally Ward springs, downstream along the Wakulla River spring run to the confluence with the St. Marks River (Figure 1).

Near the City of St. Marks, the Wakulla River discharges into the St. Marks River. The St. Marks River originates in eastern Leon County. The St. Marks River flows south approximately 35 miles and discharges into Apalachee Bay and the Gulf of Mexico (Figure 1). The St. Marks River contains the St. Marks River Rise, a first magnitude spring, and numerous smaller springs and minor tributaries which contribute to its flow. The District established a minimum flow for the St. Marks River Rise in June 2019 (Rule 40A-8.031, F.A.C.).

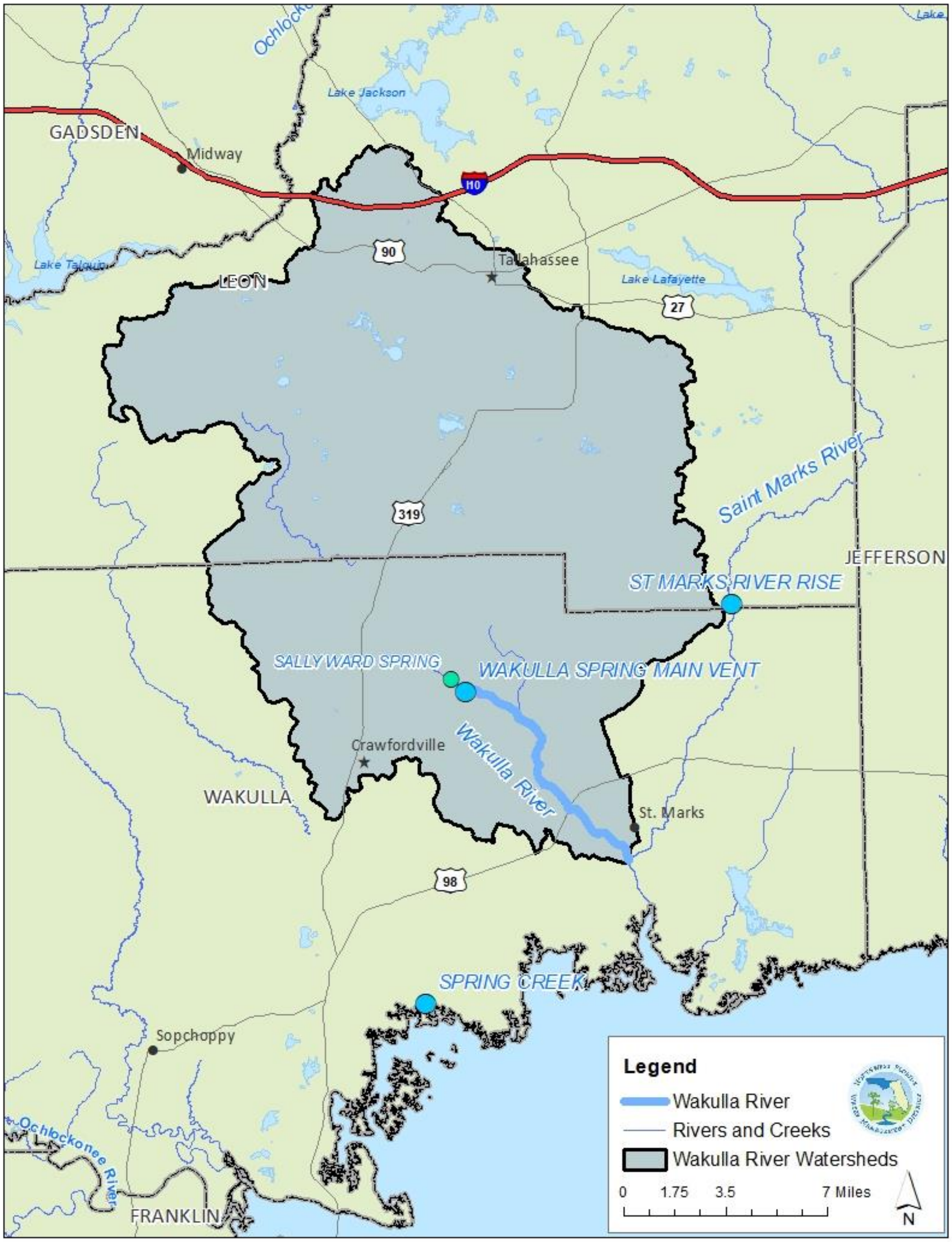

Figure 2: Wakulla River Surface Watershed

1.3.3 Physiography

The Wakulla River surface watershed is comprised of two major physiographic regions divided by the Cody Escarpment (Cody Scarp) (Figure 3). The Cody Scarp is a geomorphic feature that approximates a prehistoric shoreline present when sea level was considerably higher than today. This feature was created by the dissolution of carbonate rocks (limestone and dolostone) by streams and groundwater combined with head ward erosion by streams (Upchurch 2007). The Gulf Coastal Lowlands is the dominant physiographic region found south of the Cody Scarp (DEP2001; Pratt et al. 1996). Shoreline elevations adjacent to the Wakulla River along spring run elevations range from approximately 6 ft North American Vertical Datum of 1988 (NAVD 88) near the Wakulla Spring Vent to 2.0 ft NAVD 88 near the confluence with the St. Marks River.

The Tallahassee Hills is the dominant physiographic region found north of the Cody Scarp (Figure 3). Land elevations of the Tallahassee Hills tend to be quite high, exceeding 300 ft NAVD88 in some areas, compared with the Coastal Lowlands where elevations are generally less than 50 ft NAVD88. The Tallahassee Hills is characterized by Pleistocene age sands and clays sediments dating back to approximately 2.6 million years (NWFWMD, 2017). Beneath this layer are clayey sediments which function as a semi-confining unit between the surficial sands and Floridan aquifer system. Despite the semi-confining layer, the Tallahassee Hills region exhibits connectivity between surface waters and the Floridan aquifer, as a result of numerous karst features including disappearing streams, swallets, and several lakes with sinkholes. Some surface waters flowing from the Tallahassee Hills region enters sinkholes and swallets and flows underground towards the coast where it can discharge at large springs including Wakulla Spring, St. Marks River Rise, and the Spring Creek Spring Group (Spring Creek) (Davis and Verdi, 2014). This is particularly true for "closed basins" where flow from intermittent streams discharges into swallets connected to the underlying Floridan aquifer system.

Semi-confining sediments which could inhibit or reduce surface water infiltration into the Floridan aquifer system are thin or absent south of the Cody Scarp (NWFWMD, 2017). As a result, precipitation directly recharges the Floridan aquifer with little surface runoff. Many karst features exist including sinkholes, swallets, Wakulla Spring, the Spring Creek Spring Group, St. Marks River Rise, and many smaller springs (Section 1.5) (Davis and Verdi, 2014).

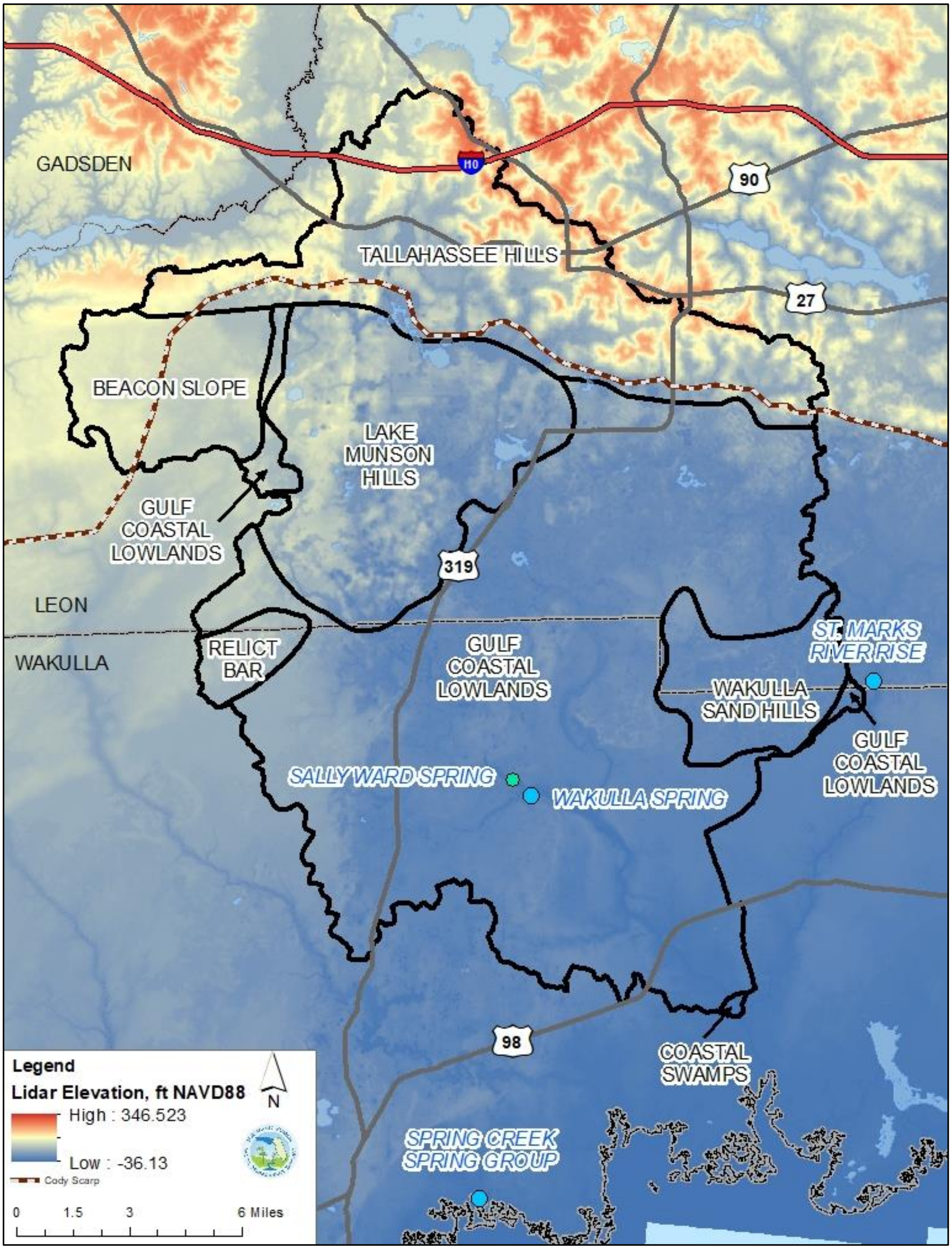

Figure 3: Physiographic Regions within the Wakulla River Watershed

1.3.4 Land Use, Population, and Structural Alterations

Land uses within the Wakulla River surface watershed are dominated by natural areas (70 percent) including upland forest (55 percent), wetlands (14 percent), and open water (1 percent) (Figure 4, Table 2). Developed land uses (25 percent) are concentrated in and around the City of Tallahassee, which is located in the northern portion of the study area. Agriculture represents a relatively small portion of the surface watershed (4 percent) and is generally scattered throughout the Wakulla River watershed south of the City of Tallahassee. The immediate vicinity of Wakulla and Sally Ward springs and the Wakulla River consists primarily of state-managed lands and undeveloped, privately-owned lands comprised largely of wetlands and upland forest along with a small portion of developed land (Figure 4, Figure 5). Within the surface watershed, a total of 107 mi^2 is under public ownership and managed as parks, including the Wakulla Spring State Park and portions of the Apalachicola National Forest (Figure 5).

The population residing within Leon and Wakulla counties, and the portion of Jefferson county within the District is currently 325,972 individuals as of 2015 (NWFWMD 2018). The majority (81 percent) of the population resides within Leon County (284,443 individuals in 2015), which includes the City of Tallahassee. Most of the population resides inside the Wakulla River watershed. Wakulla and Jefferson counties are largely rural with relatively small populations (31,283 and 10,246 individuals, respectively, during 2015). Within the Florida portion of the combined St. Marks and Wakulla River surface watershed, Leon County is predicted to exhibit the largest population growth through 2040, with a projected population of 351,951 individuals. Wakulla County population is projected to increase to 42,735 individuals by 2040. The population of Jefferson County is predicted to increase slightly to 11,321 individuals by 2040. Much of the population residing within the Wakulla River watershed obtains its fresh water from public supply utilities, with the largest utility being the City of Tallahassee (NWFWMD, 2014). The City of Tallahassee withdrew approximately 27.1 mgd during 2019 from the Floridan aquifer system (NWFWMD unpublished data) with this extraction occurring primarily within the Wakulla/Sally Ward groundwater contribution area (e.g., springshed). More than half of water pumped from the Floridan aquifer is returned to the aquifer at the City of Tallahassee's Southeast Sprayfield. In 2019, 17.58 mgd was applied at the Southeast Farm sprayfield. Outside of the City of Tallahassee, much of the population utilizes domestic Floridan aquifer wells for their drinking water supply although public supply utilities serve some rural areas.

The Wakulla River and Sally Ward Spring Run have undergone several structural alterations. The Wakulla River boat tour route (approximately 1 mile downstream of the main vent) and the entire Sally Ward Spring Run received river channel modifications in the late 1960s to early 1970s (DEP 2007). Edward Ball dynamited parts of the Wakulla River and Sally Ward Spring Run to make it more accessible for boats (DEP 2018b). Currently, there are deep channels on either side of the Wakulla River which are used for river tour boats. Spoil banks from the dredged areas remain on the banks of both waterways and these areas have since been recolonized by native vegetation; however, elevated ground surfaces associated with these spoil banks remain in many areas and are particularly visible along the Sally Ward Spring Run. Two road bridges have been installed which cross the Wakulla River (U.S. Hwy 98 and Shadeville Road) (Figure 6), and one pedestrian bridge was installed which crosses the Sally Ward Spring Run. The bridges crossing the Wakulla River contain submerged pilings which can impede water flow, while the Sally Ward bridge contains no submerged pilings. Effects of these structural alterations were considered but data are unavailable regarding the magnitude of potential effects on the ecology, water resources, or the quantity of spring flow discharged from Wakulla and Sally Ward springs. All three bridges are represented in the HEC-RAS model, described in Chapter 3. Currently there are no permitted surface water extractions from the Wakulla River.

Table 2: Land Use within the Wakulla River Watershed Study Area, Florida (DEP2017)

Land Use Category[1]	Total Area (mi^2)	Percent Watershed Area (%)
Agriculture	11.08	4
Developed	75.02	25
Open Land	2.75	1
Upland Forest	166.54	55
Open Water	3.05	1
Wetlands	43.10	14
Total	**301.53**	**100**

[1] Land use in Florida portion of the watershed; 2015-2016 land use data for NWFWMD.

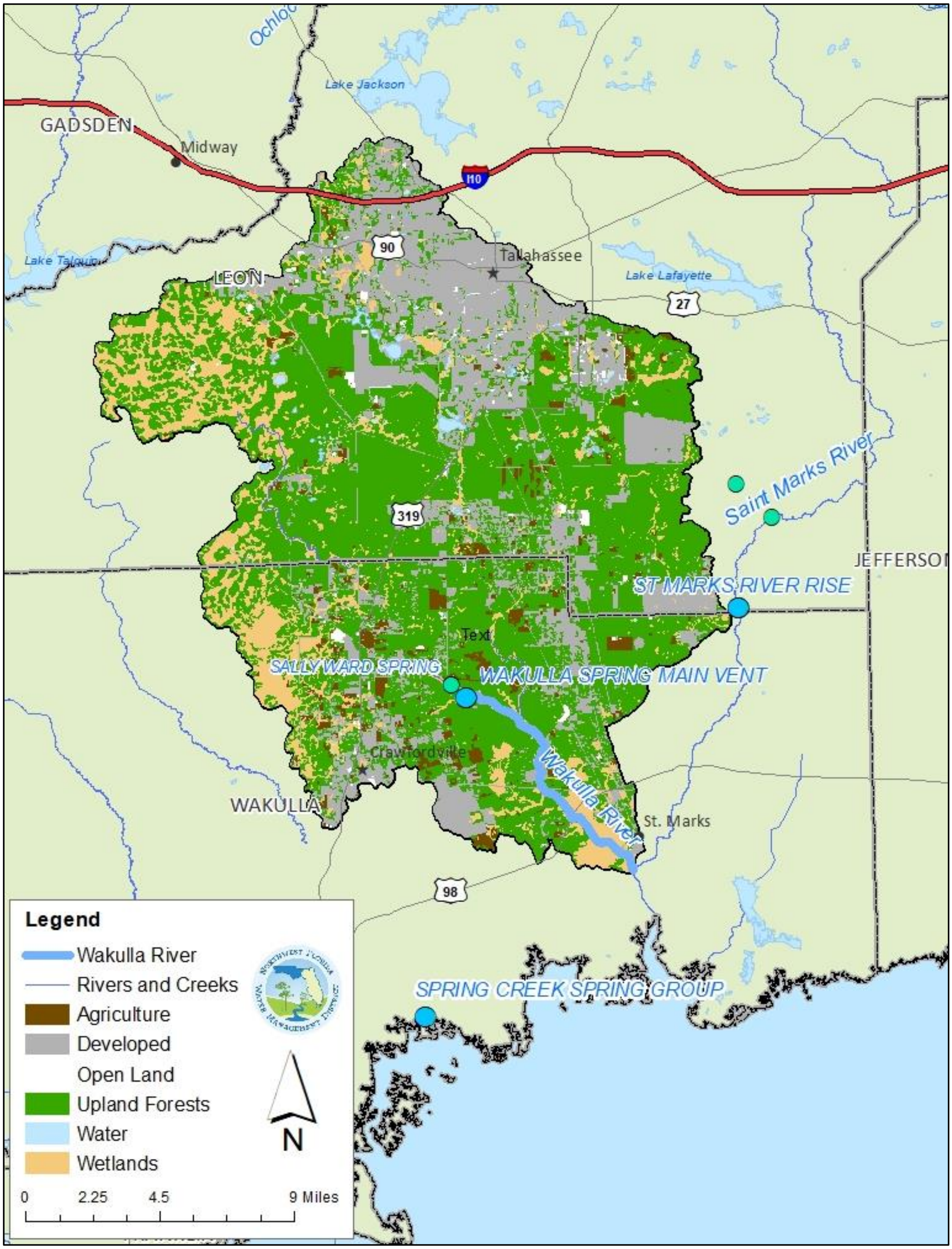

Figure 4: Land Use within the Florida Portion of the Wakulla River Watershed (2015-2016 Land Use Data From NWFWMD)

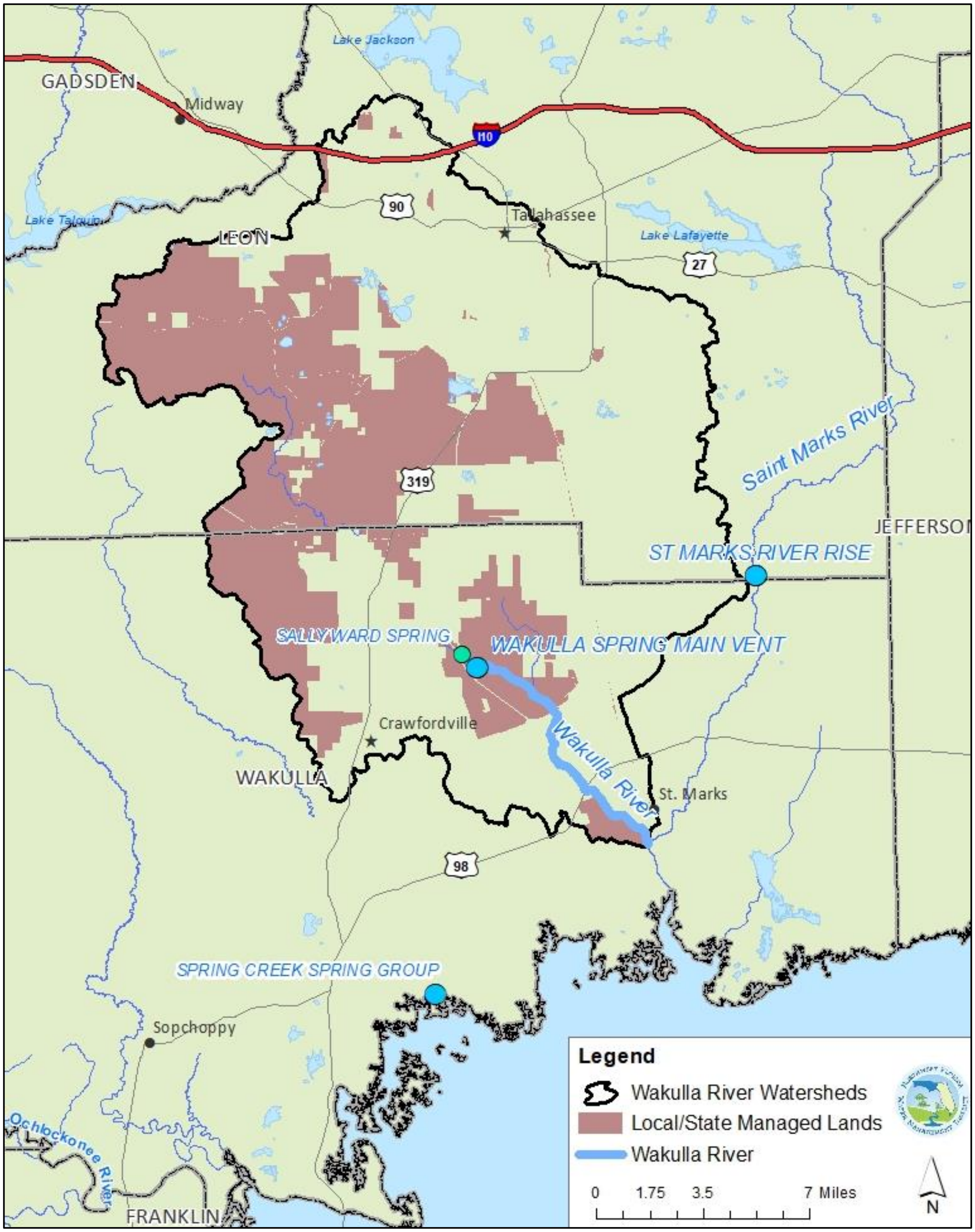

Figure 5: Publicly Owned Lands Near the Wakulla River (Wakulla River Watershed Only)

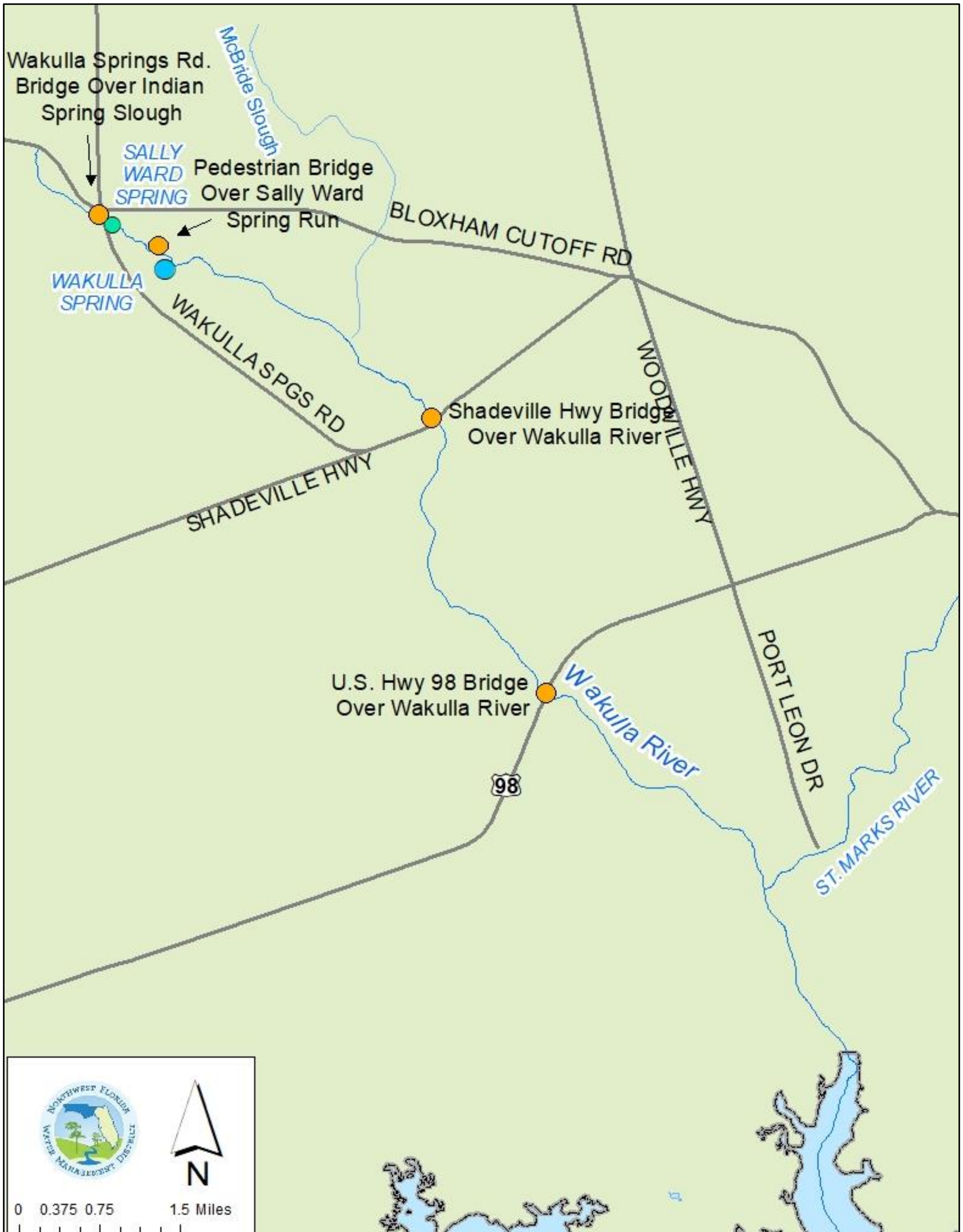

Figure 6: Location of Bridges Crossing the Wakulla River and Sally Ward Spring Run

1.4 Precipitation

Precipitation averaged 61.7 inches annually at the Tallahassee Regional Airport between 1886 and 2020. During this period annual precipitation ranged between 31 inches (1954) and 104 inches (1964) (Figure 7). Precipitation displays bimodal seasonality with highest mean precipitation volumes occurring during the summer months of June, July, and August (6.9 inches, 7.8 inches, and 7.1 inches, respectively), along with a smaller peak during March (5.2 inches) (Figure 8). Monthly mean precipitation minimums were observed during the months of April (3.8 inches), October (2.9 inches, and November (3.0 inches). No long-term trends in monthly precipitation totals were identified at the numerous rain gages located near Wakulla and Sally Ward springs (Appendix A); however, several extended periods of above average and below average rainfall have occurred.

In addition to short-term fluctuations among and within years, the Atlantic Multidecadal Oscillation (AMO) is long-term fluctuation in sea surface temperature that has direct effects on long-term precipitation and temperature patterns in north Florida (NOAA 2020). Northwest Florida tends to receive less rainfall during warm periods and more rainfall during relatively cold periods. Since the mid-1990s the Atlantic has been in a warm period. Annual precipitation totals at the Tallahassee regional airport have shown a reduced number of years with precipitation totals exceeding the long-term average (Table 3). The period of record extending from 1996 through 2020 shows a total of 11 years (44 percent) with precipitation totals exceeding 58.9 inches. The ten-year average annual precipitation totals show that since 2003, precipitation has been below the long-term average in all years except 2018 (80 inches) which produced record precipitation volumes across the southeastern United States. (Figure 9). This indicates that the area has been in a precipitation deficit for an extended period possibly associated with the AMO cycle.

To determine periods of above and below average rainfall, the 12-month standard precipitation index (SPI) was computed for the Tallahassee Regional Airport (Figure 10) using the SPI generator available from the National Drought Mitigation Center (https://drought.unl.edu/droughtmonitoring/SPI/SPIProgram.aspx). The SPI is calculated from the historical precipitation record, where precipitation accumulation over a specified period of time is compared to that same period of time throughout the historical record at that location. Positive SPI values represent wet conditions, the higher the SPI, the wetter the hydrologic conditions. Negative SPI values represent dry conditions; the lower the SPI, the more unusually dry a period is. A 12-month SPI was utilized to evaluate decadal climatic trends. Figure 10 illustrates a period of less precipitation from the early 1900s to the early 1960's coinciding with a warm AMO, followed by a period of higher precipitation to 1995 coinciding with a cool AMO and again a period of lower precipitation from 1995-present coinciding with the recent warm AMO. Based on the 12-month SPI, recent periods of low rainfall or drought include years 2000, 2006-2007, 2011, and 2019.

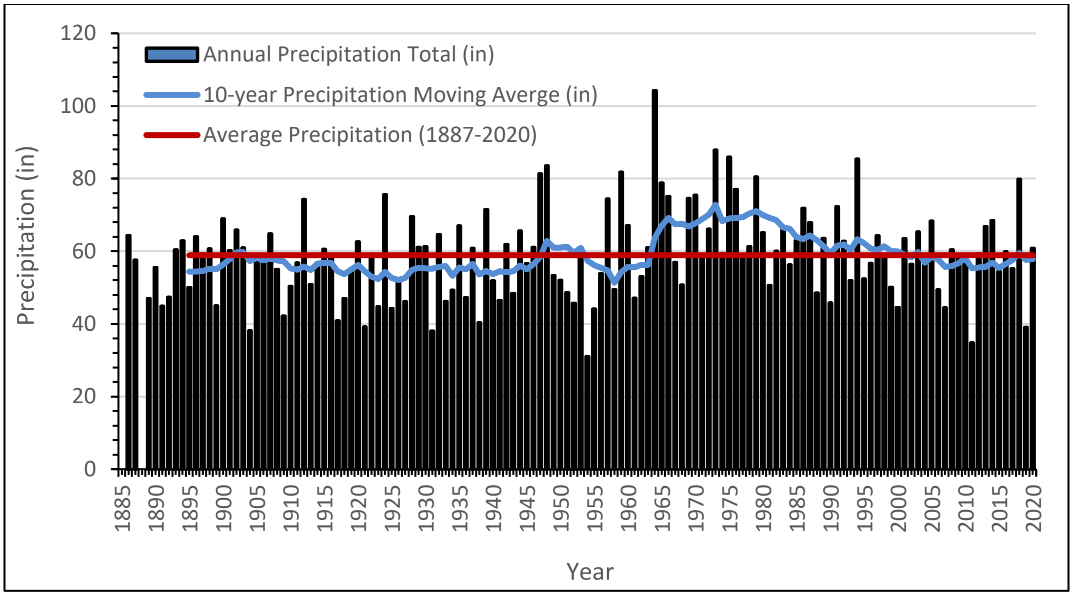

Figure 7: Annual Precipitation Totals at the Tallahassee Regional Airport (1946-2019). Blue line indicates the long term average annual precipitation total of 58.9 inches.

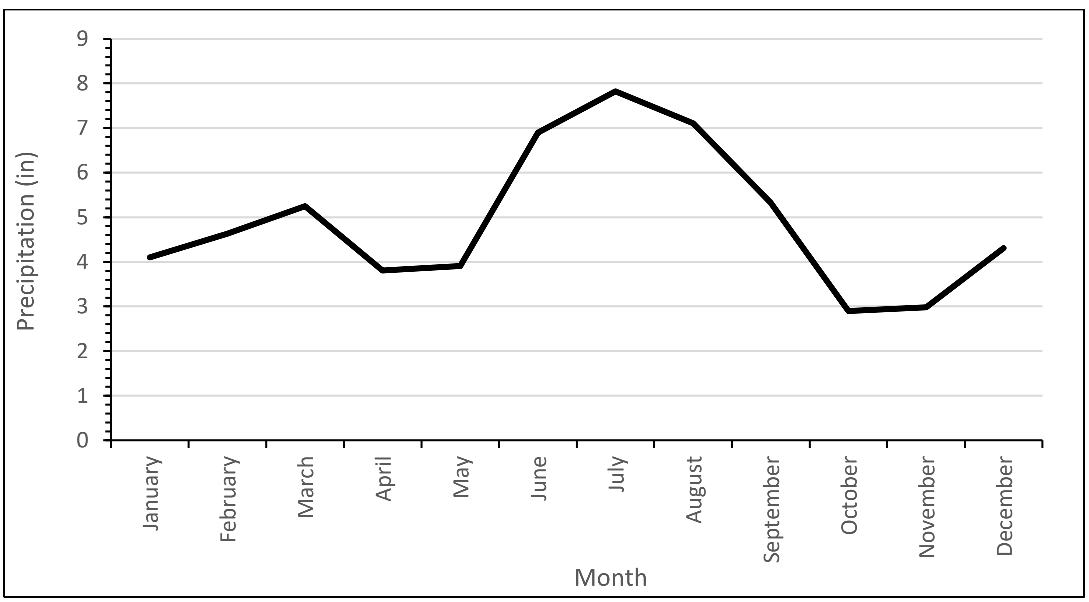

Figure 8: Monthly Precipitation Averages at the Tallahassee Regional Airport (1886-2019)

Table 3: Number of Years with Precipitation Totals Exceeding the Long-Term Average. *Time Period Only includes Five Years.

Period of Record	**Number of Years with Annual Precipitation Total Exceeding the Long-Term Average (58.9 Inches)**
January 1, 1886 – December 31, 1895	3
January 1, 1896 – December 31, 1905	7
January 1, 1906 – December 31, 1915	3
January 1, 1916 – December 31, 1925	3
January 1, 1926 – December 31, 1935	5
January 1, 1936 – December 31, 1945	4
January 1, 1946 – December 31, 1955	4
January 1, 1956 – December 31, 1965	6
January 1, 1966 – December 31, 1975	6
January 1, 1976 – December 31, 1985	8
January 1, 1986 – December 31, 1995	6
January 1, 1996 – December 31, 2005	4
January 1, 2006 – December 31, 2015	4
January 1, 2016 – December 31, 2020	3*

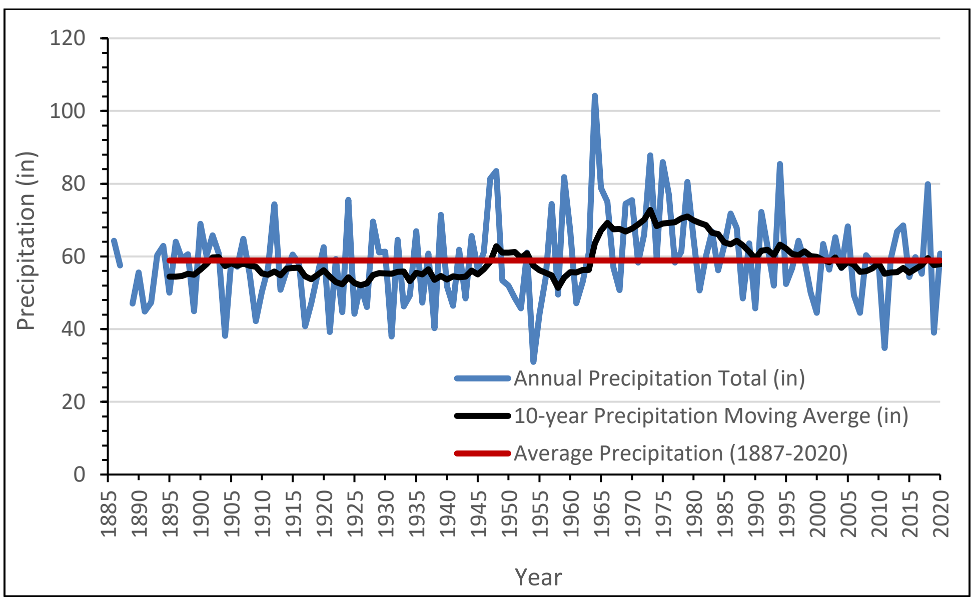

Figure 9: Average Annual Precipitation Totals for the Prior Decade

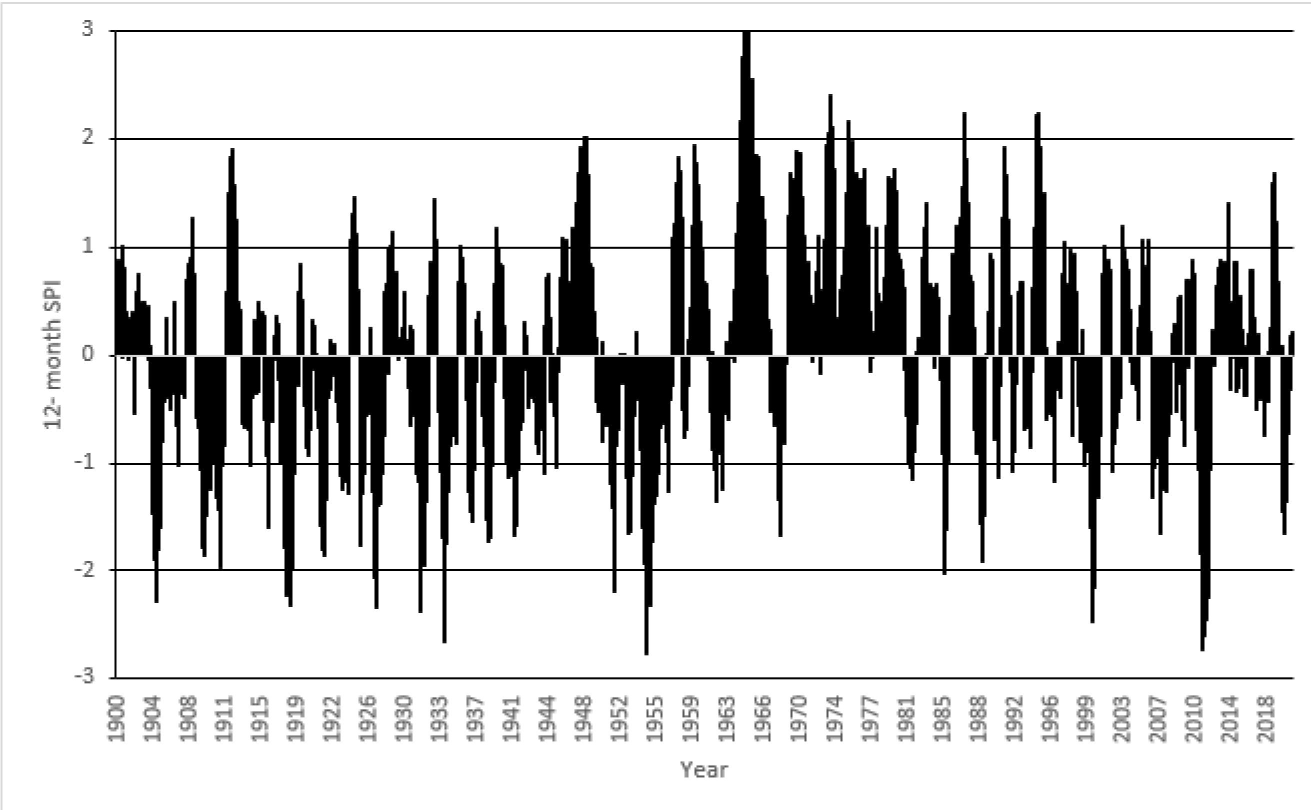

Figure 10: Twelve Month Standard Precipitation Index for the Tallahassee Regional Airport

1.5 Hydrogeology

The Wakulla River is within the Woodville Karst Region, one of the four groundwater regions in the District (Pratt et al. 1996). In this region, meteoric diagenesis of carbonate rocks has resulted in dissolution within the Floridan aquifer and the widespread development of karst features such as sinkholes, swallets, springs, disappearing streams, and an extensive network of karst underground conduits near Wakulla Spring (Figure 11). The region is characterized by a strong hydraulic connection between ground and surface waters, high aquifer recharge, and high groundwater availability (NWFWMD, 2014).

The transmissivity of the Floridan aquifer can vary widely in the study area ranging from approximately 1,300 feet squared per day to approximately 1,300,000 feet squared per day (Davis, 1996). The distribution of Floridan aquifer transmissivity is associated with the thickness of the aquifer and the permeability of sediments overlying the aquifer. Floridan aquifer transmissivity in the study area is also affected by the development of secondary porosity (e.g., voids and conduits) caused by the dissolution of carbonate rocks.

As noted previously, the Cody Scarp is a prominent geomorphic feature that runs east to west through southern Leon and Jefferson counties, which separates the Tallahassee Hills to the north from the Gulf Coastal Lowlands to the south (White, Puri, and Vernon., 1998). The Wakulla River watershed extends north of the Scarp where Plio-Pleistocene and Miocene-aged sediments act as a semi-confining unit for the Floridan aquifer. South of the Cody Scarp the Plio-Pleistocene and Miocene-aged sediments are thin or absent and the Floridan aquifer system is unconfined. Wakulla and Sally Ward springs and the entire Wakulla River are located south of the Cody Scarp. Both the surficial aquifer and intermediate confining unit are absent along the spring run. The Floridan aquifer system is unconfined and the top of rock is generally within 10 to 15 ft of land surface. In order of increasing age, the Floridan aquifer in this area is comprised of the St. Marks Formation, Suwannee Limestone, Ocala Limestone, Avon Park Formation, and Oldsmar Formation (Davis and Katz, 2007). The Floridan aquifer is exposed along portions of the Wakulla River channel, most notably, within the boundaries of Edward Ball Wakulla Springs State Park. Due to the high availability and good quality of groundwater, the Floridan aquifer system is the primary water source for the region.

In northernmost Leon, Jefferson, and Gadsden counties, the Floridan aquifer potentiometric surface is approximately 60 ft above sea level (Figure 12). From there, hydraulic head gradually decline as groundwater flows to the south and discharges to numerous springs and the Gulf of Mexico. South of the Cody Scarp in Wakulla County, the potentiometric surface is relatively flat and aquifer water levels are generally within 10 ft of sea level. Regional discharge features in the Woodville Karst Plain include at least 51 springs (Barrios, 2006), including Wakulla Spring, Sally Ward Spring, the St. Marks River Rise, the Spring Creek Spring Group, the Wakulla and St. Marks rivers, and the Gulf of Mexico.

As a result of regional karst development and the conduit network described above, flow emerging from Wakulla Spring is a varying combination of groundwater from the Floridan aquifer and surface water inputs to the aquifer from karst features such as sinkholes and swallets. Davis and Verdi (2014) proposed a mechanism for describing the varying flows using the connections between Wakulla Spring, the Spring Creek Spring Group, and nearby swallets such as Lost Creek Sink. Three phases were described based upon a changing balance between precipitation events, baseflow, and equivalent freshwater head pressure at the Spring Creek Spring Group submarine vents. Phase 1 occurs when there is an extended period of low precipitation and estuarine/saltwater flows into the Spring Creek Spring Group vents and recharges the Floridan aquifer where freshwater discharge is blocked due to the higher density salt water. Many times during phase 1 saltwater begins flowing into the springs in the Spring Creek Spring Group. During this phase, groundwater which would be discharged at Spring Creek can be diverted towards Wakulla Spring where discharge increases. Phase 2 is characterized by a heavy precipitation event where large volumes of surface water flow into the subsurface creating enough head pressure to overcome the saltwater plug, resulting in freshwater discharge at Spring Creek in addition to increased flow at Wakulla Spring (due to increased surface water inputs). Phase 3 begins once streams return to baseflow conditions and flow at Wakulla Spring declines with the Spring Creek Spring Group continuing to discharge fresh water.

During periods of extended flow reversals (negative discharge) at the Spring Creek Spring Group, water discharging at Wakulla Spring can subsequently display increases in specific conductivity. These increases persist until flows at the Spring Creek Spring Group begin to return to positive discharge. These trends in specific conductivity at Wakulla Spring can be viewed in Section 1.6.

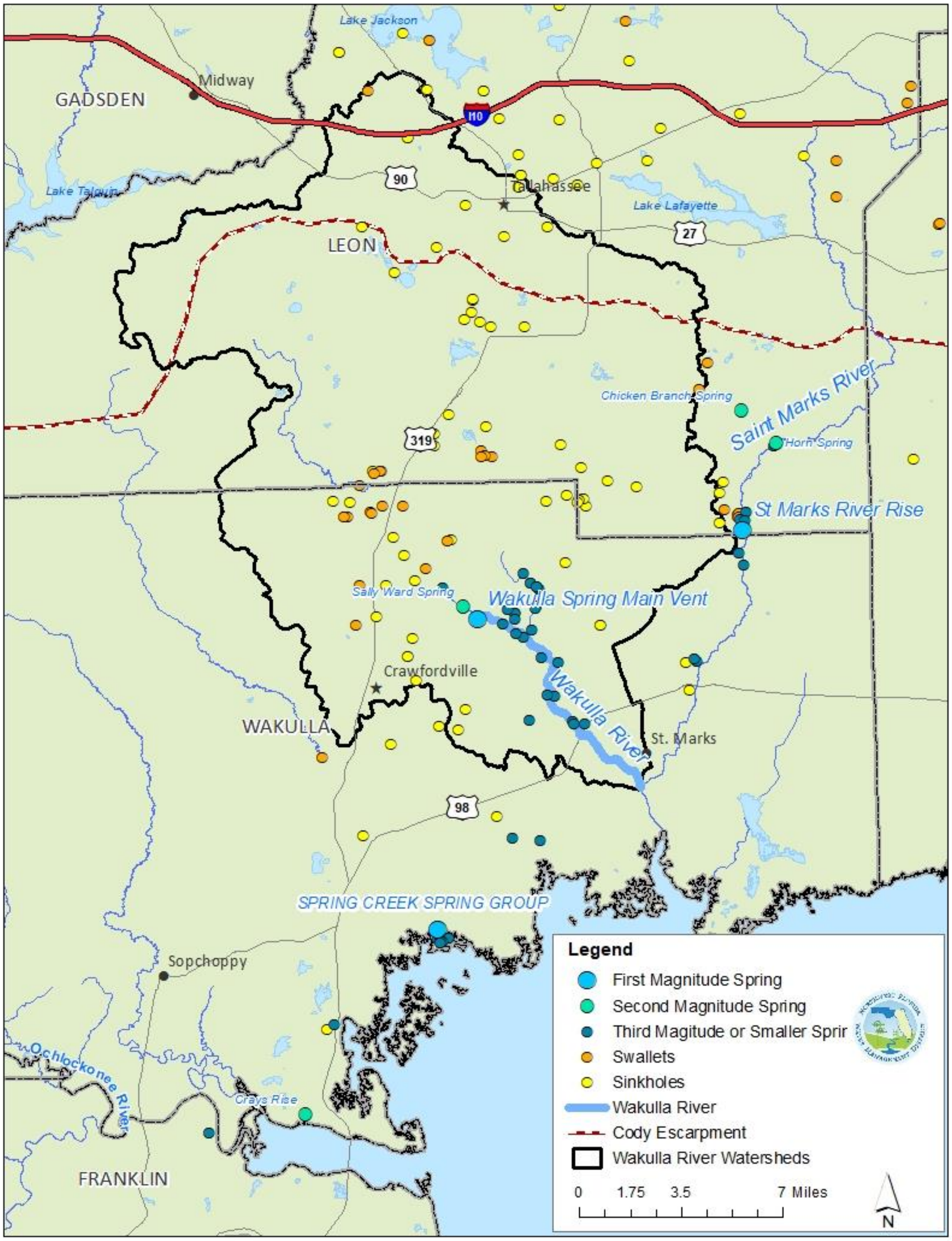

Figure 11: Documented Springs, Sinkholes, and Swallets Within and Near the Wakulla River Watershed

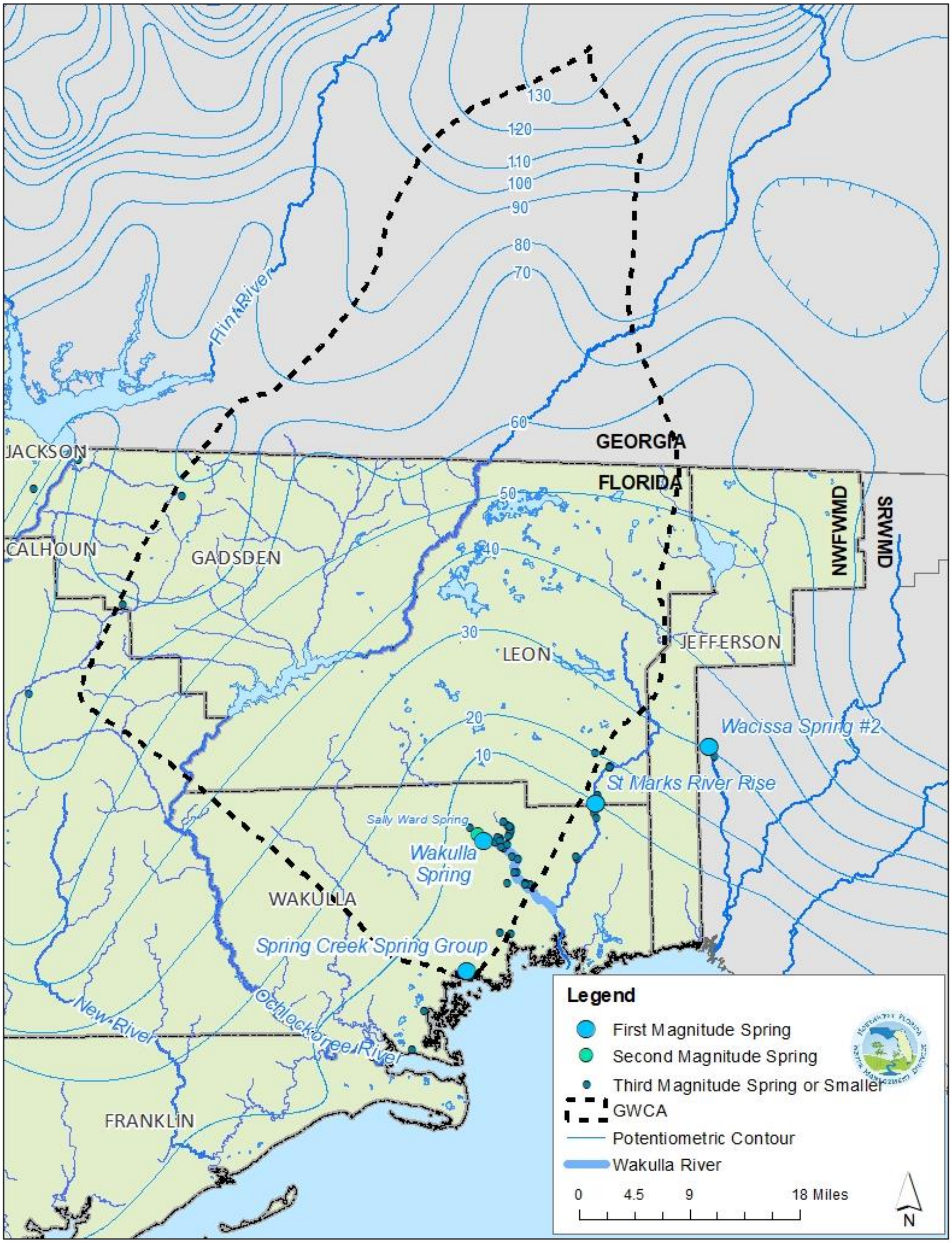

Figure 12: Groundwater Contribution Area and 2010 Potentiometric Contour Map for Wakulla and Sally Ward Springs

1.6 Water Quality

Most of the Wakulla River watershed has relatively good water quality (NWFWMD 2017). Within the Gulf Coastal Lowlands, the St. Marks National Wildlife Refuge, Apalachicola National Forest, and state park lands provide substantial protection to water resource quality. Additionally, the Wakulla River is designated as an Outstanding Florida Water (OFW) (Section 62-302.700, F.A.C.).

The upper Wakulla River was identified by DEP as impaired for nutrients (DEP 2018). In response, a total maximum daily load (TMDL) for nitrate concentration in the upper Wakulla River of 0.35 mg/L was established in 2012. Subsequently, a Basin Management Action Plan (BMAP) was developed to reduce nitrate loading within the groundwater contributing areas to Wakulla Spring in order to achieve the target 0.35 mg/L nitrate concentration over a 20-year horizon (DEP 2018). As described in Section 1.6.2, several projects have been implemented to achieve this goal. An additional water quality concern raised by stakeholders is the clarity of water in Wakulla Spring. Several studies have been conducted to better understand the mechanisms affecting water clarity emerging from Wakulla Spring as described further in sections 1.6.1 and 1.6.5. Wakulla Spring water clarity has historically been quite variable, ranging from the clear blue commonly associated with many Florida springs to darker, more tannic stained. The multitude of sources of water contributing to Wakulla Spring discharge as well as the potential for several water quality constituents to affect water clarity add to the complexity.

1.6.1 Previous Investigations of Wakulla Spring Water Quality

Several studies have been conducted to characterize Wakulla Spring water quality, with a particular focus on analysis of source input for nitrates and drivers of water clarity. The District conducted a groundwater chemical characterization of Wakulla Spring and Jackson Blue Spring basin in 2004-2005 (NWFWMD 2005). The purpose of this study was to identify principal contributing areas within the basin for parameters including nitrates. The DEP subsequently developed a Nitrogen Source Inventory Loading Tool (NSILT) to determine the major sources of nitrogen in the Wakulla Spring groundwater contributing area (DEP 2018). The NSILT is a geographic information system (GIS) and spreadsheet-based tool that provides spatial estimates of contributions from major nitrogen sources. Figure 13 presents the relative nitrate loading by source, based on NSILT estimates. As described further in section 1.6.2, upgrades to the City of Tallahassee's water reclamation facility completed in 2012 led to reductions in nitrate loading and concentrations at Wakulla Spring. The NSILT results shown in Figure 13 represent conditions as of 2018, showing that wastewater treatment plant effluent now represents only a small fraction of total nitrogen loading. Septic systems represent the largest source of nitrogen to Wakulla Spring (34%).

Kulakowski (2010) evaluated relative effects on Wakulla Spring water clarity from five intermittent creeks draining to swallets connected to the Floridan Aquifer in the vicinity of the spring. The study focused on chromophoric (or colored) dissolved organic matter (CDOM), which is a product of decaying organic material, such as vegetation, and represents a subset of the total amount of dissolved organic matter. This study concluded contributions of chromophoric dissolved organic matter (CDOM) from these creeks greatly exceeded CDOM levels during baseflow conditions at Wakulla Spring, and that excess CDOM from these creeks may remain in the aquifer and continue to affect Wakulla Spring during times when the creeks stop flowing. Luzius and others (2018) evaluated the relative contribution of CDOM from several conduits leading directly to Wakulla Spring. This study concluded that CDOM affecting Wakulla Spring water clarity predominantly came from the conduits southwest of the spring driven from surface runoff and associated tannins generated in the Apalachicola Forest. Conduits trending north of the spring vent were relatively clear and had lower CDOM levels.

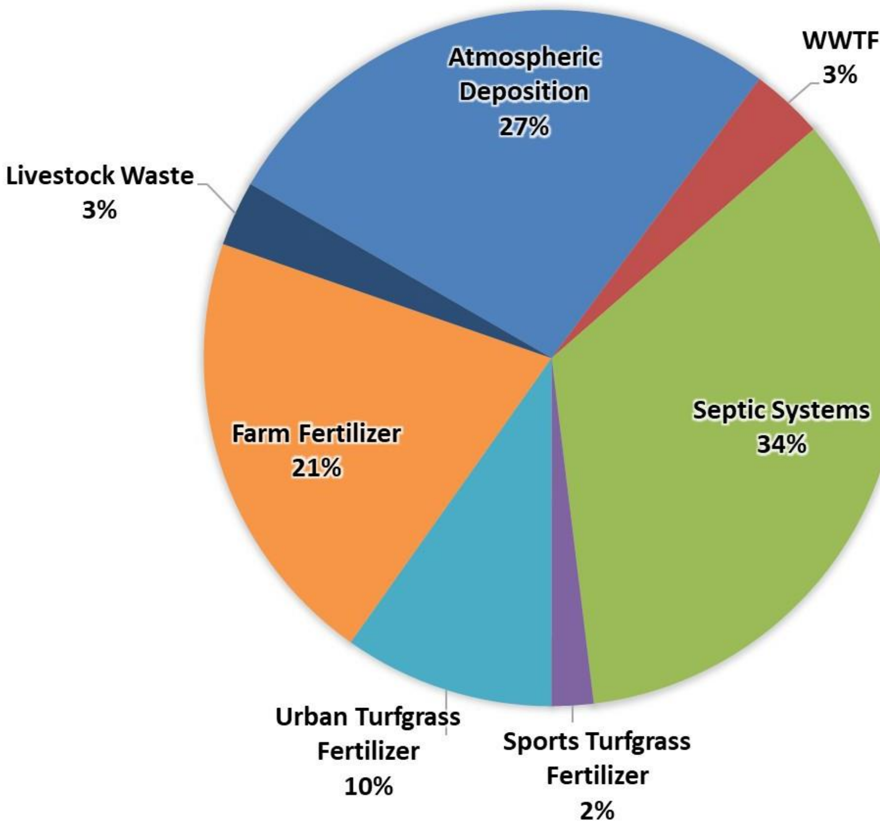

Figure 13: Loading to groundwater by source in the Upper Wakulla River and Wakulla Spring BMAP area (Reprinted from FDEP 2018).

1.6.2 Wakulla River Basin Management Action Plan

The DEP adopted a BMAP for the upper Wakulla River and Wakulla Spring basin in June 2018 with the goal of reducing nitrate levels to 0.35 mg/L (DEP 2018). In 2012, the largest source of nutrient loading to Wakulla Spring, the City of Tallahassee's Thomas P. Smith Water Reclamation Facility (TPS), was upgraded to Advanced Wastewater Treatment (AWT) to reduce nitrate concentrations by approximately 80 percent (NWFWMD 2017).

To further reduce nitrogen loading, Leon and Wakulla counties and the City of Tallahassee, in coordination with the DEP, NWFWMD, and the Florida Department of Health (FDOH), are implementing a coordinated initiative to reduce pollutant loading from onsite sewage treatment and disposal systems (OSTDS) throughout the watershed, with emphasis on the Upper Wakulla River and Wakulla Spring BMAP area. Primary focus areas (PFAs) have been defined within the BMAP area to prioritize projects in areas where there is a known connectivity between groundwater pathways and Wakulla Spring. Multiple projects are currently being funded and implemented to connect existing septic systems to central sewer systems within designated PFAs. To date, 736 existing homes on septic systems have been connected to central sewer and an additional 1,128 homes have been funded to be connected to central sewer but are not yet completed. Where connection to central sewer is not feasible, efforts are being made to deploy advanced passive OSTDS that achieve substantially greater pollutant removal than conventional systems. To date, seven existing homes on septic systems have been replaced with advanced passive OSTDS systems and an additional 208 septic systems have been funded to be replaced with passive OSTDS systems but are not yet completed. Additional efforts to reduce nitrate loading to Wakulla Spring specified in the BMAP include implementation of best management practices (BMPs) pertaining to urban turfgrass, golf courses and other sports facilities, farm fertilizer use, and livestock waste (DEP 2018). Wakulla Spring nitrate levels have been declining since 1997, with several recent measurements below the TMDL of 0.35 mg/L (Figure 14). The mean nitrate concentration in 2020 was 0.36 mg/L. Ongoing and anticipated future spring restoration projects are anticipated to result in further decreases in nitrate levels.

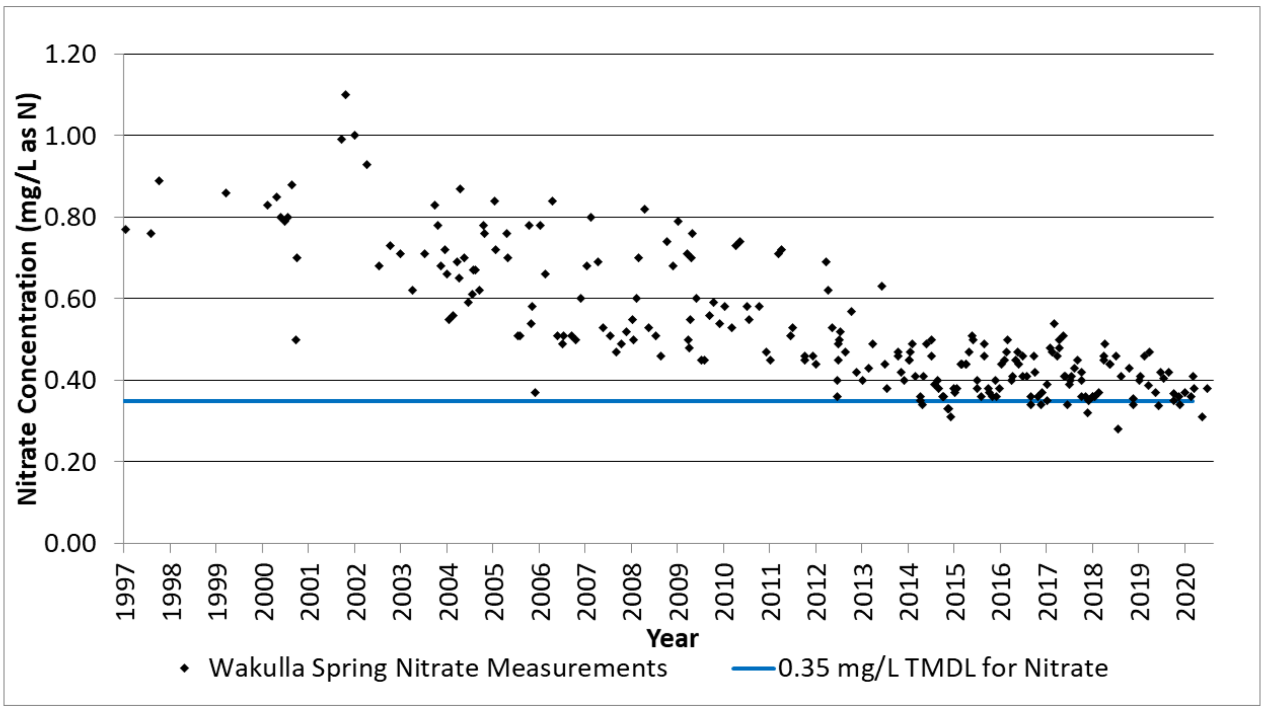

Figure 14: Trends in Wakulla Spring Nitrate Concentration (1997-2020)

1.6.3 Wakulla Spring Water Quality Data Collection

Water quality data has been collected for Wakulla Spring as a collaborative effort by the District, DEP, and USGS over the past several decades. Prior to 1989, periodic lab processed grab samples were collected by the USGS at the boat dock located approximately 100 meters downstream from the vent. The USGS continues to periodically collect grab samples at the boat dock and has recently implemented a real-time data logger at the boat dock. Beginning in 1989, the District in conjunction with DEP began collecting lab processed grab samples for Nitrates (Nitrate + Nitrite, total as N) directly within the spring vent. Data collection frequency has varied but has generally been conducted quarterly. Starting in April 2000, additional parameters, including specific conductance and dissolved oxygen were included from these grab samples. Table 4 summarizes instantaneous water quality measurements collected at Wakulla Spring.

Table 4: Wakulla Spring Water Quality Summary Statistics. * Data collected by the NWFWMD Florida DEP, and USGS. Data is available from NWFWMD= databases, DEP WIN, Storet, and the USGS National Water Information System Web Interface

Parameter	Date Range	Number of records	Minimum	Maximum	Period of Record Avg	Median
Nitrate + Nitrite (Total as N)*	1966-2019	293	0.05 mg/L	1.17 mg/L	0.52 mg/L	0.47 mg/L
Specific Conductivity*	1946-2019	343	218 ųS/cm	894 ųS/cm	318 ųS/cm	310 ųS/cm
Dissolved Oxygen*	1967-2019	350	0.90 mg/L	8.85 mg/L	2.17 mg/L	1.99 mg/L

1.6.4 Trends in Wakulla Spring Nitrate Concentration

Trends in Wakulla Spring nitrate concentration (nitrate + nitrate, total mg/L as N) as a function of time and flow were evaluated to determine if observed long term declines in nitrate concentration are statistically significant. Two statistical tests were conducted to evaluate observed declines in nitrate concentrations. The first test evaluated observed declines in nitrate concentration as a function of time, removing the effect of Wakulla Spring discharge increases. This test was performed to determine if recent spring protection efforts associated with the Wakulla Spring BMAP have contributed toward reduced nitrate concentrations at the spring. The second test evaluated observed declines in nitrate concentration as a function of Wakulla Spring discharge, removing the effect of time. This test was performed to determine if a dilution effect from increased flows contributed toward reduced nitrate concentrations at the spring.

For this analysis, trends were evaluated for the paired dataset of observed nitrate concentration and Wakulla Spring vent discharge from October 25, 2004, to December 16, 2019, to coincide with the baseline time period used for this MFL evaluation (Figure 15). A total of 195 paired observations were available during this time period, with approximately one measurement per month. To avoid redundancy, the median of nitrate measurements taken on the same day was used for days with multiple nitrate measurements. This resulted in 192 unique daily nitrate concentration values for the time period of October 25, 2004, to December 16, 2019.

Methods used to evaluate trends in Wakulla Spring nitrate concentration were based on techniques presented in Helsel and Hirsch (1992). Similar methods were utilized for evaluation of Rainbow River nitrate concentration trends (SWFWMD, 2017b). Two tests were conducted to evaluate observed declines in nitrate concentrations. The first test evaluated observed declines in nitrate concentration versus time from October 2004 to December 2019. Although visual observation of Figure 15 suggests a declining nitrate concentration trend, the potential dilution effect of declining nitrate concentrations with increased flows should be accounted for to better discern actual trends in nitrate concentration with time.

To remove the effect of flow, a LOWESS (locally weighted scatterplot smooth) was fit using nitrate concentration as the response variable and flow as the exogenous variable. Flow adjusted residuals were then computed as the difference between observed nitrate concentration and nitrate concentration estimated from this LOWESS-fitted relationship. Figure 15 shows flow-adjusted residuals versus time. This chart depicts changes in nitrate concentration with time, with effects of flow being removed. Examination of Figure 16 shows an apparent nonlinear trend in flow-adjusted nitrate concentration residuals versus time, with increasing values from 2004 to 2010 followed by declining values from 2010 to 2019. A LOWESS was fit to data shown in this plot to better depict this trend. Recent declines in nitrate concentration are due in part to the ongoing efforts to reduce nitrate loading to the spring, with noticeable reductions in both nitrate concentration at the Wakulla Spring vent and flow adjusted nitrate concentration residuals over the past decade. Ongoing and anticipated future spring restoration projects are anticipated to result in further decreases in nitrate levels. Since the apparent trend was not monotonic, statistical trend testing using the Mann Kendall trend test was not performed.

Since both Wakulla Spring flow and nitrate concentration are changing with time, trends in nitrate concentration as a function of flow treating time as an exogenous variable was also evaluated. This method is analogous to that for evaluating temporal changes in nitrate concentration described above. Time adjusted residuals were computed as the difference between observed nitrate concentration and nitrate concentration estimated from the LOWESS fitted relationship of nitrate concentration versus time. Figure 15 shows time-adjusted nitrate concentration residuals plotted versus flow. This chart depicts changes in nitrate concentration versus flow, with effects of time being removed. Examination of Figure 15 shows an apparent pattern of declining time-adjusted nitrate concentration residuals versus flow. This suggests the presence of a dilution effect, although a high degree of variability exists. The potential for withdrawals to cause significant harm to nitrate concentrations by reducing spring flows, based on potential dilution effects, is evaluated in Section 5.3.

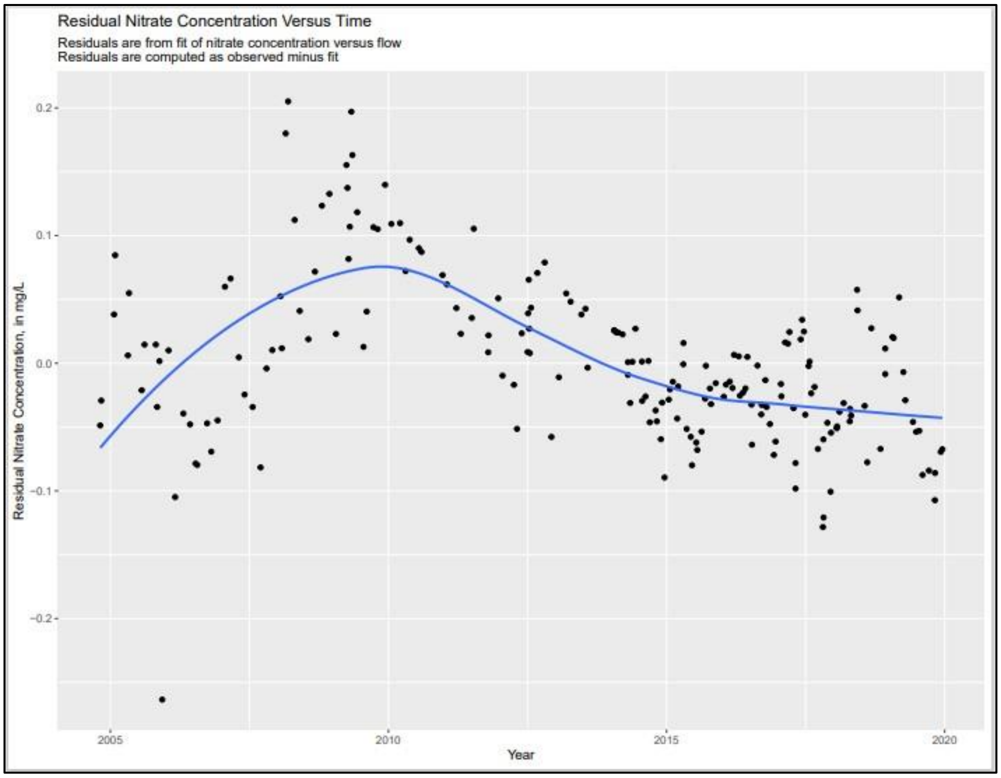

Figure 15: Flow Adjusted Nitrate Residuals versus Time

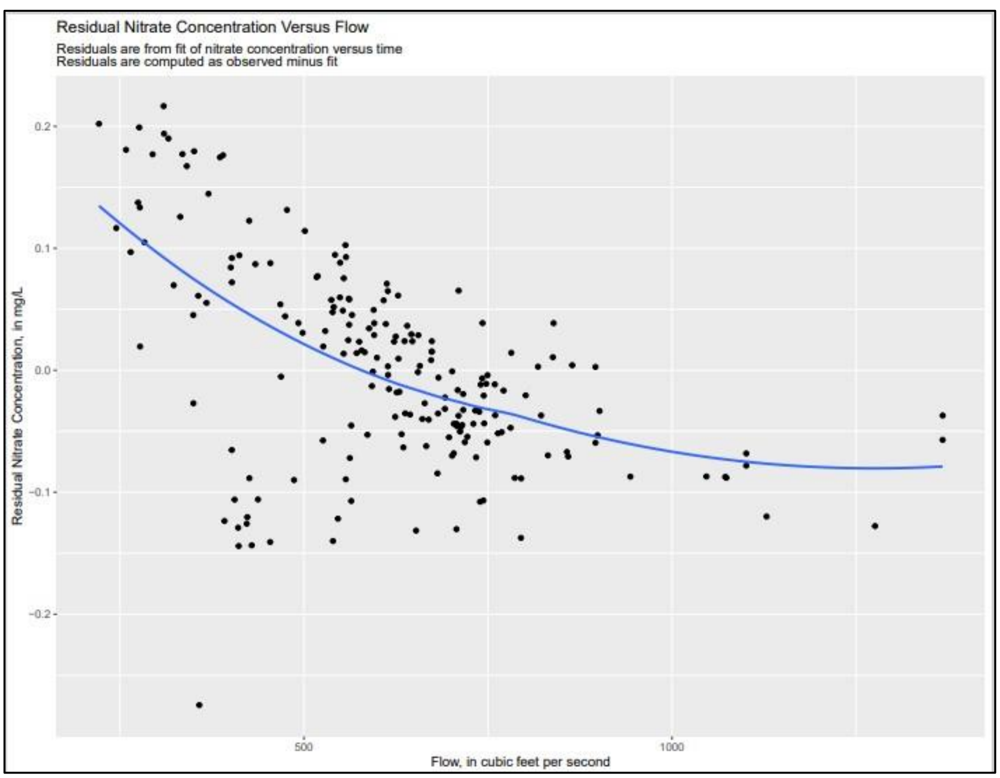

Figure 16: Time Adjusted Nitrate Residuals versus Flow

1.6.5 Wakulla Spring Water Clarity

Water clarity at Wakulla Spring has been a concern for nearly a century and fluctuations in Wakulla Spring water clarity have been reported back throughout the recorded history of the spring. In 1945 and 1946, letters were sent to Edward Ball mentioning dark water during the summer of 1945 (WSA 2021). A similar letter was sent to Edward Ball in 1962 describing dark water at the spring and in 1965 filming for the movie, "Around the World Under the Sea" was delayed due to dark water. Prior to 1957, water clarity was reported to be good for most of the year, however since 1957 the clarity at Wakulla Springs has been more susceptible to seasonal fluctuations (DEP 2007). On April 16, 1992, the Wakulla Springs Water Quality Working Group met for a second time to discuss declines in water clarity and glass bottom boat days.

The factors influencing clarity of water emerging from Wakulla Spring are complex and are an area of ongoing investigation. Wakulla Spring water clarity is quite variable, ranging from the clear blue commonly associated with many springs to darker, more tannic stained. In addition, there may be periods where tannins in water flowing from the spring vent are relatively low. As previously discussed, groundwater emerging from Wakulla Spring reflects multiple inflows that mix within the Floridan aquifer system. Inflow to the Floridan aquifer include (1) recharge by rainfall via infiltration through soils and sediments, (2) additional recharge at the City of Tallahassee sprayfield, (3) inflow from sinking streams which can contain high levels of tannins and may be connected to Wakulla Spring by underground conduits, (4) inflow from other karst features such as sinkholes, karst windows, and sinkhole lakes, and (5) other unknown inputs. During periods of increased precipitation, surface water can enter the aquifer from the numerous swallets and sinkholes where it mixes with the existing groundwater. These waters from the vicinity of Black Creek and Fisher Creek watersheds within the Apalachicola National Forest may flow towards Wakulla Spring, potentially reducing water clarity discharging at Wakulla Spring.

Although a considerable amount of variability is present, reduced water clarity is typically associated with increased spring vent discharge and improved visibility is generally associated with lower flows. The District collected turbidity, fDOM, and chlorophyll data at the Wakulla Spring Boat Dock located approximately 100 meters downstream from the spring vent between 2015 and 2017. Parameters such as these are known to reduce water clarity with increasing concentration (Biber et al. 2015). All parameters displayed increasing values with increasing spring flows (Figure 17, 18, and 19), largely as a result of periodic high measurements taken during high flows. It should be noted that parameters often associated with reduced water clarity (turbidity, fDOM, and chlorophyll) display considerable variability during high flows. While more tannic water is often observed during periods of high flows, there are also periods of relatively clear water during periods of moderate flows.

Despite the fact that improved visibility is associated with lower spring flows, concern has been raised by stakeholders, that perceived increases in the number of days tannin or chlorophyl-A laden water is emitted from Wakulla Spring during the past two decades may be related to groundwater withdrawals. However, analyses of available data indicate that reported changes in water clarity are unrelated to withdrawals. Estimates of groundwater extraction by the City of Tallahassee have remained relatively constant since 1995 while, in contrast, water clarity has been reported to have significantly declined over this same time period. Aquifer levels near Wakulla Spring also have remained relatively stable, with some variability in response to precipitation (Appendix A). Although changing water clarity may be of concern, it is outside the scope of this MFL evaluation as available data indicates that is unrelated to groundwater withdrawals. Additional discussion of Floridan Aquifer levels and groundwater extraction through time are provided in Section 2.

During the time since 1995, when water clarity is reported to have been reduced, the spring pool stage has declined and spring discharge has increased significantly (Section 2.6). Available data indicates that the observed changes in spring pool stage are due to changes in Wakulla River hydraulics such as the scouring of sediments as described in Section 2.6. As part of the District's adaptive management approach to MFLs, additional data concerning local water levels, Wakulla River water levels, and water clarity will be examined as it becomes available.

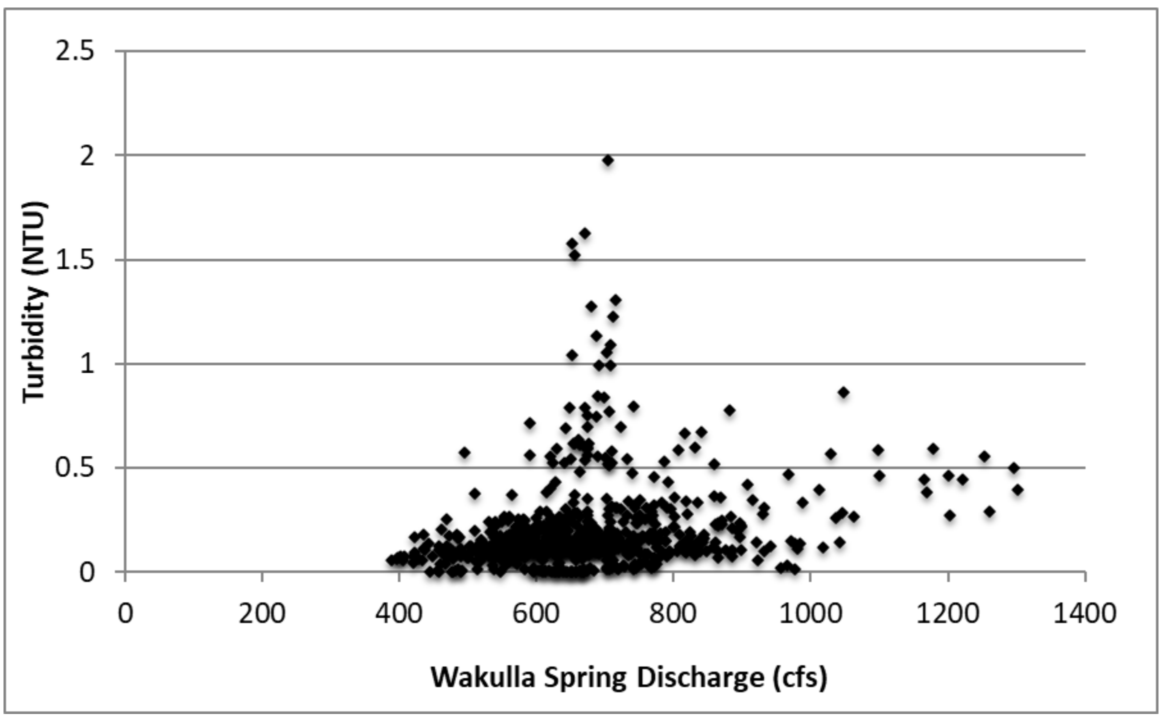

Figure 17: Turbidity Versus Wakulla Spring Discharge (2015 – 2017)

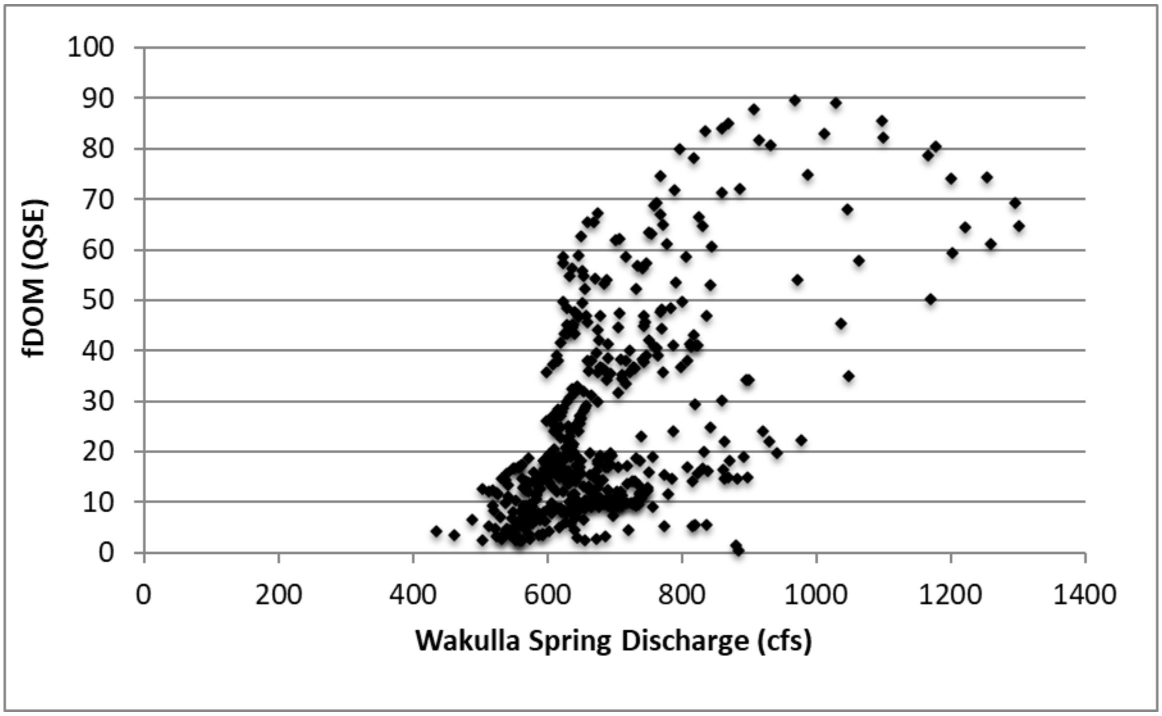

Figure 18: Fluorescent Dissolved Organic Matter Versus Wakulla Spring Discharge (2015 – 2017)

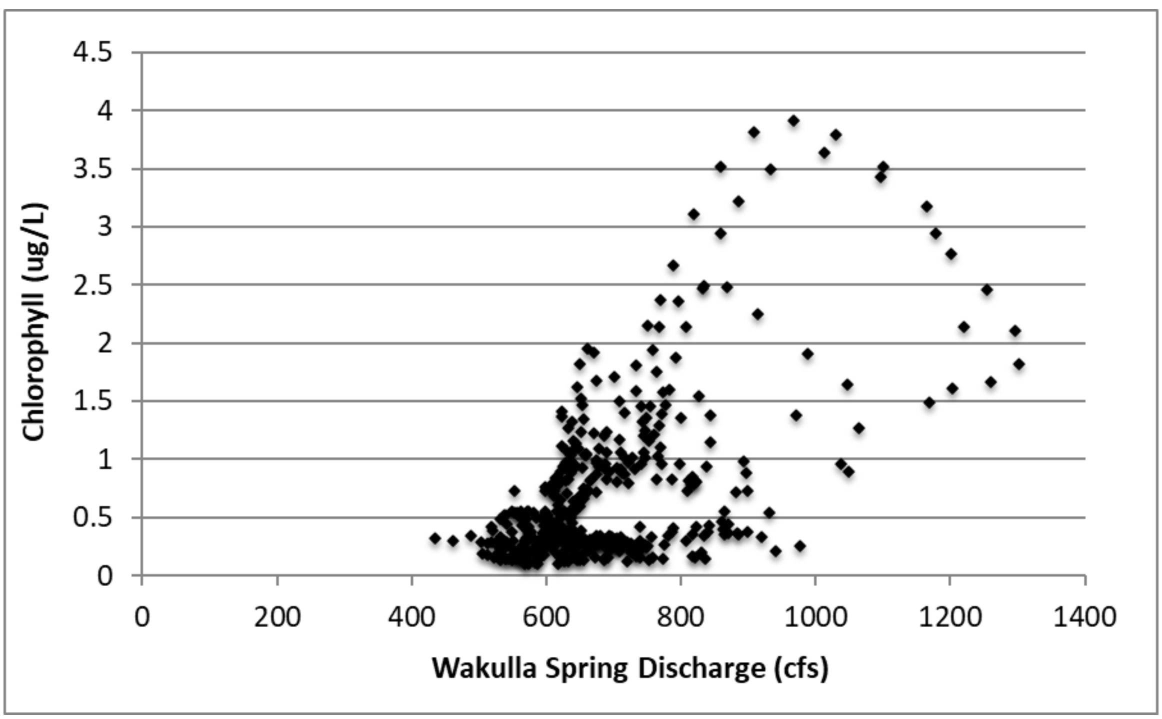

Figure 19: Chlorophyll Versus Wakulla Spring Discharge

1.6.6 Dissolved Oxygen and Specific Conductance

Effects of spring flow reductions on salinity (specific conductance) in the downstream portions of the Wakulla River where estuarine conditions are present will be assessed directly by the Estuarine Resources WRV through the use of an EFDC hydrodynamic model. The potential effects of reduced spring flows on low salinity habitats are addressed under the Estuarine Resources WRV. Details on salinity in the estuarine portion of the Wakulla River and WRV metrics can be found in Section 3.3.

Water quality was also assessed at the Wakulla Spring pool. Temporal trends were evaluated for dissolved oxygen and specific conductance measured at Wakulla Spring. Trends were assessed using a two-sided Mann-Kendall test with a significance level (α) of 0.05. Flow adjustments were not needed for specific conductance or dissolved oxygen as these parameters did not display a relationship with flow (Figure 20 and Figure 21). Trends were evaluated from October 23, 2004, to December 31, 2019, consistent with the Wakulla Spring discharge baseline time period. Trend tests were based on annual median values to reduce the effect of serial correlation.

Both dissolved oxygen and specific conductivity displayed no statistically significant trend from October 23, 2004, to December 31, 2019 (Figure 22 and Figure 23). Despite displaying no long-term trend, Wakulla Spring displays periodic increases in specific conductivity. Short-term increases in specific conductivity associated with flow reversals from the Spring Creek Spring Group have been documented during the last 15 years (Figure 21, Figure 22, Section 2.1.6). When flow reverses at the Spring Creek Spring Group, saltwater begins flowing into the Floridan aquifer. After a period of time of variable length (typically ranging between one and two months) and following a flow reversal event, specific conductivity at Wakulla Spring can begin to increase when saltwater flows north and reaches the spring.

Short-term increases in specific conductivity have reached nearly 900 µS/cm (<0.5 ppt salinity). However, these values are below the threshold used for freshwater habitats in the Estuarine Resources metric evaluation (<0.5 ppt) and are all considered to be “fresh” water in this MFL analysis. Numerous researchers have documented that many submerged and emergent floral and faunal species common to freshwater systems may not be capable of surviving extended periods of increased salinity. As a result, if increases in specific conductivity at Wakulla Spring associated with Spring Creek Springs Group reversals persist or occur at increased periodicity in the future, changes in ecological communities along the Wakulla River could occur.

As explained elsewhere in this report, reversals at Spring Creek Spring Group typically occur following low rainfall periods. The submarine vents comprising the Spring Creek Spring Group fill with saltwater as freshwater discharge from the Floridan aquifer diminishes. When the vents fill with saltwater, the equivalent freshwater head at the coast increases due to the dense saltwater. Spring flow reversals occur when the equivalent freshwater head at the coast (Spring Creek Spring Group) exceeds the head farther inland. Sea level rise is affecting this gradient by increasing the equivalent freshwater head at the coast. Changes in the spring pool stage resulting from changes in the Wakulla River hydraulics can also affect the head gradient and thus affect flow reversals. While this is an area of ongoing interest and evaluation, changes in the Wakulla Spring water quality potentially due to sea level rise are outside the scope of this MFL evaluation.

Although an MFL is not a suitable tool for mitigating effects of salinity spikes occurring as a result of sea level rise, during future MFL evaluations, trends in the salinity of water flowing from the Wakulla Spring vent, coastal sea levels, and Floridan aquifer levels near Wakulla Spring will be reviewed, in addition to any new information which becomes available.

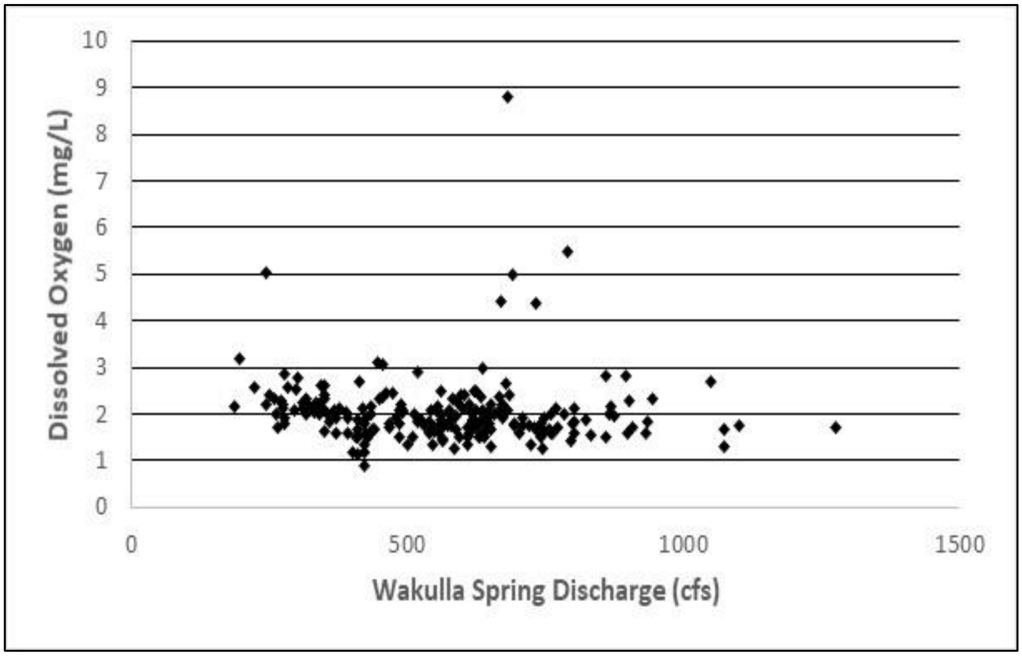

Figure 20: Dissolved Oxygen versus Wakulla Spring Discharge

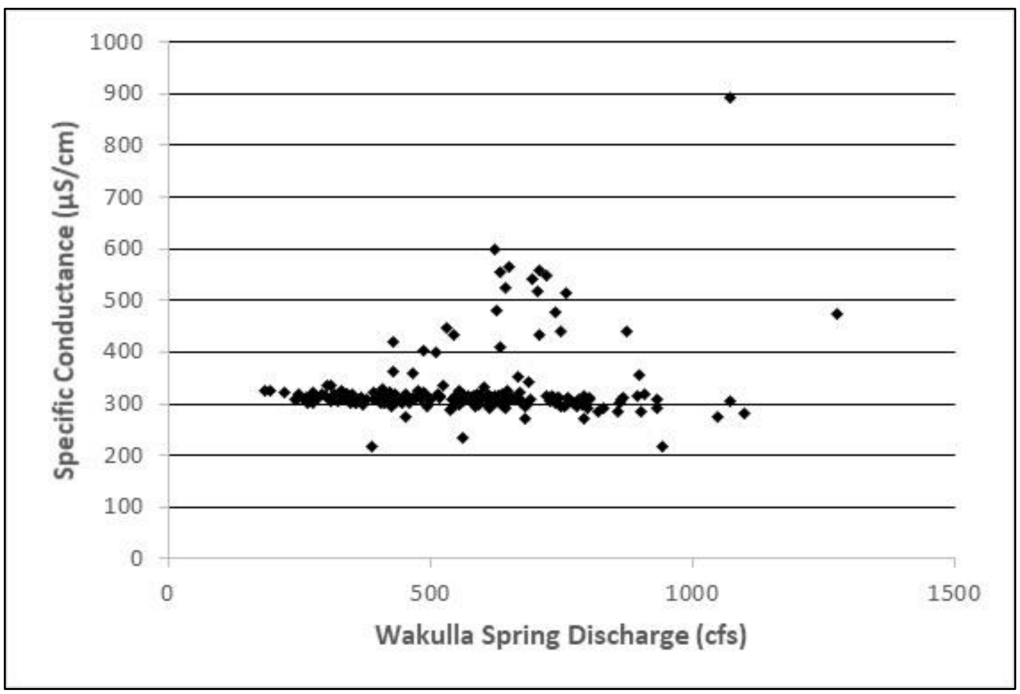

Figure 21: Specific Conductance versus Wakulla Spring Discharge

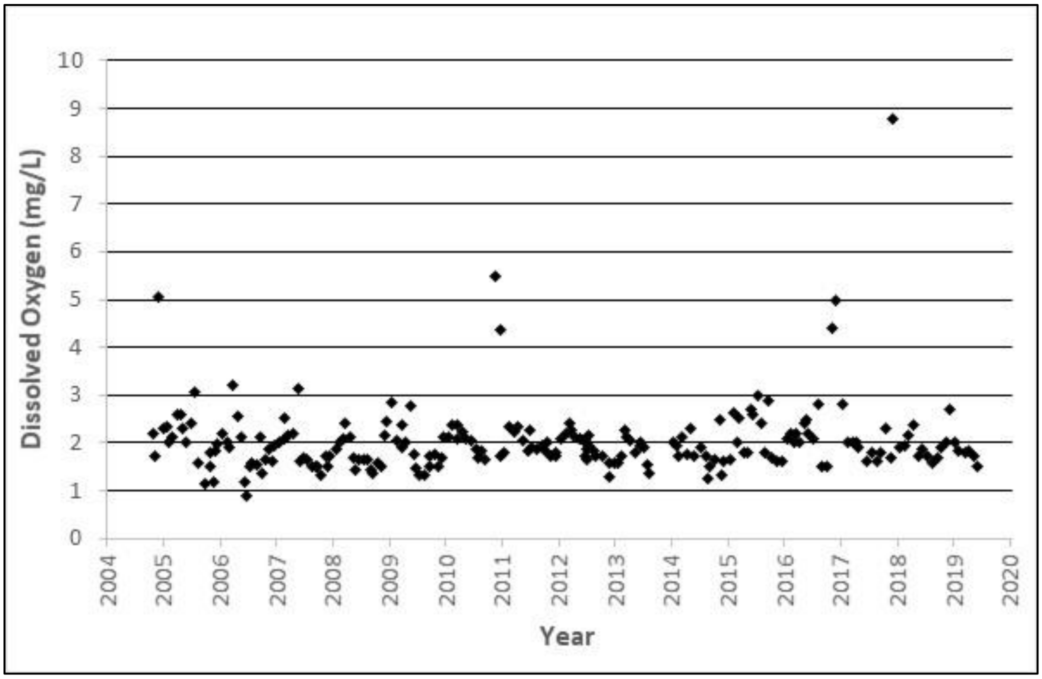

Figure 22: Dissolved Oxygen at Wakulla Spring Between 2004 and 2020

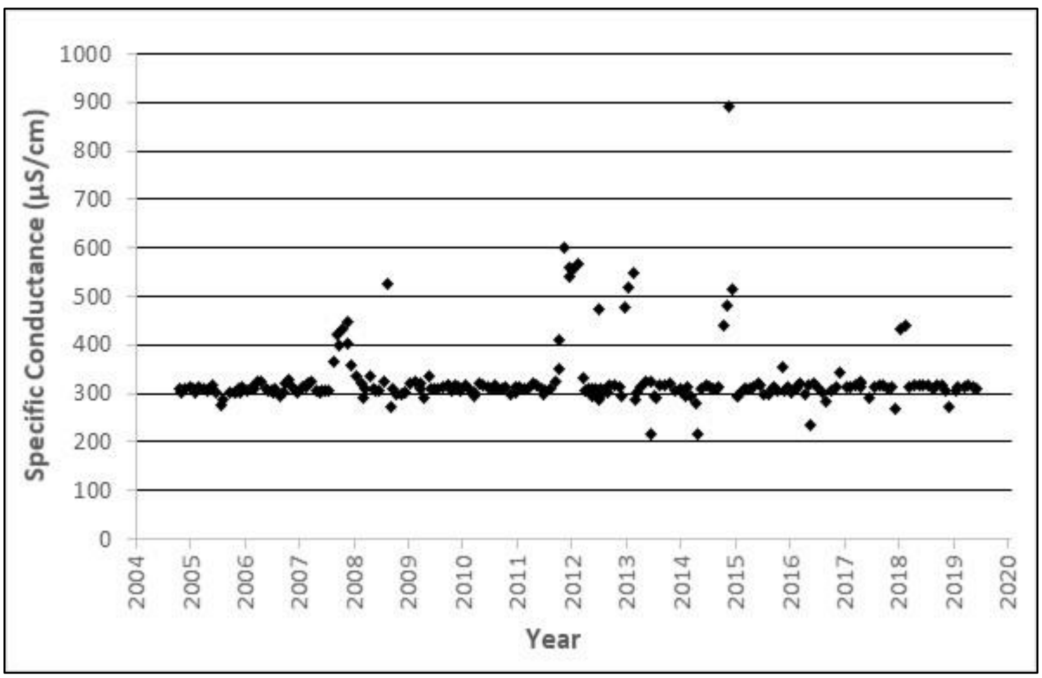

Figure 23: Specific Conductance at Wakulla Spring Between 2004 and 2020

1.7 Biology

The Wakulla River and its associated floodplain are home to a diverse assemblage of wildlife habitats. Additionally, there is relatively little development and much of the river and floodplain are located on state-owned lands. The biological characteristics of the Wakulla River and floodplain are described below. Data concerning the presence of species in the study area was obtained from multiple sources including wildlife surveys from the Edward Ball Wakulla Springs State Park, Florida Natural Areas Inventory (FNAI) Biodiversity Matrix, reports and peer reviewed documents, and observations by District staff.

1.7.1 Vegetation

The Florida Fish and Wildlife Conservation Commission's Cooperative Land Cover Project (2016) describes the majority of the Wakulla River riparian communities as floodplain swamps. Forested floodplain communities are present along the Wakulla River from the most upstream locations at Wakulla and Sally Ward springs to near the confluence with the St. Marks River. At the confluence, forested swamp communities are replaced by floodplain marsh and salt marsh communities. Data collected along floodplain transects and discriminant function analysis were used to categorize community types based on dominant tree species (NWFWMD 2016). Although sample sizes were small for some communities, the analysis provides an overview of the mixtures of tree species present. Research Planning Inc. (NWFWMD 2016) identified a total of five floodplain vegetation communities along the eight transects sampled along the Wakulla River (Table 5).

Tupelo cypress hardwood mix communities were the most widely distributed community and were found along seven of the eight vegetation transects. Tupelo cypress hardwood mix communities were dominated by swamp tupelo (*Nyssa sylvatica* var. *biflora*) with bald cypress (*Taxodium distichum*) and pumpkin ash (*Fraxinus profunda*) being subdominant species. This wetland community is described as seasonally inundated.

Tupelo cypress swamp communities are semi-permanently flooded wetlands observed along two transects along the Wakulla River. Swamp tupelo was the dominant species in this community with bald cypress being subdominant and red maple (*Acer rubrum*), dahoon holly (*Ilex cassine*) and sugar maple (*Acer saccharum*) comprising the less abundant species. Tupelo hardwood swamp communities are semi-permanently flooded wetlands dominated by swamp tupelo with pumpkin ash (*Fraxinus profunda*) being subdominant and lesser amounts of swamp bay (*Persea palustris*) and sugar maple.

Bay hardwood hammock communities are seasonally inundated wetlands dominated by swamp bay and pumpkin ash, with lesser amounts of button bush (*Cephalanthus occidentalis*) and swamp tupelo. Hardwood hammock communities are seasonally inundated wetlands no species being dominant. Swamp bay, ironwood (*Ostrya virginiana*), water oak (*Quercus nigra*), wax myrtle (*Morella cerifera*), cabbage palm (*Sabal palmetto*), American elm (*Ulmus americana*), and swamp tupelo are the most abundant species counted in hardwood hammock communities. Additional details of floodplain community species composition can be found in RPI 2016.

The Sally Ward Spring Run is dominated by swamp communities. Abundant tree species present in the spring run includes bald cypress, red maple, swamp tupelo, and other wetland species.

Near the City of St. Marks, forested floodplain communities along the Wakulla River are replaced by estuarine herbaceous communities (saltmarsh and floodplain marsh) (RPI 2016). Sawgrass (*Cladium jamaicense*) marsh is abundant along the shoreline in this area with hardwood forests (oaks, cedar, cabbage palm, and swamp bay) present at higher elevations further away from the river (NWFWMD 2016). Sawgrass marshes are interspersed with black needle rush (*Juncus roemerianus*). Below the confluence with the St. Marks River, the lower St. Marks River becomes increasingly more saline, with saltmarsh cordgrass (*Spartina alterniflora*) and black needle rush becoming increasingly dominant in shoreline communities.

Submerged aquatic vegetation is present in varying densities along the Wakulla River. Tapegrass/American eelgrass (*Vallisneria americana*) is one of the most abundant submerged aquatic vegetative species. This species is present along much of the Wakulla River from the spring vent to near the confluence with the St. Marks River. Hydrilla (*Hydrilla verticillata*) and filamentous algal mats were once extremely abundant near the spring pool but have been reduced in cover during the past several decades. These species can replace tapegrass as the dominant species where abundant. Additional submerged aquatic species and littoral herbaceous species observed along the Wakulla River include bulltongue arrowhead (Sag*ittaria lancifolia*), pickerelweed (*Pontederia cordata*), cattail (*Typha* sp.), red ludwigia (*Ludwigia repens*), swamp rose (*Rosa palustris*), maidencane (*Panicum hemitomon*), bulrush (*Scirpus* sp.), climbing hempvine (*Mikania scandens*), blueflag iris (*Iris hexagona*), smartweed (*Polygonum* sp.), and alligator lily (*Hymenocallis palmeri*).

Also present in many areas along the river are small islands and isolated trees consisting primarily of bald cypress with swamp rose, climbing hempvine, and other species common on the associated hummocks. These areas are present mostly in the upper half of the river. Approximately 2.2 miles downstream of Wakulla Spring, the river becomes braided and consists of multiple narrow shallow channels for a 0.7-mile stretch. After this area, the river channel widens and becomes deeper for the remainder of the river.

The presence of nuisance/exotic vegetation was once extremely common in the spring runs of Wakulla and Sally Ward springs. In the early 2000's, the Sally Ward spring run and much of the area upper and middle reaches of the Wakulla Spring became covered by dense mats of hydrilla (*Hydrilla verticillata*) and algal mats (DEP 2012). Concerted efforts of hydrilla removal using herbicide began in 2002 and were conducted regularly in subsequent years. Since its peak, the coverage of hydrilla and algal mats has declined in both spring runs presumably as a result of herbicide treatments and declining trends in nitrate in the spring water.

Four vegetation species listed by the State of Florida have been documented in the lands surrounding Wakulla Spring, Sally Ward Spring and Run, and Wakulla River (Table 6). Godfrey's spiderlily (*Hymenocallis godfreyi*), Little club-spur orchid (*Platanthera clavellata*), Florida willow (*Salix floridana*), and beaked spikerush (*Eleocharis rostellata*) have all been documented. Specimens of Godfrey's spiderlily were documented in estuarine habitats near the confluence of the St. Marks and Wakulla rivers in communities consisting of a mix of sawgrass and black needlerush (University of South Florida Herbarium 2018). Little club-spur orchids are found in wet hammocks and stream banks of the southeastern United States (DEP 1998, Wunderlin and Hansen 2003). Florida willow inhabits swamps and banks of calcareous spring-fed streams and rivers (Tobe et al. 1998, Wunderlin and Hansen 2003, University of South Florida Herbarium 2018). Beaked spikerush occurs in marshes, wet prairies, and swamps (Wunderlin and Hansen 2003). Listed plant species potentially occurring in the study area are not discussed but included in Table 6.

Table 5: List of Vegetation Communities and Dominant Tree Species Documented During Floodplain Vegetation Monitoring on the Wakulla River, Florida (RPI 2016). *Indicates dominant species. **Indicates subdominant species.

Vegetation Community	**Dominant Species**	**FEDP Status (FAC 62-340.450)**
Bay Hardwood Hammock	Swamp bay (*Persea palustris*)** Pumpkin ash (*Fraxinus profunda*)** Buttonbush (*Cephalanthus occidentalis*)	Obligate Obligate Obligate
Hardwood Hammock	Swamp bay (*Persea palustris*)** Ironwood (*Carpinus caroliniana*)** Water oak (*Quercus nigra*)** Wax myrtle (*Morella cerifera* or *Myrica cerifera*)** Cabbage palm (*Sabal palmetto*)** American elm (*Ulmus americana*)** Swamp tupelo (*Nyssa sylvatica* var. *biflora*)**	Obligate Facultative Wet Facultative Wet Facultative Facultative Facultative Wet Obligate
Tupelo Cypress Hardwood Mix	Swamp tupelo (*Nyssa sylvatica* var. *biflora*)* Bald cypress (*Taxodium distichum*)** Pumpkin ash (*Fraxinus profunda*)**	Obligate Obligate Obligate
Tupelo Cypress Swamp	Swamp tupelo (*Nyssa sylvatica* var. *biflora*)* Bald cypress (*Taxodium distichum*)** Red maple (*Acer rubrum*) Dahoon holly (*Ilex cassine*) Sugar maple (*Acer saccharum*)	Obligate Obligate Facultative Wet Obligate Obligate
Tupelo Hardwood Swamp	Swamp tupelo (*Nyssa sylvatica* var. *biflora*)* Pumpkin ash (*Fraxinus profunda*)** Swamp bay (*Persea palustris*) Sugar maple (*Acer saccharum*)	Obligate Obligate Obligate Obligate

Table 6: Listed Vegetation Species Described by the Florida Natural Areas Inventory as Documented or Potentially Occurring within the Lands Surrounding the Wakulla River, Wakulla Spring, and Sally Ward Spring Run. SE=State Endangered, ST=State Threatened, and NL=Not Listed by the State of Florida.

Occurrence	***Scientific Name***	**Common Name**	**Status**
Documented	*Hymenocallis godfreyi*	Godfrey's spiderlily	SE
Documented	*Platanthera clavellata*	Little club-spur orchid	SE
Documented	*Salix floridana*	Florida willow	SE
Documented-Historic	*Eleocharis rostellata*	Beaked spikerush	SE
Potential	*Agromonia incisa*	Incised grove-bur	ST
Potential	*Andropogon arctatus*	Pine-woods bluestem	ST
Potential	*Asclepias viridula*	Southern milkweed	ST
Potential	*Asplenium heteroresiliens*	Wagner's spleenwort	NL
Potential	*Calamovilfa curtissii*	Curtiss' sandgrass	ST
Potential	*Carex chapmanii*	Chapman's sedge	ST
Potential	*Forestiera godfreyi*	Godfrey's swampprivet	SE
Potential	*Gentiana pennelliana*	Wiregrass gentian	SE
Potential	*Leitneria floridana*	Corkwood	ST
Potential	*Liatris provincialis*	Godfrey's blazing star	SE
Potential	*Litsea aestivalis*	Pondspice	SE
Potential	*Lythrum curtissii*	Curtiss' loosestrife	SE
Potential	*Matelea floridana*	Florida spiny-pod	SE
Potential	*Nolina atopocarpa*	Florida beargrass	ST
Potential	*Oxypolis greenmanii*	Giant Water-dropwort	SE
Potential	*Phoebanthus tenuifolius*	Narrow-leaved phoebanthus	ST
Potential	*Phyllanthus liebmannianus ssp. Platylepis*	Pinewood dainties	SE
Potential	*Physostegia godfreyi*	Apalachicola dragonhead	ST
Potential	*PItyopsis flexuosa*	Zigzag silkgrass	SE
Potential	*Platanthera integra*	Yellow fringeless orchid	SE
Potential	*Rhexia parviflora*	Small-flowered meadowbeauty	SE
Potential	*Rhexia salicifolia*	Panhandle meadowbeauty	ST
Potential	*Rhynchospora thornei*	Thorne's beaksedge	NL
Potential	*Ruellia noctiflora*	Nightflowering wild petunia	SE
Potential	*Satyrium titus*	Coral hairstreak	NL
Potential	*Schisandra glabra*	Bay star-vine	SE
Potential	*Stachydeoma graveolens*	Mock pennyroyal	SE

1.7.2 Soils

Soils along the Wakulla River floodplain vegetation transects are almost exclusively mucky mineral soils (NWFWMD 2016). Sandy soils are rarely encountered. At vegetation transects sampled along the Wakulla River the depth to seasonal high saturation was six inches or less in riparian wetlands, indicative of high water-table conditions.

1.7.3 Wildlife

The Wakulla River and its floodplain have been extensively monitored for wildlife species at the Edward Ball Wakulla Springs State Park. Available wildlife data includes species observed on Wakulla Springs Tour Boats operated by park staff, Wakulla River wildlife surveys completed bi-annually since 1989, Florida Natural Areas Inventory species records, Florida Museum of Natural History fish collection records, publications, and personal observations by District staff. Habitat descriptions and requirements are provided for species listed on the Florida Fish and Wildlife Conservation Commission's list of "Florida's Endangered and Threatened Species" (2017).

Although detailed, quantitative studies concerning wildlife abundance along the Wakulla/Sally Ward Spring System are unavailable; based upon observation by state park staff it has been reported that overall wildlife abundance has declined during the last several decades (Deyle 2019, Thompson 2017). These changes in wildlife abundance have been attributed to the use of herbicide to reduce hydrilla abundance in the river (Deyle 2019) described in section 2.6 which eliminated food and structure for many species. It should be noted however, that populations for many bird and other species have declined across the eastern United States in recent years (Rosenberg et al. 2019).

Fish

A total of 86 taxa of fish have been identified in the Wakulla River including species inhabiting fresh, estuarine, and marine waters (Table 7). The abundance of estuarine and marine fish encountered is a result of the Wakulla River's proximity to Apalachee Bay and the Gulf of Mexico. Largemouth bass (*Micropterus salmoides*) are extremely abundant in the Wakulla River and are the deepest bodied freshwater fish species observed. Long-nose gar can reach lengths up to approximately 6 ft and large specimens can also be relatively deep bodied compared to other species. Striped bass (*Morone saxatilis*) are the largest bodied fish anecdotally reported, although not verified, in the St. Marks River (FWC 2019a, FWC 2019b). Striped bass have not been reported in the Wakulla River.

No State or Federally listed fish species have been documented in the Wakulla River. While the Wakulla River is located between rivers designated as critical gulf sturgeon (*Acipenser oxyrhincus desotoi*) habitat, no gulf sturgeon has been reported in the Wakulla River (Adam Kaeser USFWS, personal communication, 2017) and this system is not designated as critical habitat (USFWS 2018).

The State of Florida lists multiple fish species present in the Wakulla River as being species of Greatest Conservation Need (FWC 2019f). These species include mud sunfish, mountain mullet, spotted bullhead, American eel, Suwannee bass, and redeye chub. Little information is available for these species in relation to their abundance and use of the Wakulla River. Suwannee bass, while a species of concern in the State of Florida and are found only in an extremely limited range (Suwannee River, Ochlockonee River, Wacissa River, St. Marks River and Wakulla River) and are thought to be introduced into the Wakulla and St. Marks Rivers (Barthel et al. 2015, Najid et al. 2015).

Table 7: List of Fish Species Documented in the Wakulla River. Data Collected from District Staff observations, reported by Cailteux et al. 2003, Florida Natural Areas Inventory 2018, Walsh and Williams 2003, or FWC 2019a, Northwest Florida Water Management District staff observations. * Indicates Species of Greatest Conservation Need by the State of Florida (FWC 2019f).

Scientific Name	**Common Name**	**Scientific Name**	**Common Name**
Acantharcus pomotis	Mud sunfish*	*Lepisosteus osseus*	Longnose gar
Agonostomus monticola	Mountain mullet+	*Lepisosteus oculatus*	Spotted gar
Ameiurus catus	White bullhead	*Lepisosteus platyrhincus*	Florida gar
Ameiurus natalis	Yellow bullhead	*Lepisosteus sp.*	Gar
Ameiurus nebulosus	Brown bullhead	*Lepomis auritus*	Redbreast sunfish
Ameiurus serracanthus	Spotted bullhead*	*Lepomis gulosus*	Warmouth
Amia calva	Bowfin	*Lepomis macrochirus*	Bluegill
Anguilla rostrata	American eel*	*Lepomis marginatus*	Dollar sunfish
Aphredoderus sayanus	Pirate perch	*Lepomis microlophus*	Redear sunfish
Archosargus probatocephalus	Sheepshead	*Lepomis punctatus*	Spotted sunfish
Arius felis	Hardhead catfish	*Lepomis sp.*	Sunfish
Bairdiella chrysoura	American silver perch	*Lucania goodei*	Bluefin killifish
Bagre marinus	Gafftopsail catfish	*Lucania parva*	Rainwater killifish
Centrarchus macropterus	Flier	*Lutjanus griseus*[4]	Gray snapper
Cynoscion nebulosus	Spotted seatrout	*Megalops atlanticus*	Tarpon
Cynoscion nothus	Silver seatrout	*Microgobius gulosus*	Clown goby
Cyprinodon variegatus	Sheepshead minnow	*Micropterus notius*	Suwannee bass*
Elassoma evergladei	Everglades pygmy sunfish	*Micropterus salmoides*	Largemouth bass
Elassoma gilberti	Gulf coast pygmy sunfish	*Minytrema melanops*	Spotted sucker
Elassoma okefenokee	Okefenokee pygmy sunfish	*Morone saxatilis*	Striped bass
Elassoma zonatum	Banded pygmy sunfish	*Mugil cephalus*	Striped mullet
Elops saurus	Ladyfish	*Notemigonus crysoleucas*	Golden shiner
Elassoma okefenokee	Okefenokee pygmy sunfish	*Notropis chalybaeus*	Ironcolor shiner
Enneacanthus obesus	Banded sunfish	*Notropis cummingsae*	Dusky shiner
Erimyzon sucetta	Lake chubsucker	*Notropis harperi*	Redeye chub*
Esox americanus	American pickerel	*Notropis petersoni*	Coastal shiner
Esox niger	Chain pickerel	*Noturus gyrinus*	Tadpole madtom
Etheostoma fusiforme	Swamp darter	*Noturus leptacanthus*	Speckled madtom
Eucinostomus argenteus	Spotfin mojarra	*Opsopoeodus emiliae*	Pugnose minnow
Fundulus chrysotus	Golden topminnow	*Paralichthys albigutta*	Gulf flounder
Fundulus confluentus	Marsh killifish	*Percina nigrofasciata*	Blackbanded darter
Fundulus escambiae	Russetfin topminnow	*Poecilia latipinna*	Sailfin molly
Fundulus grandis	Gulf killifish	*Pogonias cromis*	Black drum
Fundulus seminolis	Seminole killifish	*Pomoxis nigromaculatus*	Black crappie
Gambusia holbrooki	Mosquitofish	*Pteronotropis metallicus*	Metallic shiner
Gobiosoma bosc	Naked goby	*Pteronotropis hypselopterus*	Sailfin shiner
Heterandria formosa	Least killifish	*Sciaenops ocellatus*	Redfish
Ictalurus punctatus	Channel catfish	*Semotilus thoreauianus*	Dixie chub
Jordanella floridae	Flagfish	*Strongyla marina*	Atlantic needlefish
Labidesthes sicculus	Brook silverside	*Strongylura timucu*	Timucu
Labidesthes sicculus vanhyningi	Southern brook silverside	*Syngnathus scovelli*	Gulf pipefish
Lagodon rhomboides	Pinfish	*Syngnathus sp.*	Pipefish
Leiostomus xanthurus	Spot	*Trinectes maculatus*	Hogchoker

Mammals

Multiple mammal species have been documented in the Wakulla River floodplain including Florida manatee (*Trichechus manatus latirostris),* Florida black bear (*Ursus americana florida*), feral hog (*Sus scrofra*), grey squirrel (*Sciurus carolinensis*), raccoon (*Procyon lotor*), river otter (*Lantra canadensis*), and white-tailed deer (*Odocoileus virginianus*) (Table 8). Sherman's fox squirrel (*Sciurus niger shermani*) may occur in the vicinity of the Wakulla River, however, this species inhabits open, fire-maintained longleaf pine, turkey oak, sandhills, and flatwoods. These upland habitats are not likely to be adversely impacted by changes in river stage/duration associated with potential reductions in spring discharge. No documented mammal species, with the exception of Florida manatee, are listed as endangered or threatened by the State of Florida.

Manatees can be found along the Gulf of Mexico coast from Florida to Texas during summer months, migrating to warm water habitats (i.e., artesian springs and power plant discharge canals) primarily south of Crystal River, Florida prior to the onset of cold winter temperatures (FWC 2018a). These warm water habitats are required due to manatee's susceptibility to cold stress at temperatures less than 20°C due to their low metabolic rate and thermal capacity (Bossart et al. 2002). The Florida Fish and Wildlife Research Institute (FWRI) has been tracking manatee mortality in Florida since April 3, 1974. Since this time, one manatee death (April 20, 2014) has been attributed to cold-water stress in the Wakulla River (near the confluence with the St. Marks River) (FWC 2018b). In addition, two other manatee deaths have been attributed to cold stress in Wakulla County, one in Dickerson Bay near Panacea, Florida and one near the mouth of the Ochlockonee River in Ochlockonee Bay, Florida.

Manatees have been documented in the Wakulla River since 1983 when six sightings were reported during July (Rathbun et al. 1990). Historically however, Wakulla Spring has not functioned as significant manatee habitat. Manatee observations in Wakulla Spring prior to 2002 were sporadic and did not occur annually. Since 2002, manatees have been regularly observed in the spring pool, with numbers increasing after 2007 (Figure 24). Beginning in the winter of 2007/2008 manatees have been regularly observed throughout the year near the spring pool with numbers increasing during the winter months (Figure 25). Park staff attributed the high numbers of manatees during 2007 to an increase in hydrilla that occurred during that same period (Peter Scalco personal communication 2017). Hydrilla was treated and has since declined in coverage, however, manatee numbers have remained elevated above historical levels during the winter months. Currently, park staff routinely observes manatees throughout the year with numbers increasing during winter months (Figure 25) (Edward Ball Wakulla Springs State Park, unpublished data). These counts often occur only in the vicinity of the boat tour and do not encompass the lower portions of the Wakulla River or the lower St. Marks River south of the confluence, however, and manatee numbers may be higher than those reported. Manatees have been reported foraging in the Sally Ward Spring Run and pool, however details of manatee use and counts near Sally Ward Spring are not available.

Although historically classified as a secondary thermal refuge (Taylor 2006), Wakulla Spring has recently been listed as primary thermal refuge habitat for manatees (Valade et al. 2020). Compared with other first magnitude springs designated as Primary Thermal Refuge in Florida, Wakulla Spring is the only spring to not have a high thermal quality designation (Valade et al. 2020). Water temperatures at Wakulla Spring regularly and naturally fall below 20°C. Manatees are subject to cold stress at reduced temperatures which may result in dehydration, skin lesions, gastrointestinal disorders, and death (Bossart et al. 2002). Previous MFLs for springs have used two separate criteria for the protection of manatee thermal refuge (Rouhani et al. 2007, SRWMD 2013, SWFWMD 2004, SWFWMD 2008, SWFWMD 2012a, SWFWMD 2012b, SWFWMD 2017a). Most often, these include a chronic stress limit of water temperature ≤20°C for periods in excess of 3 days and an acute stress limit of water temperature ≤15°C for periods in excess of 4 hours.

Unlike many other karst springs, the temperature at Wakulla Spring regularly drops below the 20°C chronic stress temperature criterion during winter months for extended periods of time (Figure 26). As previously discussed, water temperature at the vent may not only be affected by groundwater from the aquifer, but also by the surface water flowing into the aquifer system via multiple sinkholes and swallets. During winter months, high precipitation is often associated with cold fronts where air temperature (and as a result surface water temperature) regularly drops below 20°C (i.e., 1998, 2003, 2004, 2013, 2014, 2015, 2018, 2019). There appears to be a lag time between precipitation/air temperature and vent temperature of approximately 7 to 10 days. As a result, the effects of low air temperature on water temperatures on Wakulla Spring vent temperature may not be detected at Wakulla Spring for more than a week after the system passes and air temperatures have increased. In addition, the reduced vent temperature can remain below the 20°C, three-day chronic stress threshold for an extended time.

The coldest water at the vent on record is 19.36°C which occurred on March 7, 2013. During this time the vent temperature dropped below 20°C for 10 consecutive days. This year also coincided with the second highest number of manatees recorded at Wakulla Springs with no reported manatee mortalities due to cold stress in the Wakulla County, Florida (FWC 2018b). One manatee death has been attributed to cold stress in the Wakulla River (April 20, 2014), but was found downstream of US 98 near the town of St. Marks (30.16034, -84.22044), i.e., not in the spring or immediate spring run. No other manatee deaths have been recorded in or near the Wakulla or St. Marks Rivers.

Despite increased numbers of manatees using Wakulla Spring as a thermal refuge in recent years, the percentage of habitat used by manatees is extremely small compared to the amount of available space. Rouhani et al. (2006) described a surface area of 28.5 ft^2 (2.65 m^2) for an adult manatee. Using a Wakulla Spring pool diameter of 315 ft (NWFWMD 2017), the spring pool surface area alone could hold an estimated 2,733 manatees. Recent estimates report that the northwest Florida region had a winter 2015/2016 manatee population of 270 individuals (Hostetler et al. 2018). Based on these estimates, the Wakulla Spring pool alone could fit more than 10 times the entire northwest Florida estimated population of manatees. The 2,733 manatees which could potentially utilize Wakulla Spring pool, represents 82 percent of the west-coast of Florida population estimated between January 28 and February 2, 2019 (n=3339) (FWC 2020a). It should also be noted that the size of the spring pool described above is conservative and the amount of available thermal refuge provided by the pool is considerably larger when considering the volume of space as opposed to surface area. The Wakulla Spring pool is extremely deep with most areas exceeding 13 ft in depth and a maximum depth near the vent of 183 ft (Appendix A). In addition, water of suitable temperature and depth (>3.8 ft) also extends further downstream from the spring pool. For example, during thermal profile sampling for model calibration, water of suitable temperature (i.e., >20°C and >15°C) was detected more than 0.5 miles downstream from the spring vent.

Table 8: List of Documented Mammal Species Documented Near the Wakulla River. FT=Federally Threatened. (Observations from Wakulla Springs State Park Staff and District Staff).

Scientific Name	Common Name	Status
Lantra canadensis	River otter	
Odocoileus virginianus	White tailed deer	
Procyon lotor	Raccoon	
Sciurus carolinensis	Gray squirrel	
Sus scofra	Feral hog	
Trichechus manatus (latirostris)	West Indian manatee (Florida manatee)	FT
Ursus americana florida	Florida black bear	

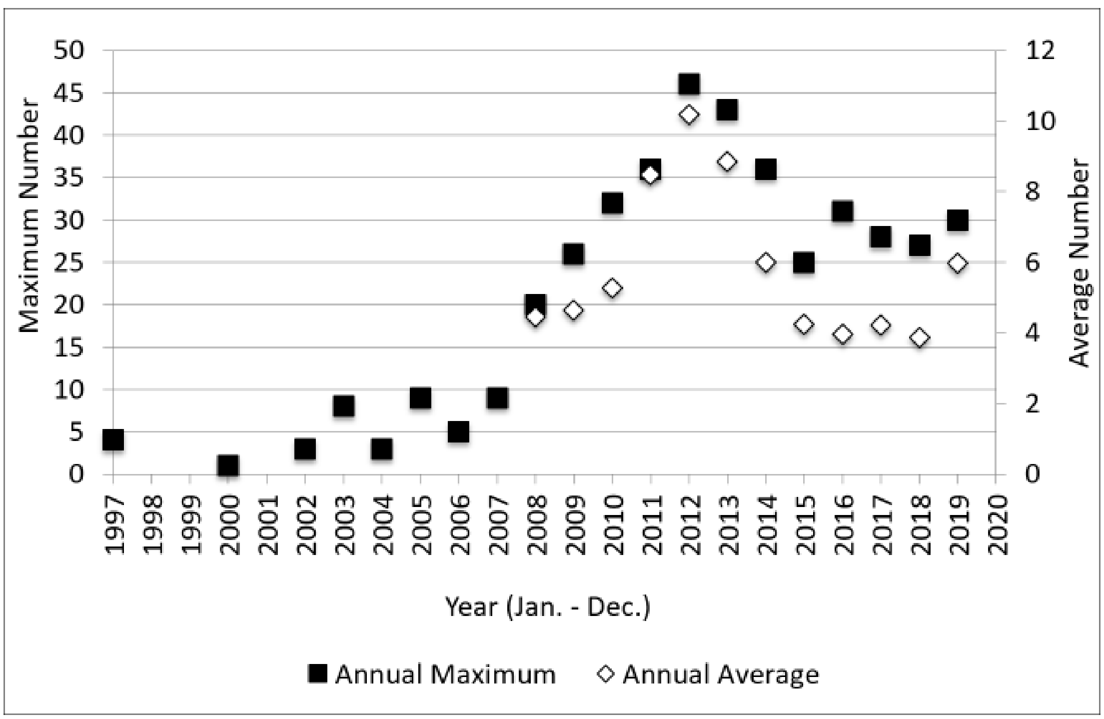

Figure 24: Maximum Daily Manatee Observation During Each Year from 1997 through 2019, Daily manatee count data from the Edward Ball Wakulla Springs State Park staff prior to 2008 are not available and averages are not presented.

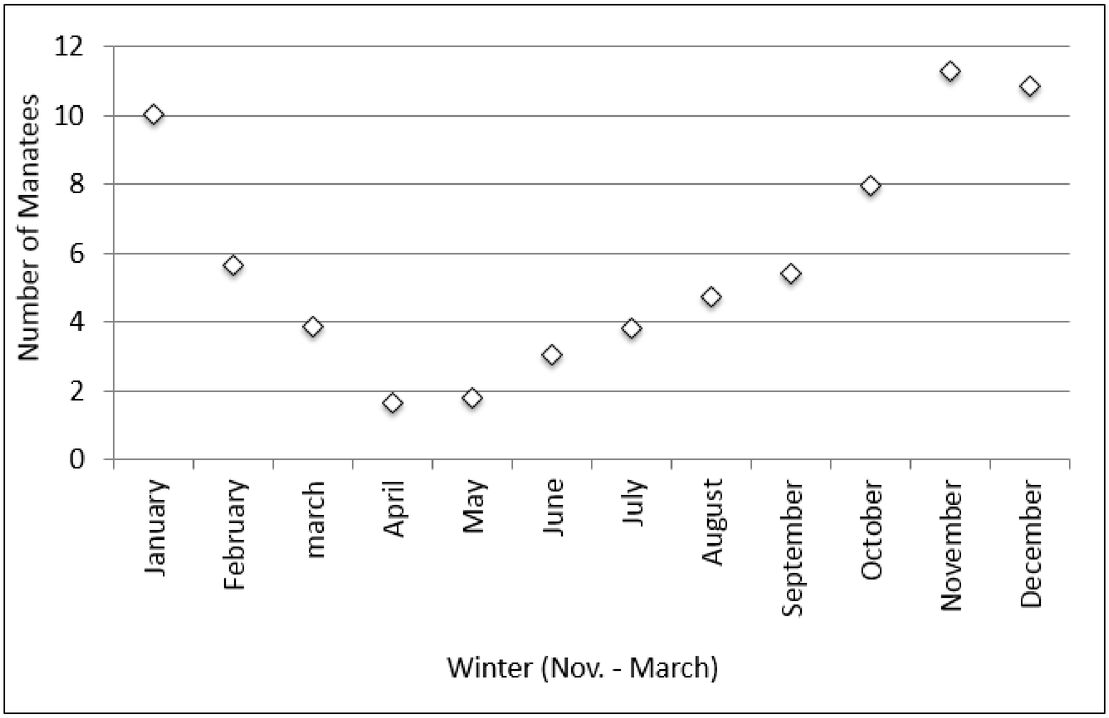

Figure 25: Average Monthly Manatee Use (Number of Daily Sightings) at Wakulla Spring Between 2008 and 2018.

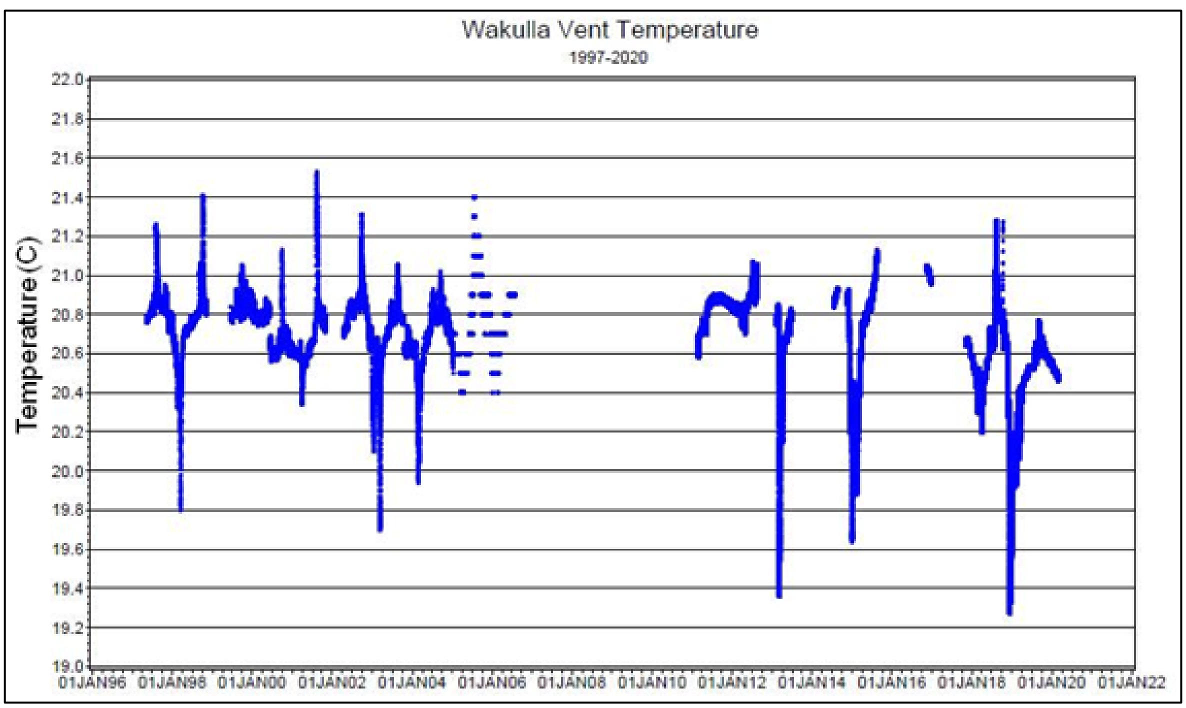

Figure 26: Temperature of Water Emerging from Wakulla Spring (May 9, 1997 – February 28, 2020). Figure reproduced from Appendix D: Wakulla Spring MFL: Hydrodynamic Model for Thermal Evaluation

Birds

Numerous bird species have been documented along the Wakulla River floodplain presumably as a result of the intact floodplain and surrounding lands, in addition to the routine wildlife surveys at the Edward Ball Wakulla Springs State Park. A total of 13 observed bird species are listed by the state of Florida for the Wakulla study area (Table 9). Two species are federally listed: red-cockaded woodpecker (*Picoides borealis*, federally endangered) and wood stork (*Mycteria americana*, federally threatened). Red-cockaded woodpeckers (*Leuconotopicus borealis*) have been translocated to and documented in the nearby St. Marks National Wildlife Refuge which is outside the study area. This species inhabits old-growth, mature pine forests with sparse mid-story vegetation (FWC 2003), which are unlikely to be impacted by changes in spring discharge. Wood storks inhabit freshwater and estuarine wetlands and nest in cypress or mangrove swamps (USFWS 2018). Eight species are listed as State Threatened including Wakulla seaside sparrow (*Ammodramus maritimus juncicola*), Marian's marsh wen (*Cistothorus palustris marianae*), limpkin (*Aramus guarauna*), snowy egret (*Egretta thula*), little blue heron (*Egretta caerulea*), tricolored heron (*E. tricolor*), American oystercatcher (*Haemaopus palliates*), and roseate spoonbill (*Platalea gigig*). Wakulla seaside sparrow (*Ammodramus maritimus juncicola,* state threatened) inhabit tidal marshes from Taylor County to St. Andrews Bay (Kale 1983). This species has not been reported along the Wakulla River spring run; however, this sparrow breeds in black needle rush and a small amount of potentially suitable saltmarsh habitat exists near the City of St. Marks. Marian's marsh wren (*Cistothorus palustris marianae*) has been identified as possibly occurring along the nearby St. Marks River (FNAI 2017). This species inhabits tidal marshes dominated by black needle rush and cordgrass such as that found in the lower St. Marks River below the confluence with the Wakulla River. Little blue heron (*Egretta caerulea*), tricolored heron (*Egretta tricolor*), and roseate spoonbill (*Platalea ajaja*) are all wading birds documented along the Wakulla River and are listed as state threatened in Florida. Wading birds require a variety of wetland habitats for nesting and foraging, many of which can be found along the Wakulla River, Sally Ward spring run, and associated floodplains. American oystercatcher (*Haematopus palliates*) is a shorebird inhabiting beaches, sandbars, spoil islands, shell rakes, salt marsh, and oyster reefs (FWC 2019c). These habitats are found outside the study area in coastal areas with waters containing elevated salinities not likely to be affected by changes in spring flows. Two types of sandhill cranes inhabit Florida, one of which (Florida sandhill crane, *Antigone canadensis pratensis*) is listed as threatened by the State of Florida (FNAI 2019). Both species are uncommon in north Florida and inhabit prairies, marshes, and pasturelands which are uncommon along the Wakulla River and its floodplain. Species confirmation of the individual(s) documented along the Wakulla River was not available. The Southeastern American Kestrel (*Falco sparverius Paulus*) is a non-migratory subspecies of kestrel listed as threatened in the State of Florida (FWC 2019d). Although confirmation of the identification of these individuals as the threatened southeastern American kestrel is unavailable, this species inhabits the open pine savannahs, sandhills, prairies, and pastures in Florida which are unlikely to be affected by changes in spring flow. Three species documented along the Wakulla River were once listed but are no longer listed and are included in the FWC Species Management Plan. Limpkins (*Aramus guarauna*) were once common in the area; however, numbers have declined in the region, presumably in response to a reduction in apple snail populations (NWFWMD 2009). Snowy egret (*Egretta thula*) and white ibis (*Eudocimus albus*) are wading birds requiring a variety of wetland habitats. Osprey are common along the Wakulla River but are not listed outside of Monroe County, Florida and are not included in the table below.

Table 9: List of Documented Bird Species Documented Along or Near the Wakulla River. FE=Federally Endangered, ST=State Threatened, FWCISMP=Species no longer listed, but included in the FWC Species Management Plan

Occurrence	Common Name	Scientific Name	Status
Listed Species	*Ammodramus maritimus juncicola*	Wakulla seaside sparrow	ST
	Aramus guarauna	Limpkin	FWCISMP
	Cistothorus palustris marianae	Marian's marsh wren	ST
	Egretta caerulea	Little blue heron	ST
	Egretta thula	Snowy egret	FWCISMP
	Egretta tricolor	Tricolored heron	ST
	Eudocimus albus	White ibis	FWCISMP
	Falco sparverius paulus	Southeastern American kestrel	ST
	Grus Canadensis	Florida Sandhill crane	ST
	Haematopus palliates	American oystercatcher	ST
	Mycteria americana	Wood stork	FT
	Picoides borealis	Red-cockaded woodpecker	FE
	Platalea ajaja	Roseate spoonbill	ST

Reptiles/Amphibians

Numerous reptile and amphibian species have been documented along the Wakulla River and its floodplain (Table 10). Of these species, two are listed. The American alligator (*Alligator mississippiensis*) is a federally threatened species due to its similarity of appearance to another federally threatened species, the American crocodile (*Crocodylus acutus*). American alligators are extremely abundant in the Wakulla River and spring, especially within the boundaries of the Edward Ball Wakulla Springs State Park. The American crocodile is not found in the Florida panhandle. Florida pine snake (*Pithuophis melanoleucus mugitas*) is listed as state threatened which inhabits well drained sandy soils with moderate to open forest canopy (FWC 2018c), which is not a wetland habitat that is likely to be impacted by changes in spring discharge and water levels. This species inhabits lakes, rivers, swamps, and brackish waters (FWC 2018c).

Table 10: List of Documented Reptiles and Amphibians Documented Along the Wakulla River by Florida Natural Areas Inventory, Wakulla Springs State Park Staff, or Northwest Florida Water Management District Staff. FT (SA)-Federally Threatened due to Similarity of Appearance to Another Listed Species

Occurrence	Species	Common Name	Status
Documented	*Hyla chrysoscelis*	Gray treefrog	
Documented	*Hyla cinereal*	Green treefrog	
Documented	*Hyla crucifer*	Spring peeper	
Documented	*Lithobates catesbeianus*	American Bullfrog	
Documented	*Plethodon glutinosus*	Slimy salamander	
Documented	*Rana grylio*	Pigfrog	
Documented	*Rana utricularia*	Southern leopard frog	
Documented	*Siren* sp.	Siren	
Documented	*Agkistrodon piscivorus*	Water moccasin	
Documented	*Alligator mississippiensis*	American alligator	FT (SA)
Documented	*Anolis carolinensis*	Green anole	
Documented	*Apalone ferox*	Florida softshell turtle	
Documented	Chelydra *serpentina*	Florida snapping turtle	
Documented	*Crotalus adamanteus*	Eastern diamondback rattlesnake	
Documented	*Deirochelys reticularia*	Chicken turtle	
Documented	*Elaphe guttata*	Red rat snake	
Documented	*Elaphe obsoleta spiloides*	Gray rat snake	
Documented	*Farancia erytrogramma*	Rainbow snake	
Documented	*Kinosternon subrubrum*	Eastern mud turtle	
Documented	*Lampropeltis getulus*	Eastern kingsnake	
Documented	*Macrochelys temminckii*	Alligator snapping turtle	
Documented	*Natrix erythrogaster*	Red-bellied watersnake	
Documented	*Nerodia fasciata*	Banded Water Snake	
Documented	*Nerodia fasciata*	Southern watersnake	
Documented	*Nerodia taxispilota*	Brown water snakes	
Documented	*Opheodrys aestivus*	Rough green snake	
Documented	*Pithuophis melanoleucus mugitus*	Florida pine snake	ST
Documented	*Pseudemys concinna*	River cooter	
Documented	*Pseudemys floridana*	Florida cooter	
Documented	*Pseudemys sp.*	Cooter Turtle	
Documented	*Pseudemys suwanniensis*	Suwannee cooter	
Documented	*Sternotherus odoratus*	Stinkpot	
Documented	*Thamnophis sirtalis*	Eastern garter snake	
Documented	*Trachemys scripta*	Yellow bellied slider	

Invertebrates

Eighteen invertebrate species have been documented in or are reported as likely to inhabit the Wakulla River, none of which are listed (Table 11). Two listed species are reported to possibly inhabit the Wakulla River by the FNAI, although they have not been documented in the Wakulla River. The Ochlockonee moccasinshell (*Medionidus simpsolianus*) is listed as federally endangered and the purple bankclimber (*Elliptoideus sloatianus*) is listed as federally threatened. Ochlockonee moccasinshell are only found in the Ochlockonee River system in areas of moderate current and sandy, gravel substrates. Purple bankclimbers inhabit the Apalachicola and Ochlockonee Rivers in slow to moderate flowing currents with a sandy substrate (FWC 2018d).

Table 11: List of Invertebrate Species Documented Along the Wakulla River.

Occurrence	Scientific Name	Common Name
Documented	*Callinectes sapidus*	Blue crab
Documented	*Danaus plexipus*	Monarch
Documented	*Elliptio jayensis**	Flat spike
Documented	*Euphyes dion*	Dion skipper
Documented	*Hydroptila Wakulla*	Wakulla Springs var-colored microcaddisfly
Documented	*Megathymus yuccae*	Yucca skipper
Documented	*Neotrichia rasmusseni*	Rasmussen's neotrichia caddisfly
Documented	*Oxyethira Janella*	Little-entrance oxyethiran microcaddisfly
Documented	*Pomacea sp.*	Apple snail
Documented	*Satyrodes apalachia*	Apalachian brown
Documented	*Sphodros abboti*	Blue purse-web spider
Documented	*Stenocron floridense*	Mayfly
Documented	*Triaenodes furcellus*	Little-fork Triaenode caddisfly
Documented	*Vanessa atalanta*	Red admiral butterfly
Documented	*Elliptio icterina*	Variable spike
Documented	*Uniomerus carolinianus**	Florida pondhorn
Documented	*Utterbackia peggyae**	Peninsular floater
Documented	*Villosa vibex**	Southern Rainbow
Documented	*Corbicula fluminea*	Asian clam

1.7.4 Recreation

The Edward Ball Wakulla Springs State Park and the relatively undeveloped nature of the Wakulla River and surrounding lands provide numerous outdoor recreational opportunities and are used extensively for recreation. The Wakulla River can be divided into two sections based upon land management and the recreational opportunities allowed along the river: the Edward Ball Wakulla Springs State Park and the downstream river between the park and the confluence with the St. Marks River.

The upper one third of the Wakulla River (approximately 3.2 miles) is located within the boundaries of the Edward Ball Wakulla Springs State Park which is located upstream of the Shadeville Road bridge (Figure 5). The Edward Ball Wakulla Springs State Park encompasses more than 6,000 acres (9.4 mi²) and extends from both Wakulla and Sally Ward springs to the Shadeville Road bridge. Wakulla Spring, Sally Ward Spring, and numerous smaller springs are located within the park boundaries. Prior to being a state park, Wakulla Springs was managed as a private attraction focusing on wildlife preservation and surrounding habitat (Florida State Parks 2018). The property was originally purchased in 1934 by Edward Ball. The lodge located in the park was built was built in 1937 and offers overnight accommodations in multiple guest rooms, a dining room, meeting space for conferences and meetings, picnicking facilities, a playground, and the world's largest marble soda fountain (The Lodge at Wakulla Springs 2018). The Lodge remains popular with visitors. The remainder of the park consists mostly of natural lands including river floodplains, sloughs, and old-growth forests making it home to abundant and diverse wildlife populations (described above). The park contains numerous hiking and horseback riding trails making it a popular destination for nature enthusiasts and photographers. The park also offers guided riverboat tours which travel approximately one mile downstream of the main vent along a portion of the river which was artificially deepened (i.e., excavated) by Edward Ball in the late 1960s or early 1970s (Florida DEP 2007, Florida State Parks 2018). The designated swimming area is popular during summer months, as a result of the spring's consistent cool water temperatures. Outside of the swimming area public access on the Wakulla River within the park is restricted to tour boat operations. Fishing, scuba diving, canoeing and private watercraft are prohibited within the park.

Downstream of the Edward Ball Wakulla Springs State Park, the Wakulla River provides more extensive public recreation opportunities. Two public and one private boat launches allow access to the river below Shadeville Road where recreational boating is a popular activity. Canoeing/kayaking is also extremely popular along the Wakulla River with canoe/kayak rental available near the U.S. Hwy 98 bridge. While numerous riverside homes exist, the downstream portion of the Wakulla River remains in a relatively undeveloped state and is host to numerous wildlife and vegetation communities making photography, nature viewing, fishing, etc. popular activities. Limited development and commercial use of the Wakulla River is largely isolated to the City of St. Marks.

2 Hydrology

This section describes the hydrology of the Wakulla River and Sally Ward Spring run.

2.1 Hydrologic Setting

The Wakulla River originates at Wakulla Spring, and flows approximately nine miles to the southeast where it discharges to the St. Marks River at the City of St. Marks (Figure 1). Thalweg (lowest point in channel along a river cross section) elevations in the river exhibit minor variations in the portions of the river located within the Edward Ball Wakulla Springs State Park (-4.75 to 0.1 ft North American Vertical Datum of 1988, NAVD88). After the Shadeville Road bridge, thalweg elevations decline downstream, reaching a minimum of -18.2 ft NAVD88 near the City of St. Marks. Under median flow and tide conditions, the hydraulic depth (river cross sectional area divided by the width) for the Wakulla River varies between 2 ft and 9 ft, with a mean of 4.5 ft. The top width for the Wakulla River varies between 118 ft and 580 ft with a mean width of 361 ft.

The Wakulla River and Sally Ward Spring Run have undergone several structural alterations which can affect flows in the Wakulla River and Sally Ward Spring Run. The Wakulla River boat tour route (approximately 1 mile downstream of the main vent) and the entire Sally Ward Spring Run received river channel modifications in the late 1960s to early 1970s (DEP 2007). Edward Ball dynamited parts of the Wakulla River and Sally Ward Spring Run to make it more accessible for boats (DEP 2018b). Spoil banks from the dredged areas remain on the banks of both waterways and these areas have since been recolonized by native vegetation; however, elevated ground surfaces associated with these spoil banks remain in many areas and are particularly visible along the Sally Ward Spring Run. Two road bridges have been installed which cross the Wakulla River (U.S. Hwy 98 and Shadeville Road) (Figure 6), and one pedestrian bridge was installed which crosses the Sally Ward Spring Run. The bridges crossing the Wakulla River contain submerged pilings which can impede water flow, while the Sally Ward bridge contains no submerged pilings. Effects of these structural alterations were considered but data are unavailable regarding the magnitude of potential effects on the ecology, water resources, or the quantity of spring flow discharged from Wakulla and Sally Ward springs.

Flow in the Wakulla River arises primarily from Wakulla Spring and a considerably smaller portion from Sally Ward Spring and its associated spring run (Figure 1). Multiple other sources of relatively minor flow inputs exist between the spring pool and U.S. Hwy 98 including McBride Slough, diffuse groundwater inflow, and at least 10 small (less than third magnitude springs, <10 cfs) springs located adjacent to or near the Wakulla River (Figure 27). Minor amounts of overland flow from precipitation can occur from the surrounding floodplain and watershed.

Figure 27: Location of Springs Connected to the Wakulla River

2.1.1 Wakulla Spring

The Wakulla Spring pool is circular in shape with an approximate diameter of 315 ft and maximum depth of 185 ft (cover page image, NWFWMD 2017). Discharge at Wakulla Spring flows from a large vent (50 ft x 82 ft) connected to an extensive submerged cave system (Loper et al. 2005). As previously discussed, Wakulla Spring is connected to numerous springs, sinkholes, and swallets by an extensive network of underground conduits (Loper et al. 2005). The diameters of some of these underground conduits can exceed 30 ft although most near the spring appear to be in the range of 10 to 25 ft in diameter (WKPP, unpublished data). Tracer tests indicate that these conduits can transport large volumes of water long distances in relatively short time periods (FGS 2012).

2.1.2 Sally Ward Spring

The Sally Ward Spring vent (Figure 27) extends to a depth of 18 ft and is connected to a conduit system similar to the one described above. The hydraulic depth for the Sally Ward Spring run varies between 2.6 ft and 3.9 ft, with a mean depth of 3.1 ft. The top width for the Sally Ward Spring run varies between 44 ft and 97 ft with a mean width of 66 ft. The spring run extends approximately 0.7 miles southeast where it joins the Wakulla River just downstream of the main spring pool (Figure 27, Figure 28, and Figure 28). Water from Sally Ward Spring flows along the north side of the Wakulla River for another 0.3 miles where it is largely separated from the main Wakulla River by a large patch of emergent vegetation and a narrow, heavily vegetated island. Once joining the main Wakulla River, water from Sally Ward Spring can more readily mix with Wakulla Spring flow, although much of the Sally Ward Spring flow continues along a deeper portion of the river along the northern edge of the river for another 0.6 miles downstream before Wakulla River channel bottom levels stabilize across the channel. Apart from the channel deepening and deposition of materials along the banks, the Sally Ward Spring run consists of natural lands in relatively undisturbed conditions.

During periods of high precipitation, the Sally Ward Spring pool can become hydrologically connected to Indian Spring and the Indian Spring run (Figure 27, Figure 30). Indian Spring is a relatively small spring which is isolated from Sally Ward Spring under normal conditions. During periods of excessive rainfall however, a wetland slough connecting the two springs becomes inundated and surface water flows drain into the Sally Ward Spring pool where they combine with Sally Ward Spring discharge.

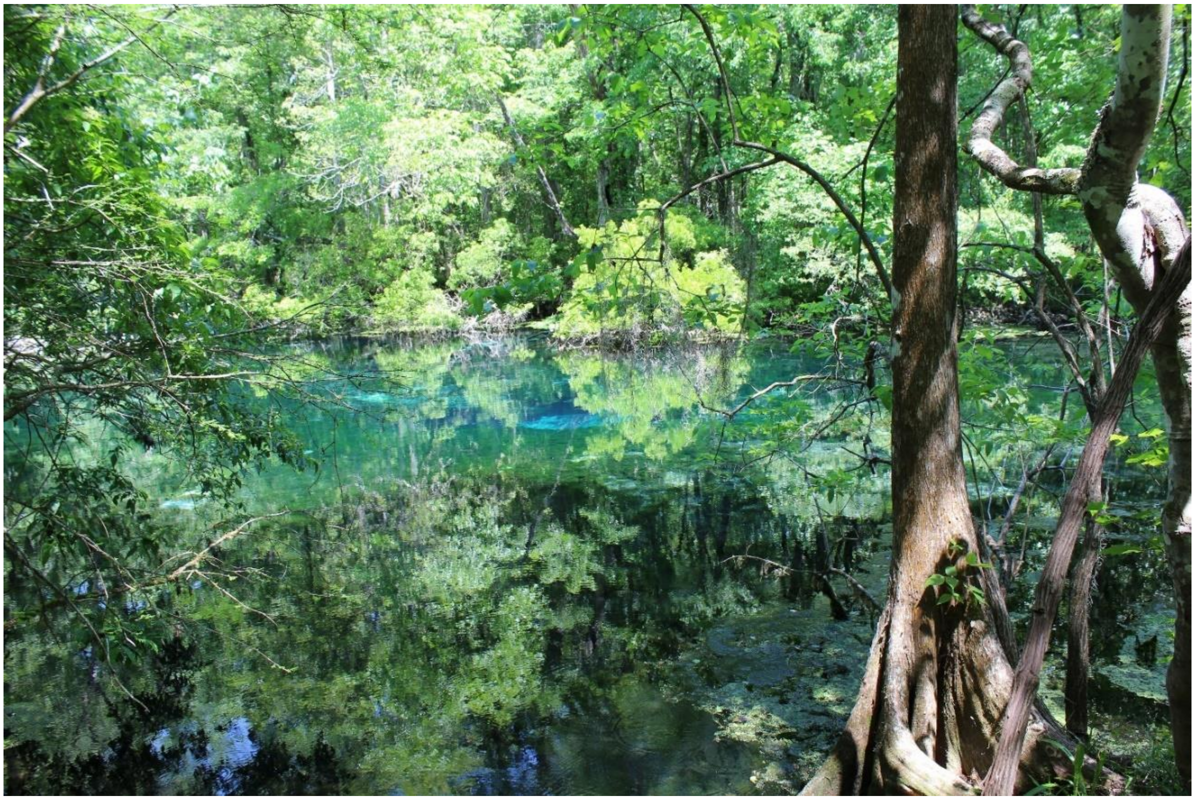
Figure 28: Sally Ward Spring Pool


Figure 29: Sally Ward Spring Run

Figure 30: Culverts Connecting Indian Spring to Sally Ward Spring

2.1.3 McBride Slough and Associated Springs

Approximately two miles downstream of Wakulla Spring, McBride Slough discharges to the north side of the Wakulla River (Figure 27). This small intermittent stream contains nine known springs, all third magnitude or smaller, which can potentially become hydrologically connected following periods of high precipitation. Just north of the Wakulla State Forest, the slough originates with Deer Spring. McBride Spring #4, Hawks Cry Spring, Root Spring, Lolly Spring, Ibis Glade Spring, and McBride Spring #3 are located within the Wakulla State Forest. McBride Spring #2 is located near the state park boundary and McBride Spring is located on private land. Palmetto Spring is located within the Edward Ball Wakulla Springs State Park and is nearest to the Wakulla River. Cumulative flow from McBride Slough into the Wakulla River has been estimated at an average of 9.87 cfs based on 64 observations between November 11, 1997 and April 10, 2018. However, during dry periods surface water connections between the springs and Wakulla River may be absent. Flows from McBride Slough have been measured ranging between 0 cfs and 59 cfs.

2.1.4 Additional Wakulla River Springs

Downstream of the Wakulla Spring vent and upstream of the U.S. Hwy 98 bridge, numerous small springs are located within the Wakulla River Floodplain or are connected to the river by a short spring run or slough. (Figure 27). In total, 15 known springs are present along this stretch of the river including three third magnitude (1 to 10 cfs) springs, five fourth magnitude (100 gallons per minute (gpm) to 1 cfs) springs, and four fifth magnitude (10 to 100 gpm) springs. One spring, Wakulla Sulfur Spring #3, is unclassified. Sweet Bay Spring, Turnaround Spring, Northside Spring #1, Northside Spring #2, Rock Spring, Chimney Spring, Homestead Spring, and No Name Spring are located between Wakulla Spring and Shadeville Rd. The remaining springs (River Plantation Spring #1, River Plantation Spring #2, Mysterious Waters Spring, Tiger Hammock Spring, Wakulla Sulfur Spring #1, Wakulla Sulfur Spring #2, and Wakulla Sulfur Spring #3) are located between the Shadeville Road and U.S. Hwy. 98 bridges. No known springs are present along the Wakulla River downstream of the U.S. Hwy. 98 bridge.

2.1.5 Lower St. Marks River

South of the study area, the lower St. Marks River is comprised primarily of the combined St. Marks and Wakulla River flows, beginning at the City of St. Marks and extending approximately five miles into Apalachee Bay (Figure 1). Although there is not a gaging station measuring continuous discharge at or below the confluence, available data suggests that most of the river flow in the reach immediately south of the confluence is comprised of groundwater inflow from Wakulla Spring, the St. Marks River Rise, and additional diffuse groundwater inflow contributions. South of the confluence, the lower St. Marks River is highly influenced by tides and is estuarine due to its proximity to Apalachee Bay and the Gulf of Mexico. Flow from the lower St. Marks River into the Apalachee Bay estuary supports in large part the diverse and healthy estuarine ecosystem.

2.1.6 Spring Creek Spring Group

The Spring Creek Spring Group (Spring Creek) is a cluster of 14 known submarine springs located approximately 11 miles south of the Wakulla Spring vent (Figure 1). The Spring Creek Spring Group discharges into a tidal estuary in Apalachee Bay, Wakulla County. This spring group is a submarine spring characterized by extensive well-developed conduit network joined by deep vertical conduits (Fleury et al. 2007). The hydraulic head is often too weak to prevent sea water from entering the conduits. Conduits have large storage capacities and well-developed internal conduit networks that drain vast recharge areas, and strong seasonal variability in groundwater discharge rates with water salinity being low during high spring flow and higher during low spring flow events.

During periods of low precipitation, flows at the Spring Creek Spring system can undergo a reversal where saline water from Apalachee Bay flows into the springs and conduit system (Davis and Verdi 2014). Wakulla spring can subsequently display an increase in discharge and specific conductivity following a lag time as some flows which would be discharged at the Spring Creek Spring Group are diverted to Wakulla Spring. As precipitation increases the Spring Creek Spring Group resumes normal conditions where they again begin discharging fresh water.

2.2 Hydrologic and Water Quality Data Collection

Surface water flow and stage are measured at multiple sites along the Wakulla River, Sally Ward Spring run, and the St. Marks River. Available data includes continuous flow and stage data collected by the USGS as well as multiple stations installed by the District to monitor flow, stage and water quality specifically for Wakulla Spring and Sally Ward Spring minimum flow development.

Discharge from Wakulla and Sally Ward springs were calculated using the index velocity method (Levesque and Oberg 2012) at two separate monitoring stations (Table 12, Figure 31). Stations 749 (Wakulla Spring Main Vent) and 774 (Sally Ward Spring Run) were both installed, operated, and maintained by the District. Discharge and water temperature data from the Wakulla Spring Main Vent has been collected since May 10, 1997, with several large data gaps present. The velocity meter at this station is located in the spring vent at a depth of approximately 185 ft making maintenance and replacement difficult, as this work must be performed by certified cavern divers. Water quality and continuous discharge along the Sally Ward Spring run have been collected since January 2015 and December 2016, respectively (Table 12). The Sally Ward monitoring station is located at a pedestrian bridge approximately 0.5 miles downstream of the spring vent. Details of the data collection methods and index velocity calculation can be found in Appendix A. While the majority of water measured at the Sally Ward station consists of spring flow, at times of high rainfall, surface water can flow into the spring pool and run from the slough connecting the Sally Ward Spring to Indian Spring. Stage and velocity data of water flowing through the Indian Spring slough is measured at District station 801 and extends from December 2014 through present. This station is located at the SR 61 bridge approximately 500 ft from the Sally Ward Spring pool and encompasses most of the surface water flows entering the spring pool. Discharge is estimated using the index velocity method as described by Levesque and Oberg (2012).

The District also monitors Wakulla River stage and water temperature at station 10822 (Wakulla Boat Tram) located on the Wakulla River approximately 0.6 miles downstream of the Wakulla Spring Main Vent (Figure 31, Table 12). Stage has been collected since 1987 and water temperature since January 2017. Temperature and stage data were used in thermal model development, calibration, and metric evaluation. The District plans on continuing to monitor the Wakulla Vent, Sally Ward Spring Run, and Boat Tram stations for further evaluations of the system.

Discharge along the Wakulla and St. Marks rivers is monitored by the USGS at one station on each river. USGS 02327022 (Wakulla River near Crawfordville, FL) is located on the Wakulla River at Shadeville Road and measures flow contributions from Wakulla Spring (1st Magnitude), Sally Ward Spring (2nd Magnitude), McBride Slough, and other surface water inputs, in addition to other minor surface water and diffuse groundwater inputs (Figure 27, Table 12). Flow and stage at USGS 02327022 have been collected since October 23, 2004. Data from this site was used for HEC-RAS and Estuarine EFDC model development and calibration. Daily flow and stage along the nearby St. Marks River (USGS station 02326900, St. Marks River Near Newport, FL) has been measured daily since 1956; with continuous flow and stage data (15-minute intervals) being collected since 1986 and 2007, respectively. Data from the St. Marks River Near Newport station was used to determine inflow boundary conditions to the HEC-RAS model along the St. Marks River.

In addition, stage and water quality data near the Wakulla Spring pool is monitored by USGS station 02327000 (Wakulla Spring Near Crawfordville, FL). This station is located at the Edward Ball Wakulla Springs State Park tour boat dock approximately 422 ft downstream of the Wakulla Spring main vent

(Figure 31). The USGS began monitoring this station in January 2017. Prior to 2017, the District operated and maintained this station. This data was used for HEC-RAS and Thermal EFDC model development and calibration.

Five temporary data collection stations (HD1 through HD5) were established by the District for use in the estuarine EFDC model development and calibration (Figure 31). Each station was equipped with continuous recording sondes measuring stage, temperature, and specific conductivity (Table 12). Sondes were installed in PVC casings with vent holes drilled in the casings to allow for water flow and pressure equalization. Two sondes were installed at stations HD-1, HD-2, HD-4, and HD-5. One sonde was fixed at 0.5 m above the substrate to sample the river stage elevation and bottom water temperature and specific conductivity. Another sonde was fixed from a float 0.5 m below the water surface to measure surface water temperature, specific conductivity, and relative depth of the sonde compared to the water surface. The elevation of a point located on a permanent structure on which the PVC casings were mounted was surveyed for converting water depths above the sonde 0.5 m above the substrate into NAVD 88 elevations using the surveyed elevations and fixed cord lengths. Station HD-3 contained a single sonde located at mid-water depth. Data at all stations was collected at 15-minute intervals. Water level data (NAVD 88) was used for both Estuarine EFDC and HEC-RAS models, while temperature and specific conductivity (converted to salinity) data were used for EFDC model calibration for the estuarine model described later in this section. This data was collected between July 2016 and August 2017.

A total of 29 in situ, vertical profile stations located along the length of the rivers were sampled monthly for depth, temperature, and conductivity to support additional estuarine EFDC hydrodynamic model calibration (Figure 31, Appendix B). Profile stations were sampled using a calibrated YSI from March 2016 through August 2016 and again from December 2016 through April 2017. Each profile station was sampled at 0.5 m increments from the surface to 0.5 m from the substrate or a maximum depth of 4.5 m, whichever was less. A total of nine stations were established in the lower Wakulla River (W-1 through W-9) (Figure 31). Stations in the St. Marks River were used in prior modeling work to establish minimum flows for the St. Marks River Rise (SM 1 through SM 20).

Thermal profile data was collected between the Wakulla Spring pool and Wakulla Boat Tram for the calibration of a thermal EFDC model. Temperature data was collected vertically at five points across the river at seven different transects (Figure 32). Vertical samples were taken at one-meter intervals to a depth of 4 meters across the Wakulla Spring vent and at a minimum of three depths or every 0.5 m at other locations, whichever was greater. Additional details of thermal profile data collection locations can be found in Appendix C which describes the thermal model creation, calibration, and MFL scenarios.

Table 12: Surface Water Monitoring Locations, Parameters, and Period of Record. *The District previously collected data prior to January 2017.

Station Number	Site Name	Parameter: Period of Record
02326900	St. Marks River Near Newport	Discharge: Oct. 1956 - present Stage: Oct 1956 – present
02327000	Wakulla Spring Near Crawfordville, Fl.	Stage: Jan. 2017 - present Specific Conductivity: May 1954 – present* Temperature: May 2001 - present Nitrate, Nitrite: March 1972 - present Dissolved Oxygen: October 2013 - present Precipitation: May 2017 - present fDOM: August 2015 – January 2017* Turbidity: August 2015 - present Chlorophyll: January 2015 – January 2017
02327022	Wakulla River Near Crawfordville, Fl.	Discharge: Oct. 2004 - present Stage: Oct 2004 – present
749	Wakulla Spring Main Vent	Discharge: May 1997 – August 2015 November 2017 – Present Temperature: May 1997 – August 2015 November 2017 – Present
774	Sally Ward Spring Run	Stage: January 2015 – Present Velocity: December 2016 - Present Discharge: December 2016 - Present pH: August 2015 – Present TDS: August 2015 - Present Temperature: August 2015 – Present Dissolved Oxygen: August 2015 - Present
801	Indian Spring Run	Stage: December 2014 - Present Velocity: December 2014 - Present Discharge: December 2014 - Present
10822	Wakulla Boat Tram	Stage: December 1987 - Present Water Temperature: January 2017 – Present
HD-1	St. Marks River at U.S.98	Stage: July 2016 - Aug. 2017 Temperature: July 2016 - Aug. 2017 Specific Conductivity: July 2016 - Aug. 2017
HD-2	Wakulla River at U.S. 98	Stage: July 2016 - Aug. 2017 Temperature: July 2016 - Aug. 2017 Specific Conductivity: July 2016 - Aug. 2017
HD-3	St. Marks River at San Marcos de Apalachee State Park	Stage: April 2008 – Present Temperature: April 2008 - Present Specific Conductivity: April 2008 - Present
HD-4	St. Marks River at Marker 44	Stage: July 2016-Aug. 2017 Temperature: July 2016 - Aug. 2017 Specific Conductivity: July 2016 - Aug. 2017
HD-5	St. Marks River at Marker 17	Stage: July 2016 - Aug. 2017 Temperature: July 2016 - Aug. 2017 Specific Conductivity: July 2016 - Aug. 2017

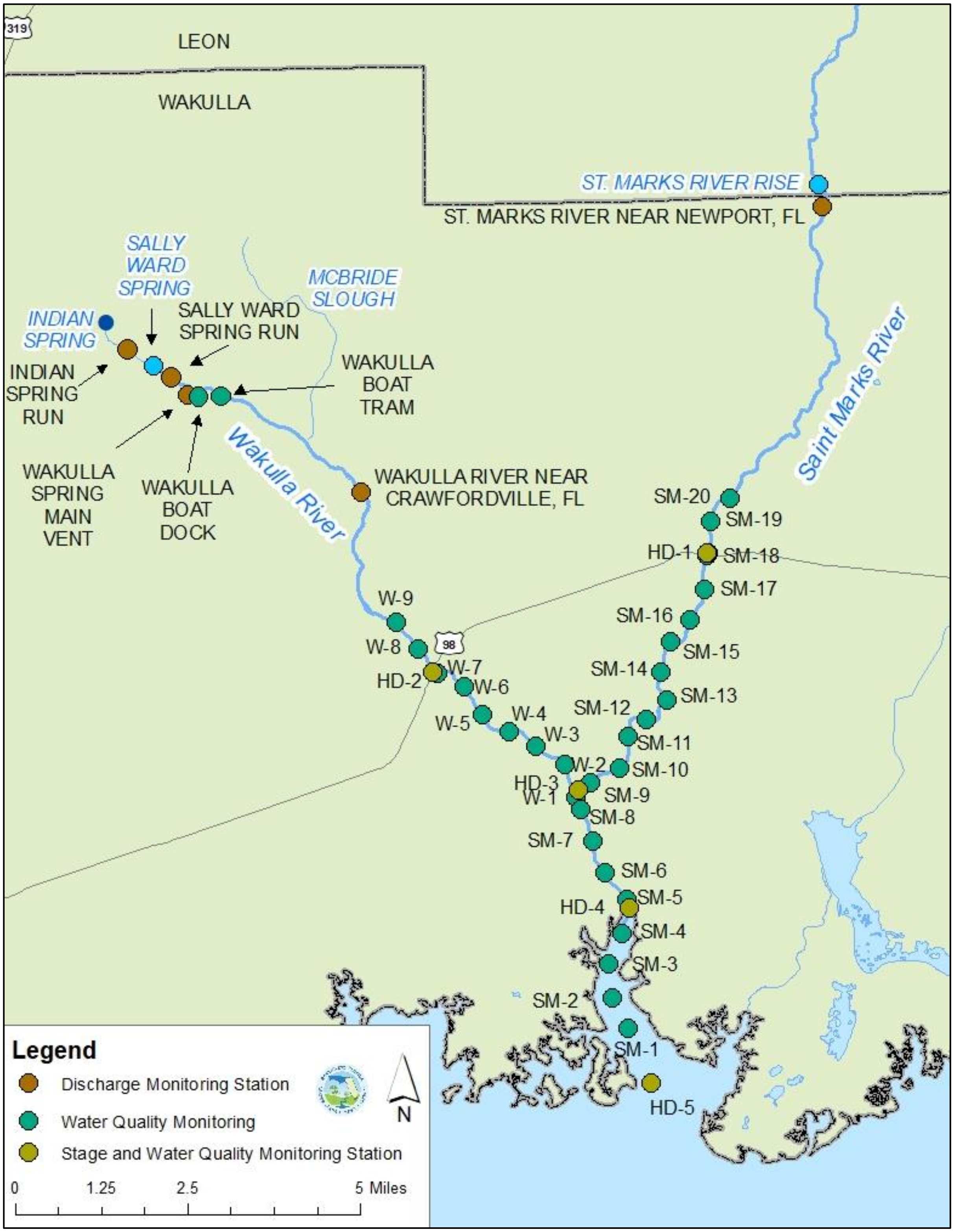

Figure 31: Surface Water Data Collection Stations Used to Determine Minimum Flows. Note: Wakulla Spring is located at the Wakulla Spring Main Vent Monitoring Station.

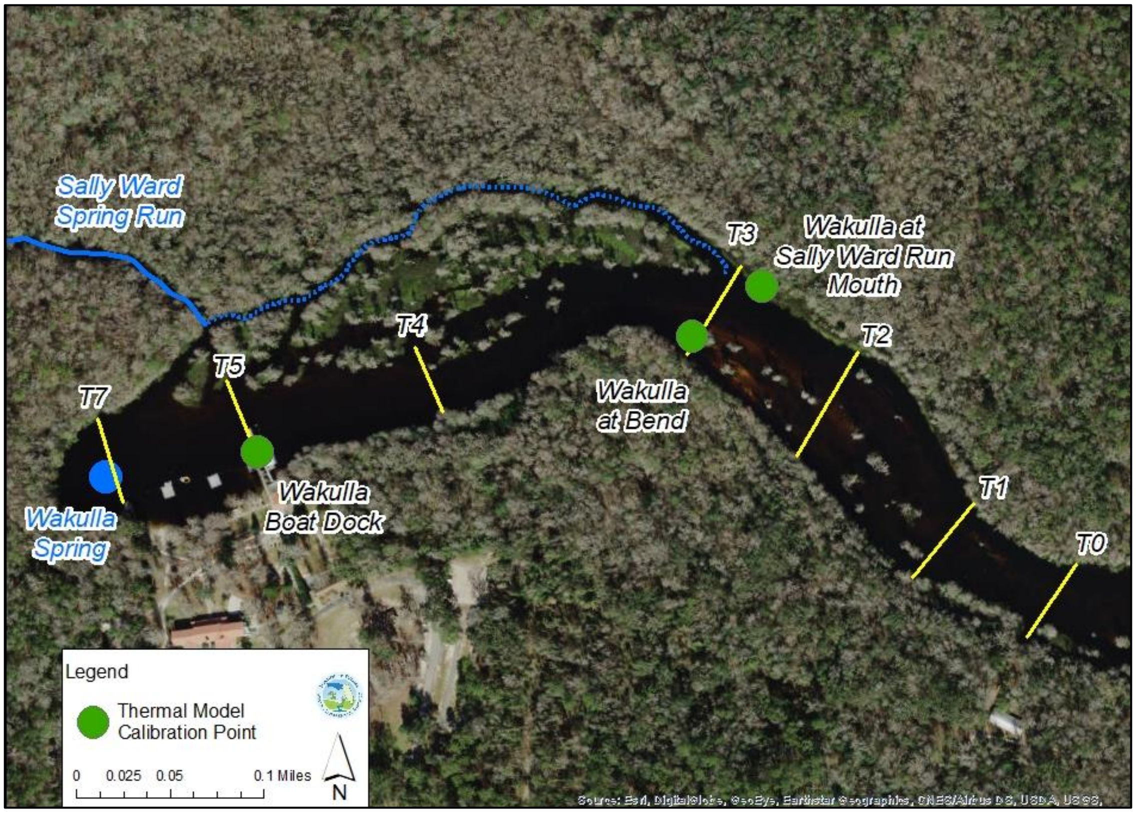

Figure 32: Location of Thermal Profile Data Collection Transects for the Thermal EFDC Model Calibration and Verification.

2.3 Wakulla Spring Discharge Measurements and Record Gap Filling

Discrete discharge measurements have been collected at irregular intervals near the Wakulla Spring vent between February 2, 1907, and December 31, 2019 (Figure 33). Discrete discharge measurements are defined here as direct field measurements of discharge (in contrast to discharge estimates from index velocity, stage-discharge, or other types of ratings) that are made using techniques described in Turnipseed and Sauer (2010). The intervals between manual discharge measurements range from less than 1 day to nearly 16 years.

Discrete discharge measurements are made during a relatively short period of time, typically less than one hour. The Wakulla Spring discharge values estimated using the index velocity method indicate that discharge can vary throughout the day (Figure 34) due to tidal influences. As a result, a single discharge measurement may not be representative of the daily average. In addition, the USGS was unable to verify whether all manual measurements were conducted randomly or if any were targeting specific events such as low or high discharges. The location of many of the discharge measurements was also unable to be confirmed. Many measurements may have been taken downstream near the Shadeville Road bridge (Ron

Knapp personal communication) and as a result may contain significant amounts of inflow added to the river below the main spring vent (more details are provided below concerning additional river pickup). There are multiple large data gaps in the manual measurement discharge time series, which when coupled with the tidal conditions, result in an inability to infer daily mean values from the “instantaneous” manual measurements. Combined with the uncertainty in sampling location, this makes it impractical to use these data for the development of a long-term discharge time series for Wakulla Spring. As a result, the manual discharge measurements prior to collection of continuous discharge beginning on May 10, 1997, were not considered further for direct use in developing a long-term discharge time series for Wakulla Spring. Recent discrete field measurements are conducted in close proximity to the spring vent and are more representative of daily average flow.

Continuous discharge estimates from Wakulla Spring are available beginning on May 10, 1997 and extend through present (Figure 33). Discharge estimates are made using an index velocity relationship between continuously recorded water velocity measured in the Wakulla Spring vent and the volume of water measured just downstream of the main vent. Velocity measurements are currently being collected at a 15-minute frequency.

Several gaps in the continuous discharge time series exist due to equipment malfunction and failure. Multiple options were reviewed for use in gap filling to create as close to a continuous record of spring discharge as possible and are documented in Appendix A. Gap filling was determined to be required in order to obtain a close to a continuous record of spring discharges as possible, especially between 2004 and 2010 when spring flows were increasing at the highest rate. Gap filling was used rather than hindcasting due to the changing relationship between Wakulla Spring flows and Shadeville Hwy flows (Section 2.8). At a result, gap filling was only conducted on periods following the initiation of data collection activities by the USGS at Station 02327022 on October 23, 2004. After review, it was determined that a LOESS regression using a 0.5 smoothing factor between Godin tidally-filtered spring discharge and Godin tidally filtered discharge measured downstream at USGS Station #02327022, Wakulla River Near Crawfordville, Fl. was the most appropriate method for gap filling. This LOESS regression was chosen based on its ability to account for a changing relationship through time between Wakulla Spring vent discharge and discharge measured downstream at USGS Station 02327022 (Figure 35). The LOESS regression proved to be useful for gap filling as number of days with missing flow estimates was reduced from 2,479 days to 570 days. Regression statistics showed that all smoothing factors provided a relatively good fit to the data and differences in RMSE and residuals were relatively small. A smoothing factor of 0.5 was selected based upon its ability to incorporate a relatively large amount of information around the estimated data point, without over-smoothing the time series. In addition, this regression provided the most appropriate distribution of residuals of those modeled.

Gap filling using this method was only possible following the initiation of data collection activities by the USGS at Station 02327022 on October 23, 2004. Additional details of regression analysis are provided in Appendix A. Following gap filling, the number of days with no Wakulla Spring Discharge data was reduced from 2,479 to 570 for the period extending from May 10, 1997 through December 31, 2019 (Table 13).

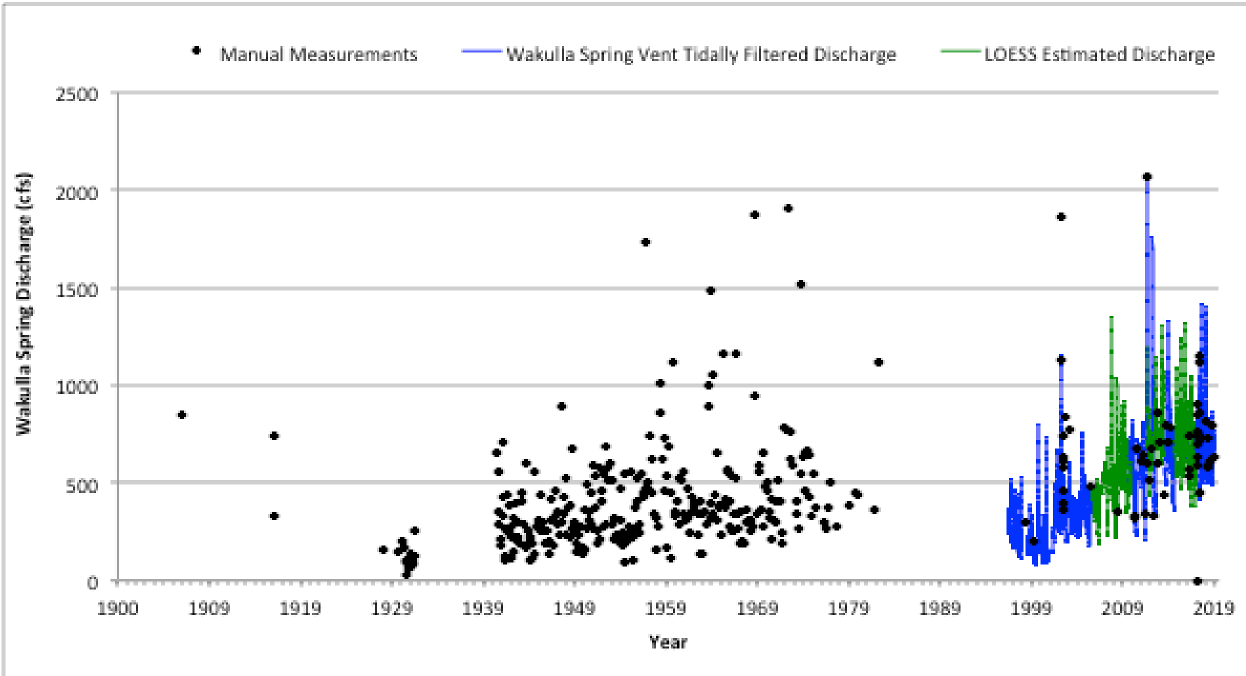

Figure 33: Available Wakulla Spring Discharge Data

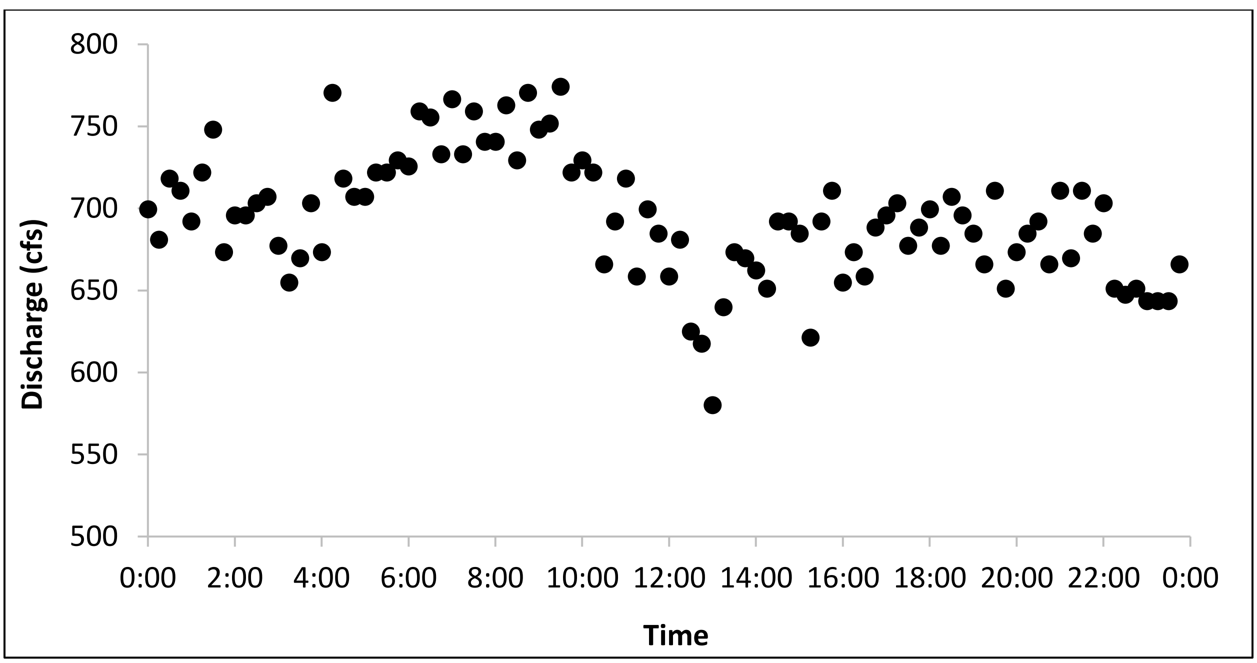

Figure 34: Tidal Variations in Index Velocity Estimated Wakulla Spring Discharge Observed on December 9, 2017

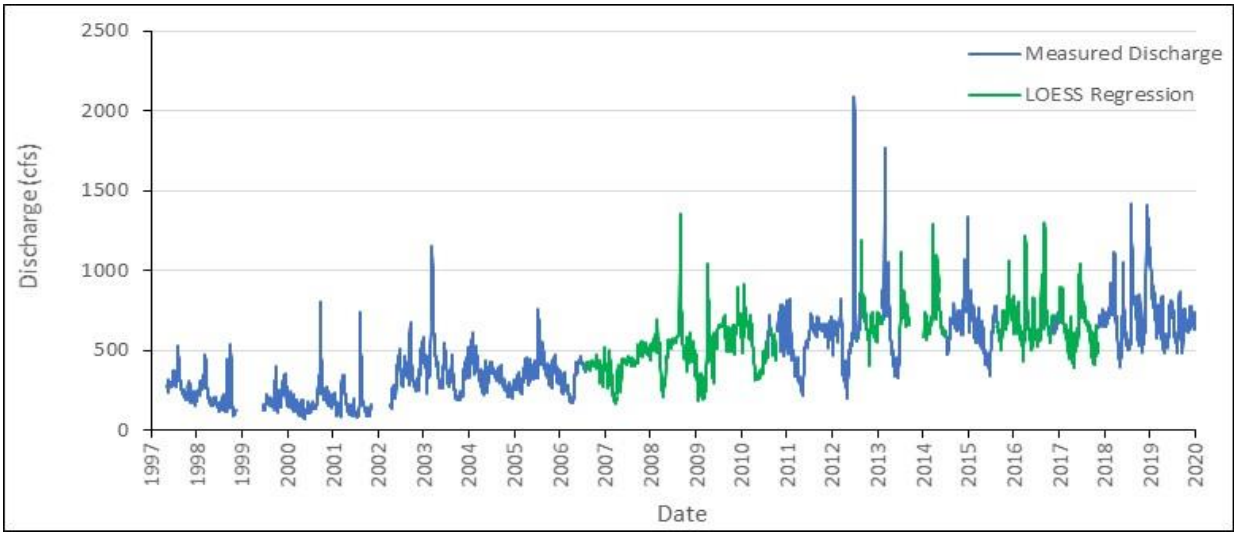

Figure 35: Full Composite Wakulla Spring Discharge Time Series from May 10, 1997, through December 31, 2019

Table 13: Gaps in the Wakulla Spring Continuous Discharge Time Series Before and After Gap Filling Exercise.

Start time	End Time	Number of Days Before Gap Filling	Number of Days After Gap Filling
October 20, 1997	October 24, 1997	5	5
November 12, 1998	June 18, 1999	219	219
November 3, 2001	April 13, 2002	163	163
July 31, 2006	July 21, 2010	1453	8
August 23, 2010	October 21, 2010	60	0
February 14, 2011	February 18, 2011	5	5
May 27, 2011	May 31, 2011	5	5
July 25, 2012	July 30, 2012	6	0
August 23, 2012	February 9, 2013	172	3
June 23, 2013	July 15, 2014	388	140
August 27, 2015	August 27, 2015	1	1
November 30, 2015	December 18, 2015	19	19
March 13, 2018	March 13, 2018	1	1
March 15, 2018	March 16, 2018	2	2

2.4 Trends in Wakulla Spring Discharge

Descriptive statistics, based on the composite Wakulla Spring discharge time series from May 10, 1997, through December 31, 2019 are shown in Table 14. Unlike most Florida springs, discharge from Wakulla Spring has increased over time. The average Wakulla Spring discharge for the full period of the composite discharge time series is 482 cfs, ranging between 72 cfs and 2,086 cfs. Wakulla Spring discharged an average of 575 cfs of water each day between October 23, 2004, and December 31, 2019. During this period, Wakulla Spring flows ranged between 168 cfs and 2,086 cfs.

Flow duration curves presented in Figure 36 further depicts recent changes in Wakulla Spring discharge. Comparison of flow duration curves from 1997 to present with 2012 to present depict significant increases in flow, particularly during low flow conditions where differences are greatest. This indicates that low flow conditions which were once prevalent occur less frequently in more recent records.

A box-whisker plot depicting annual variability in flow (Figure 37) suggests increased variability in Wakulla discharge in addition to increases in discharge magnitude over time. Seasonality in Wakulla Spring discharge was assessed by comparing average monthly discharge from May 10, 1997, through December 31, 2019 (Figure 38). Wakulla Spring average monthly discharge fluctuates modestly, ranging from a minimum of 398 cfs in May to a maximum of 545 cfs in December.

Table 14: Wakulla Spring Discharge Composite Time Series Summary Statistics

Period	Min	Mean	Median	Max
5/10/1997-12/31/2019	72	482	476	2,086
10/22/2004-12/31/2019	168	575	586	2,086
1/1/2012-12/31/2019	195	678	660	2,086

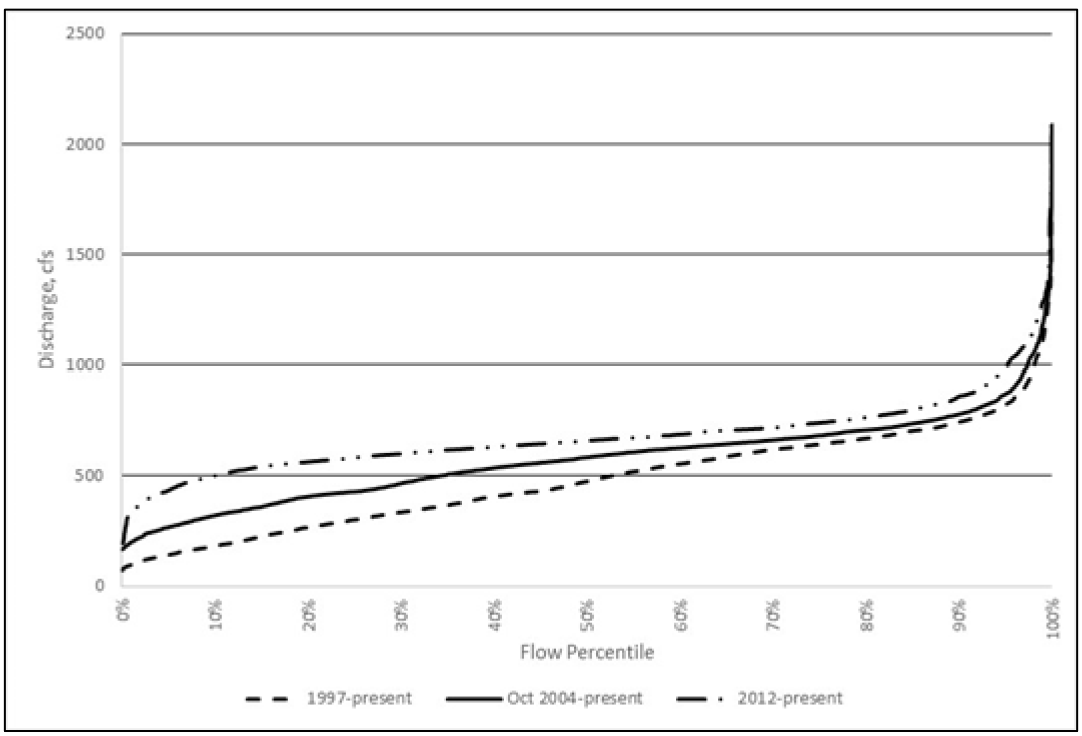

Figure 36: Comparison of Flow Frequency Curves for Wakulla Spring Discharge

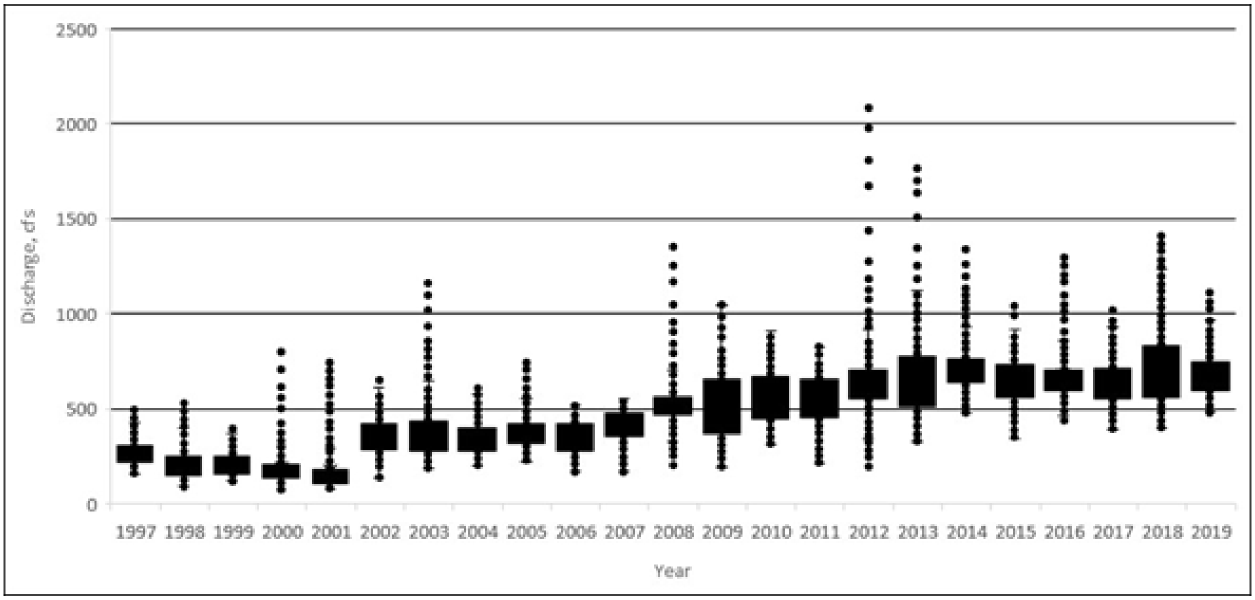

Figure 37: Box-Whisker plot of Wakulla Spring Discharge

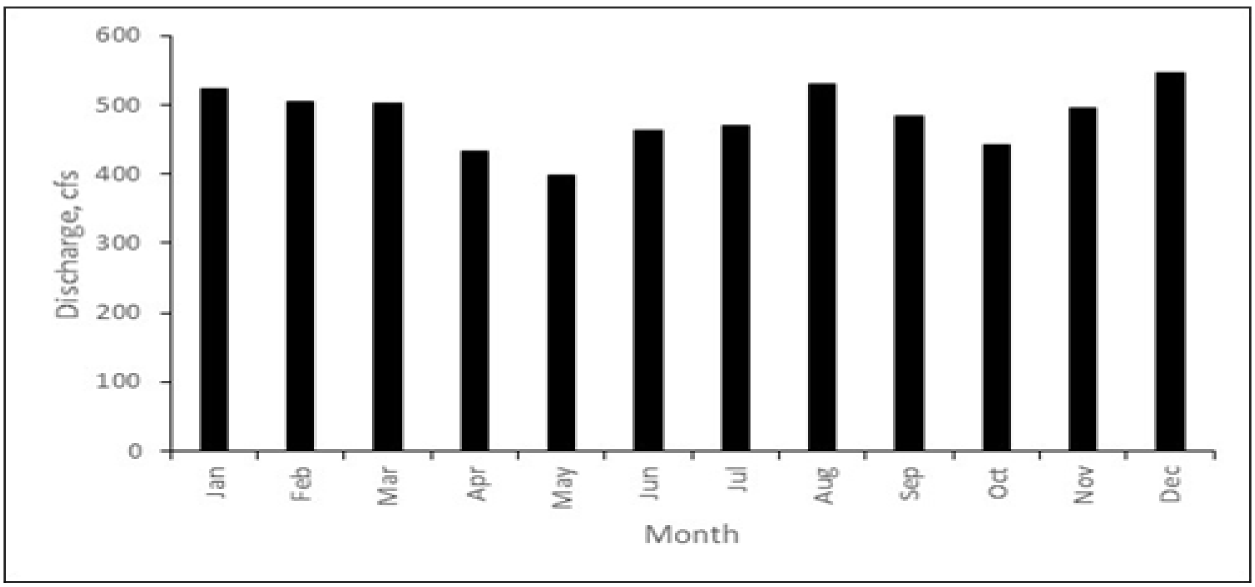

Figure 38: Average Monthly Wakulla Spring Discharge

2.5 Analysis of Wakulla Spring Discharge Increases

Although Wakulla Spring discharge has increased from 1997 to present, the rate of increase has changed during this time period. To investigate the rate of change of Wakulla Spring discharge over time, a 3rd order polynomial was fit to average monthly discharge from May 1997 to December 2019 (Figure 39). Based on this relationship, a non-linear rate of change is apparent. The early portion of the record is characterized by modest increases, followed by a period of accelerated gains in discharge, followed by a recent period with relatively stable discharge. Local extrema and inflection points depicting changes on discharge rate of change were determined from the polynomial fit shown in Figure 39. Based on this equation, a local maximum (y’=0) occurs at x=227 (April 2017). At x=209 (October 2015), y’=1, indicating a point at which rate of increase was beginning to level off. An inflection point (y’’=0) occurs at x=116 (October 2007) indicated the point at which the function goes from concave up to concave down.

A Mann-Kendall trend test was conducted on Wakulla monthly average discharge to determine the point at which increases in flows were no longer statistically significant. This analysis showed that the period from January 2012 through December 2019 displayed no statistically significant trend in Wakulla Spring discharge (p-value=0.902, τ= 0.009). This indicates that spring discharge has been relatively stable since 2012.

A double mass curve comparing cumulative annual precipitation for the Tallahassee Regional Airport and cumulative average annual Wakulla Spring discharge is shown in Figure 40. This analysis indicated a nonlinear relationship between cumulative rainfall and discharge during the 1997 to 2019 period. This suggests that changes in Wakulla Spring discharge have not occurred in proportion to changes in precipitation. Based on this figure, it is likely that during the mid-2000’s when spring discharge increases were greatest, the rate of increase of Wakulla Spring discharge was larger than the proportional change of rainfall, suggesting other factors besides changes in rainfall may have led to the increase in spring flow. Interestingly, cumulative discharge from 2012 to 2019 appears in proportion to cumulative rainfall during this period, coinciding with stabilizing Wakulla Spring discharge. Precipitation at the Tallahassee Regional Airport is further described in Section 1.5.

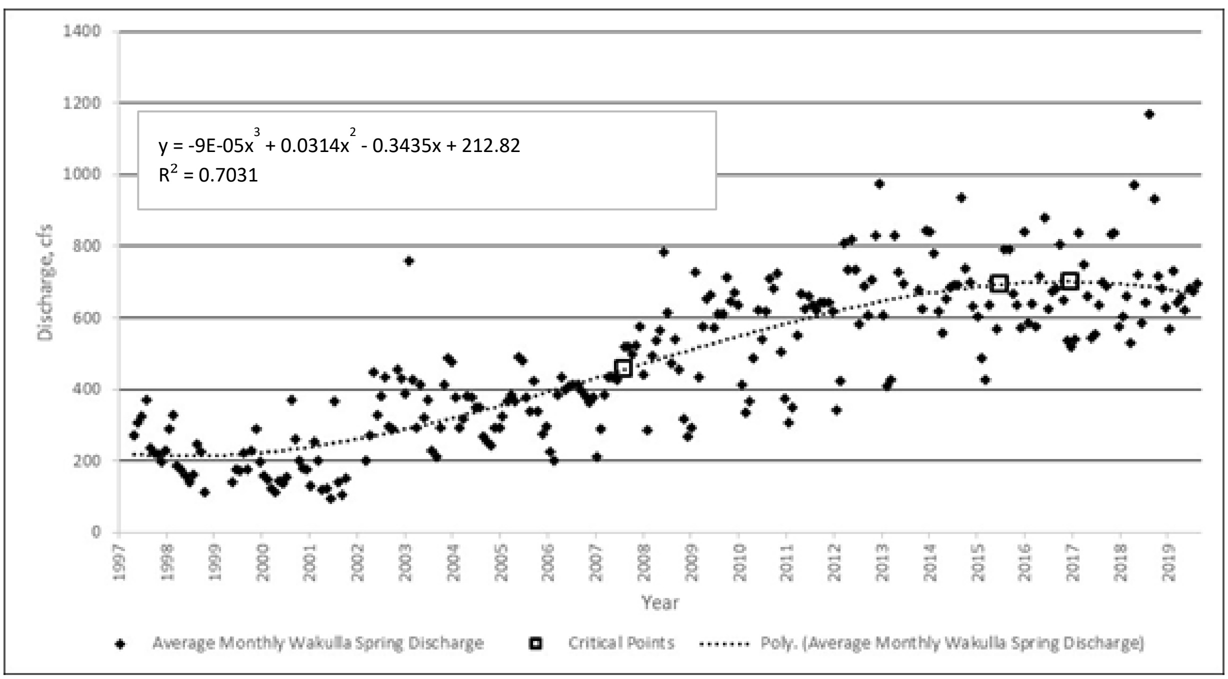

Figure 39: Third Order Polynomial Regression on Average Monthly Wakulla Spring Flows

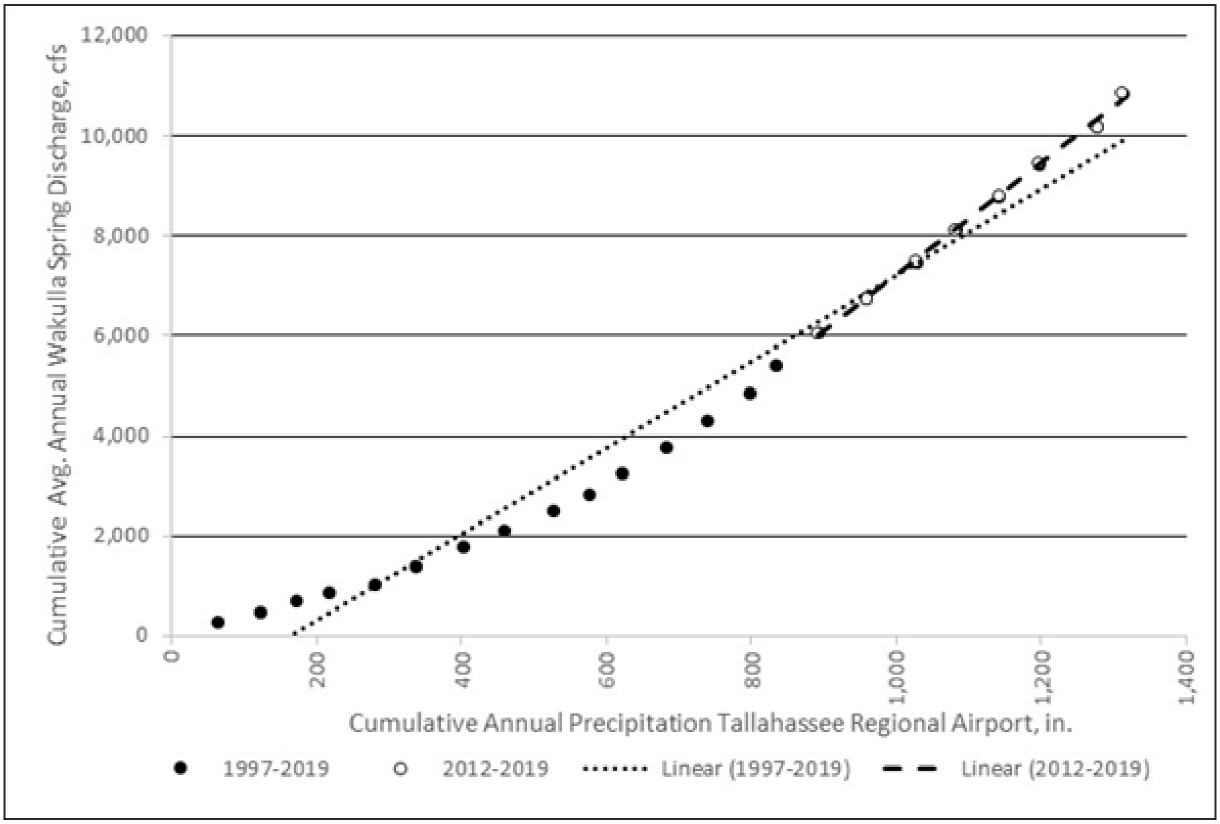

Figure 40: Double Mass Curve for Annual Precipitation at Tallahassee Regional Airport

2.6 Wakulla River Hydrodynamics

Wakulla Spring discharge and Wakulla River stages have been changing during the period of record (May 10, 1997, to December 31, 2019). The relationship between Wakulla Spring discharge and Wakulla River stage has been changing in an inverse manner. Typically, as spring discharge increases, stage along the spring run also will increase. However, in the Wakulla River discharge has been increasing with decreasing river stages.

The early period of record for continuous discharge measurements can be characterized by relatively low discharge volumes combined with high river stages as measured at the Wakulla Boat Tram (Figure 41). The early period extending between May 10, 1997, and October 21, 2004 exhibited Wakulla Spring vent flows with high nitrate concentrations and an increased density of hydrilla, *Hydrilla verticillata* (Figure 42 and Figure 43) (Van Dyke 2019). Hydrilla was first reported near the spring pool in April 1997 and approximately one year later the species dominated the upper portions of the Wakulla River. During this period hydrilla presence was so extensive that it likely created a damming effect on Wakulla River flows and caused an increase in stage. This increase in stage may have reduced the head gradient between local groundwater levels and Wakulla River stage, contributing to the very low spring discharge between 1997 and 2002. The increased vegetation in the river would result in increased channel "roughness," which affects the hydrodynamics of the river system and may have contributed to lower observed flows.

Initially, the DEP conducted a series of hydrilla removal efforts by manually harvesting the vegetation, however, these efforts were unsuccessful. Subsequently, herbicide treatments began in 2002 (Van Dyke 2019). Within one month of treatment, much of the hydrilla damming the Wakulla River flow had been flushed downstream resulting in a decrease in channel roughness and, river stage, and an increase in spring discharge (Figure 35). This increase in water velocity may have resulted in extensive scouring of sediments in the Wakulla River, which further reduced water levels and increased water velocity. Subsequent herbicide treatments have been conducted periodically near the Wakulla Spring Vent to prevent the reestablishment of hydrilla.

Following the herbicide treatments in 2002, discharge from Wakulla Spring displayed an increasing trend for nearly a decade (Figure 35). During this time, the river stage as measured at the Wakulla Boat Tram continued to decline. Following 2012, Wakulla Spring discharge appeared to stabilize with stages continuing to decline. Stage again displayed a sharp decline following Hurricane Michael in October 2018; however, stage has since returned to near pre-Michael conditions. Changes in the stage-discharge relationship have occurred between 1997 and 2019 (Figure 41). The largest variability in stage/flow relationship occurred prior to October 21, 2004, when hydrilla was significantly affecting river stage and discharge.

Field measurements collected at the USGS Station 02327022 (Shadeville Road) further demonstrate changing riverine hydraulics (Figures 44a-c). Cross-sectional area is proportional to river stage and effective channel width, and discharge is equal to the product of cross-sectional area and mean channel velocity. Discharge was relatively stable both at this location as well as at the Wakulla Spring vent after 2012. Therefore, the effects of observed declines in stage and channel width on discharge at this location after 2012 appear to be offset by increased velocity. As discussed further in Appendix D, the addition of ineffective flow areas in the upper portion of the Wakulla River in the HEC-RAS model greatly improved model performance over the model calibration period, suggesting that trends of reduced effective channel width following 2012 documented at Shadeville Road may extend throughout the upper portion of the river. Ineffective flow areas denote sections of river, typically located near edge of bank, where velocities are very low or stagnant. The effective channel width is the width of the channel excluding ineffective flow areas. The results from the HEC-RAS model calibration suggest that areas near the edge of bank are becoming more stagnant (e.g., lower water velocities), and are therefore reducing effective flow area, with the main channel of the river becoming more channelized with increased velocities. This also indicates that the river stage declines have been offset by increased velocities (since flows were relatively stable during this period). This is consistent with observed changes in rating between Wakulla Spring discharge and Wakulla Boat Tram station stage, particularly from 2012-present where rating has changed significantly. A Mann-Kendall Trend test was performed on the Shadeville Rd. field measurements to confirm statistically significant (p-value < 0.05) declining trends in stage and channel width and increasing trends in velocity following 2012. The stage at Shadeville Rd. is influenced by tidal fluctuations, resulting in increased variability in stage compared to the boat tram station.

The data and analysis presented herein, as well as insights gained from HEC-RAS model calibration, suggest that recent observed declines in stages along the Wakulla River are likely due to changes in river morphology. A review of the available data from two wells located approximately one mile northwest of Wakulla Spring indicate no apparent trends in groundwater levels in the vicinity of Wakulla Spring (Refer to Section 4.3 of Appendix A for details). Additionally, groundwater withdrawals have been stable since 1995, indicating that withdrawals are not the cause of observed river stage declines. Flow along Wakulla River appears to be gradually becoming more channelized, with increased velocities in the main channel, and expanded areas of low velocity or ineffective flow near the banks of the river. Any observed decrease in stage appears to be offset by increased velocity, as demonstrated by trends in recent years when Wakulla Spring flow has appeared to stabilize. Changes in river morphology may in part be due to extensive scouring of sediments in the Wakulla River as well as changes in submerged aquatic vegetation cover throughout the upper portions of the Wakulla River.

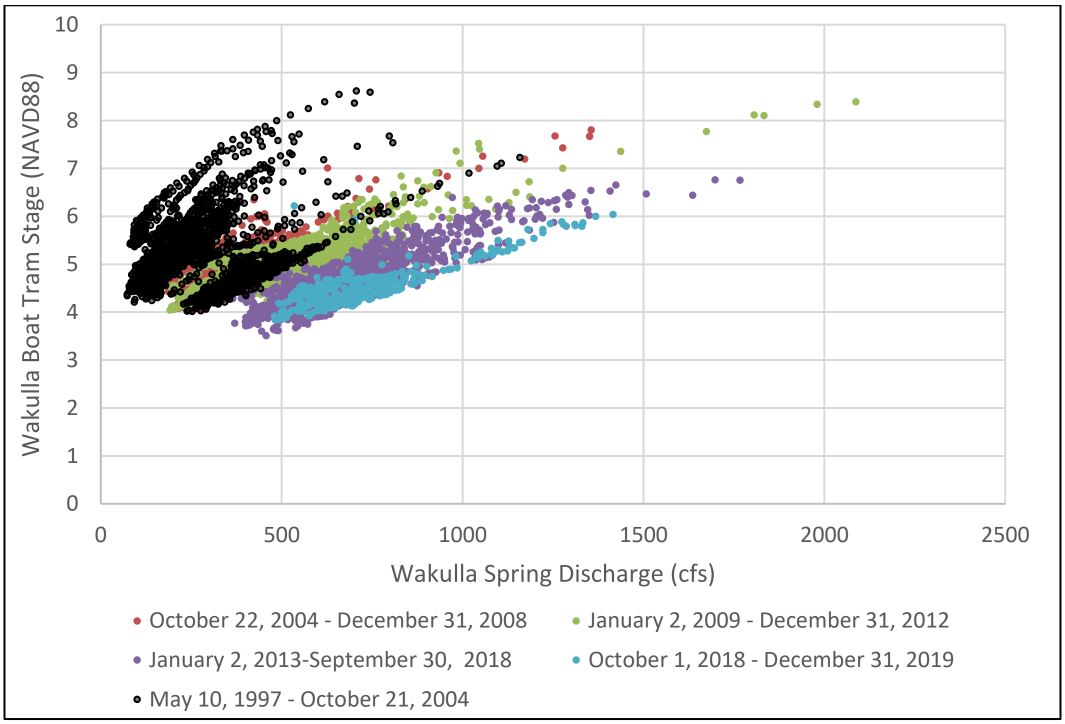

Figure 41: Changes in the Relationship Between Wakulla Spring Discharge and Wakulla Boat Tram Stage from May 10, 1997, through December 31, 2019

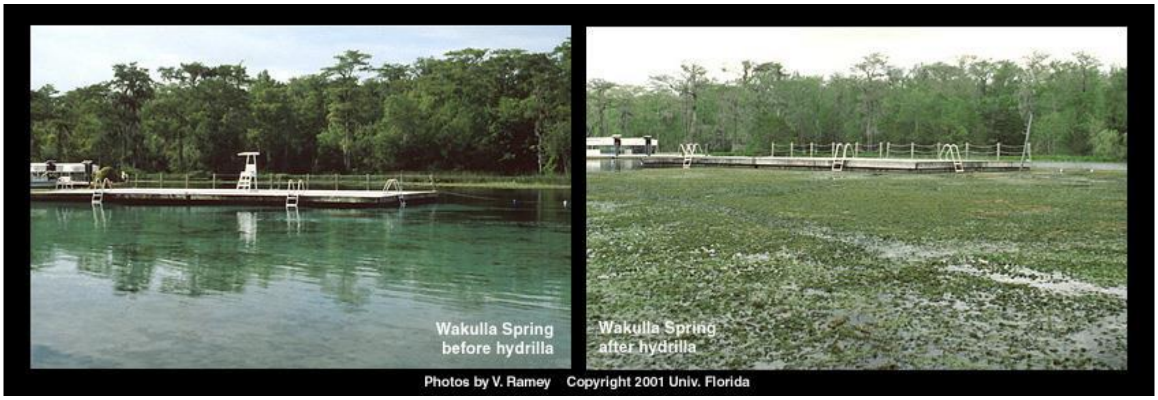

Figure 42: Wakulla Spring Pool Before and After Hydrilla Presence. Photo reproduced from Van Dyke 2019

Figure 43: Hydrilla in the Wakulla River Looking Upstream Towards the Wakulla Boat Dock. Photo reproduced from Van Dyke 2019

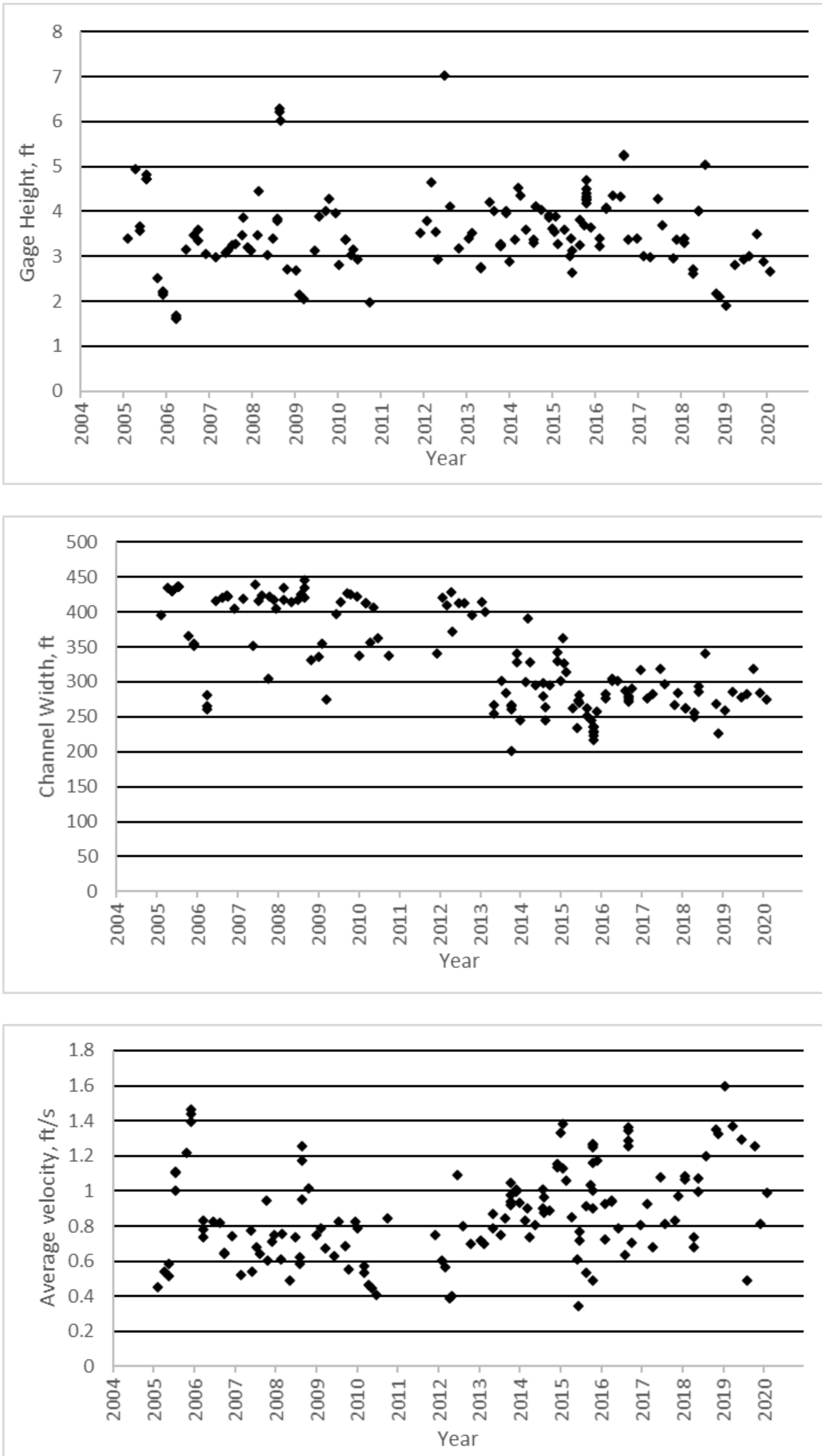

Figure 44: (a) Manual Gage Height, (b) Manual Channel Width, and (c) Manual Average Water Velocity Measurements at USGS Station 02327022 (Shadevile Rd.)

2.7 Flows Measured at USGS Station 02327022

The United States Geological Survey has been continuously measuring Wakulla River flows approximately five miles downstream from the Wakulla Spring vent since October 22, 2004, at USGS Station 02327022, Wakulla River Near Crawfordville, Florida. Estimates of flow for a full day are available since October 23, 2004. Flows measured at the Wakulla Spring vent and at the USGS station near Shadeville Road are highly correlated (Appendix A), however, a comparison of flow data from this station with that from the Wakulla Spring vent indicated that the relationship between the two stations has changed through time. In the early period of overlapping data (2004 to 2006) a significant amount of additional inflow occurred between the two stations (Figure 45). This additional inflow or “pickup” has changed through time and currently little pickup is observed between the two stations, with the exception of additional flow from Sally Ward Spring inflow. The sources of additional pickup between the Wakulla spring vent in addition to Sally Ward Spring include flow from several small springs between the Wakulla Spring main vent and USGS Station 02327022, periodic inflow from McBride Slough, and diffuse groundwater pickup. The period of significant pickup (2004 to 2006) corresponds to the period of significant Wakulla Spring flow increases whereas the period of minimal pickup (2012-2019) corresponds to the period of Wakulla Spring flow stabilization. This may suggest that groundwater flows which were historically associated with Wakulla River small spring discharge and diffuse pickup now flow directly out of the Wakulla main vent, which could be a contributing factor toward increased observed Wakulla Spring discharge.

Due to the changing pickup through time as well as the Wakulla River being in flux for much of the time following hydrilla removal, a statistical relationship between Wakulla River flows and Wakulla Spring flows to backcast Wakulla River flows would be unreliable. As a result, Wakulla River flows prior to October 23, 2004 were not estimated.

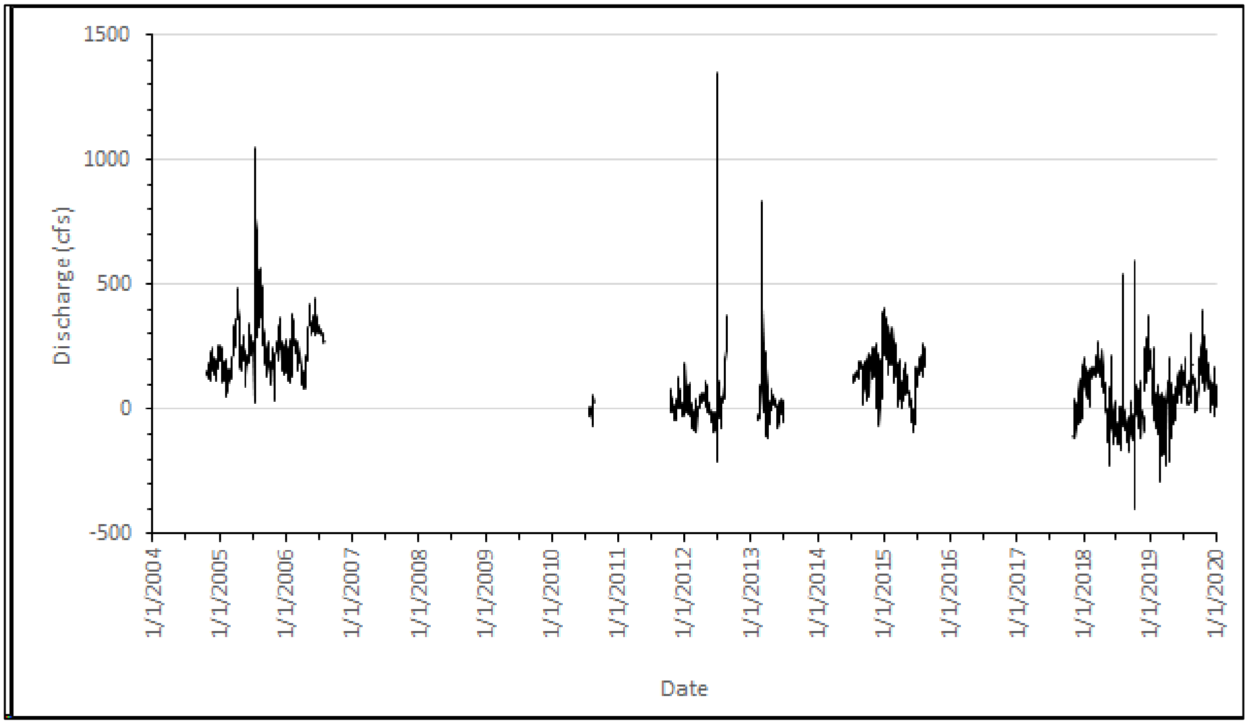

Figure 45: Observed Difference between Wakulla River Flows at downstream USGS Station 02327022 and Wakulla Spring Vent, 10/22/2004 through 12/31/2019

2.8 Groundwater Withdrawals

As indicated in Section 1.5, the combined groundwater contribution area for Wakulla Spring and the Spring Creek Spring Group encompasses 483 square miles in Florida and parts of southwest Georgia. Tracer tests performed at Bird Sink suggest that the Wakulla Spring and Spring Creek Spring Group groundwater contribution area may also overlap the contribution area for the St. Marks River Rise, which is also a first magnitude spring. Groundwater withdrawals within the combined Wakulla Spring and Spring Creek Spring Group groundwater contribution area are used for public supply, industrial/commercial/institutional, agriculture, power generation, and recreational uses. The total annual withdrawals are relatively small when compared to total inflow to this region, as represented by the annual rainfall, and have remained stable for the past two decades (Figure 46).

A water budget developed for the combined groundwater contribution area (Table 15) indicates that groundwater extractions comprised less than 1% of total inflows in 2009 and 2014. During 2011, which was a drought period, groundwater withdrawals comprised approximately 2% of the total inflow. This is a conservative estimate because additional returns resulting from irrigation and septic systems are not included in these estimates. Withdrawals within the Wakulla Spring groundwater contribution area have remained relatively stable since 1995, during which time the daily discharge at Wakulla Spring displayed an increasing trend (Figure 46, Figure 35). The City of Tallahassee represents the largest single use within the Wakulla Spring groundwater contribution area. Their withdrawals have been stable since the mid-1990s, using 25.69 mgd in 1995 compared to 25.63 mgd in 2015. In addition, per capita water use for the City of Tallahassee has decreased from 155 gal/person/day in 1995 to 125 gal/person/day in 2015, in part due to enhanced water conservation efforts by the City. Additionally, more than 50 percent of the amount of water pumped by the City of Tallahassee is returned to the aquifer system via the City of Tallahassee Southeast Sprayfield. In 2015, a total of 17.1 mgd was applied at the sprayfield resulting in a net groundwater withdrawal of 8.53 mgd. High hydraulic loading rates at the sprayfield combined with pervious sediments and an unconfined Floridan aquifer result in high recharge rates (Davis 2007).

Withdrawal effects in the region, while relatively small, affect not only Wakulla Spring but rather are distributed across multiple components of the water budget including reductions in diffuse groundwater discharge to rivers and streams connected to the Floridan aquifer, and submarine groundwater discharge to the Gulf of Mexico. The available information combined with the long-term increase in spring discharge indicate that withdrawal effects on Wakulla/Sally Ward Spring flow are minimal and are offset by other mechanisms causing spring discharge to increase. As a result, it was determined that adding additional flow to the Wakulla Spring baseline discharge time series to account for estimated withdrawal effects was inappropriate, as this would artificially inflate the spring flow time series.

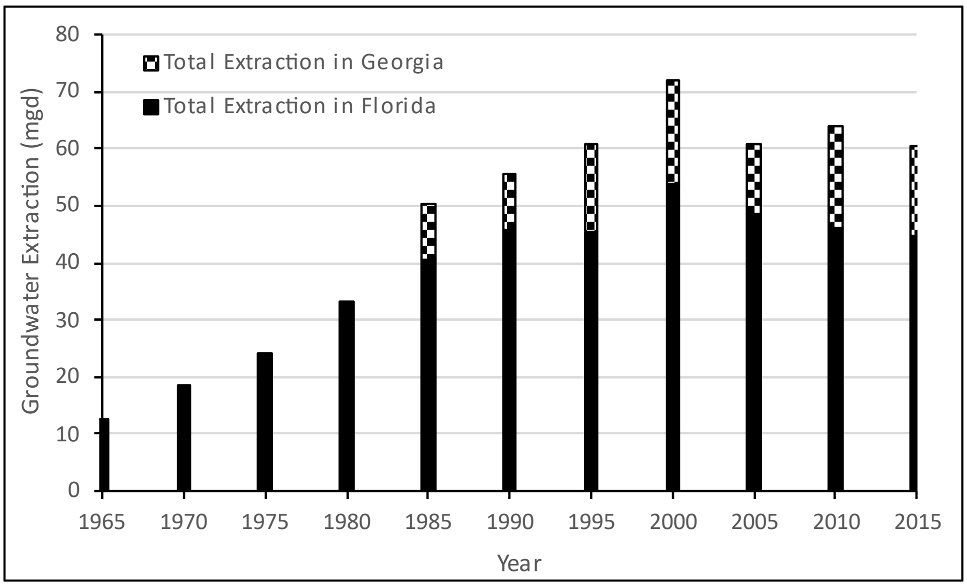

Figure 46: Groundwater Extraction in the Wakulla Spring GWCA between 1965 and 2015

Table 15: Wakulla – SCSG Groundwater Contribution Area Annual Water Budget (in/yr)

Year	Rainfall (in/yr)	COT Sprayfield Returns (in/yr)	Total Inflows (in/yr)	Spring Discharge (in/yr) (1)	Runoff (in/yr)	Withdrawals (in/yr)	ET (in/yr)	Total Outflow (in/yr)	Residual (in/yr) (2)
2009	69.93	0.17	**70.10**	4.96	10.22	0.65	37.0	**52.83**	**17.27**
2010	52.79	0.17	**52.96**	6.33	8.89	0.63	37.0	**52.85**	**0.11**
2011	39.42	0.15	**39.57**	3.51*	3.08	0.76	37.0	**44.35**	**-4.78**
2014	68.36	0.18	**68.54**	6.10	11.95	0.60	37.0	**55.65**	**12.89**

(1) Combined discharge from Wakulla Spring and Spring Creek Spring Group. Estimated discharge from the Spring Creek Spring Group was not available for 2011.

(2) The Residual term includes unquantified water budget components such as diffuse groundwater outflow to streams and rivers, discharge to 3rd magnitude and smaller order springs, and diffuse aquifer discharge to the Gulf of Mexico.

2.9 Mechanisms of Wakulla Spring Discharge Increase

As discussed previously, the discharge at Wakulla Spring exhibits an increasing trend over much of the baseline time period, with flows being relatively stable since 2012. Multiple mechanisms have been proposed for the observed increase in Wakulla Spring discharge. Due to the complex hydrology and geology of Wakulla Spring and the adjacent Floridan aquifer, there are likely multiple mechanisms that contribute to the observed increase in flow. Mechanisms that are supported by available data include:

(1) Changes Wakulla River hydraulics

(2) Long-term sea level rise has increased the equivalent freshwater head at the coast, which has contributed to flow reversals at the Spring Creek Spring Group and associated changes in head gradients in the adjacent Floridan aquifer, resulting in intermittent diversions of groundwater toward Wakulla Spring.

Based on tracer test results, the Spring Creek Spring Group, previously described in more detail above, is believed to be connected to Wakulla Spring via conduits although they have not yet been mapped (Kincaid and Werner 2008). As a result, the head difference between Wakulla Spring and the Spring Creek Spring Group can have significant impacts on the discharge at both locations. Rising sea levels in the estuary containing the Spring Creek Spring Group are increasing the equivalent freshwater head at the coast. Additionally, the water surface elevation of the Wakulla River near the Wakulla Spring pool has shown a reduction during the last several decades, which further impacts the head difference between the Wakulla Spring pool and the equivalent freshwater head near the Spring Creek Spring Group. The changes in these head differences in combination with below average rainfall since approximately 1996 (Figure 10) may be reducing freshwater discharge from the Spring Creek Spring Group. During periods when the Spring Creek Spring Group is not flowing or is under reversal conditions (Figure 47 – reversal indicated by shaded areas), the change in local head gradients in the Floridan aquifer may result in redirection of some flow toward Wakulla Spring and may be contributing to increasing flow at Wakulla Spring. Additional explanation of this process is described by Davis and Verdi (2014). Additionally, the decrease in the stage in the upper Wakulla River and spring pool may influence the local head gradient between the Floridan aquifer and Wakulla Spring. As discussed previously in this report, the change in spring pool and river stage is due to changes in the hydrodynamics of the river channel.

As indicated previously, groundwater withdrawals have been stable since 1995, as indicated by pumpage estimates and are likely not the cause for observed increases in springflow. The available aquifer level data is consistent with the pumpage estimates in that it does not indicated any regional pumpage impacts. Trend analyses of changes in Floridan aquifer levels at monitor wells were performed for period of record and post-1995 (Table 16). Caution should be used when comparing the period of record trend results, as the time periods used in the analysis vary among wells. For the post-1995 period, 10 of the 13 wells evaluated exhibit no statistically significant trends indicating that no regional declines have occurred, and aquifer levels have generally been stable. Two Floridan aquifer monitor wells exhibited increasing water levels: Wakulla Parks and Recreation monitor well and the NWFWMD HQ monitor well. One well, “C. Donahue Deep” Floridan well (total depth = 157 ft; cased depth = 113 ft) exhibited a declining trend, however, the shallower Floridan aquifer well at the same site, "C. Donahue" (total depth = 80 ft; cased depth = 56 ft) exhibited no trend. Hydrographs for each well, a map of well locations, and additional discussion of this trend analyses are provided in Appendix A.

The two Floridan aquifer monitor wells located closest to Wakulla Spring having relatively long periods of record are NWFID 7494 - Nitrate #3 (total depth = 270 ft; cased depth = 250 ft) and NWFID 7495 - Nitrate #4 (total depth = 70 ft; cased depth = 50 ft). Both are located at the same site, which is approximately one mile north of Wakulla Spring. These two wells have 13 and 17 years of record, respectively. Trend analysis results are only reported for wells with 20 or more years of data; however, visual examination of the hydrographs for the Nitrate #3 and Nitrate #4 wells do not indicate any apparent water level declines (Figures 48 and 49).

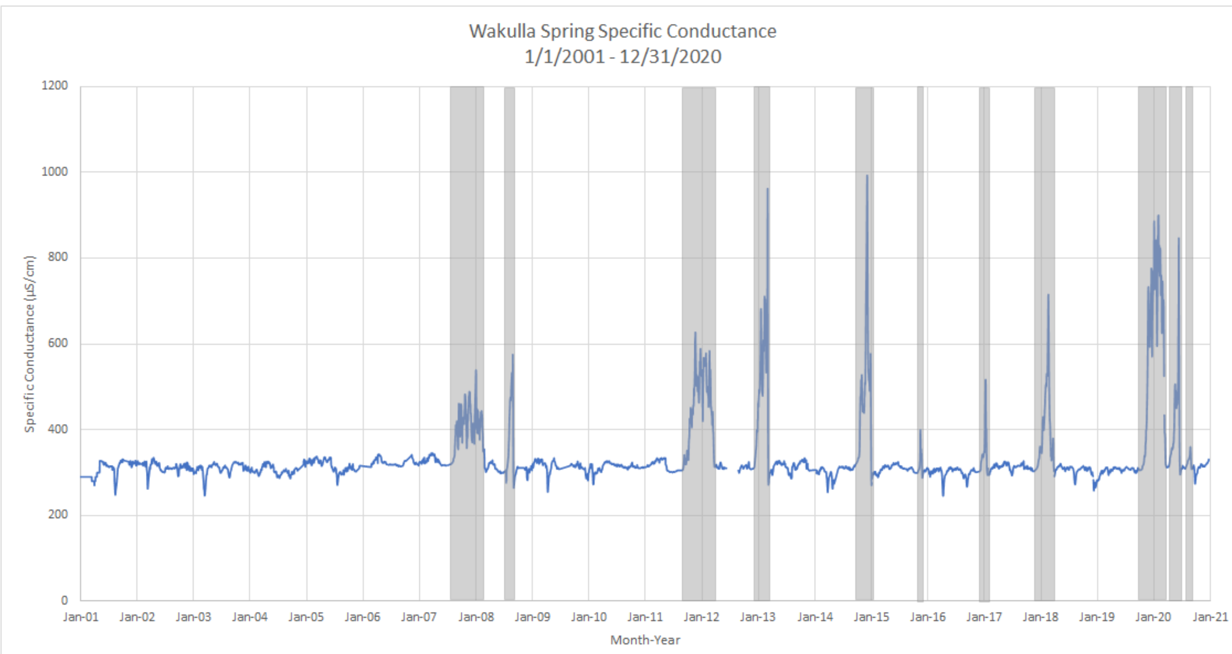

Figure 47: Specific Conductance Measured at Wakulla Spring between January 2001 and December 2020.

Table 16: Results of Mann Kendall Trend Test on Monitor Wells within the Wakulla Spring GWCA.

Station Number	Station Name	Period of Record Analysis			Analysis of Period from 1995 to 2020		
		Number of Annual Medians	p-value	Slope	Number of Annual Medians	p-value	Slope
977	C. DONAHUE	34	0.088	-0.016	26	0.191	-0.022
978	C. DONAHUE DEEP	31	0.010	-0.032	25	0.016	-0.041
3413	IFAS #4	32	0.541	-0.029	26	0.761	-0.020
2691	LAFAYETTE PARK	71	0.008	-0.057	21	0.538	0.063
3402	LAKE JACKSON FLORIDAN	55	0.009	-0.091	26	0.657	0.068
342	LESTER LEWIS	46	0.314	--	15	--	--
671	NEWPORT RECREATION	60	0.001	-0.011	26	0.575	-0.009
7494	NITRATE #3	13	--	--	13	--	--
7495	NITRATE #4	17	--	--	17	--	--
3340	NWFWMD HQ FLORIDAN	40	0.699	0.020	26	0.038	0.171
3156	OLSON RD./S677	44	0.039	-0.089	26	0.710	-0.025
965	OTTER CAMP FLORIDAN	34	0.077	0.026	26	0.118	0.026
635	USGS ARRAN WORK CENTER	44	0.258	-0.014	26	0.498	-0.029
392	USGS BENCHMARK	53	0.077	-0.010	25	1.000	0.000
372	WAKULLA PARKS AND RECREATION	34	0.029	0.036	26	0.018	0.062
305235084125101	12F036	57	0.008	0.147	26	0.168	-0.151

Note that the results are not reported for samples with less than 20 years of data. Period of record results reported for the Lester Lewis site are from a Wilcoxon-Rank Sum Test rather than a Mann Kendall Trend Test. Mann Kendall tests (Mann, 1945) were implemented using the Mann Kendall function from the R programming language Kendall Package (R Core Team, 2020; McLeod, 2015). The Wilcoxon Rank Sum tests (Wilcoxon, 1945) were implemented using the wilcox.test the R programming language Stats Package (R Core Team, 2020).]

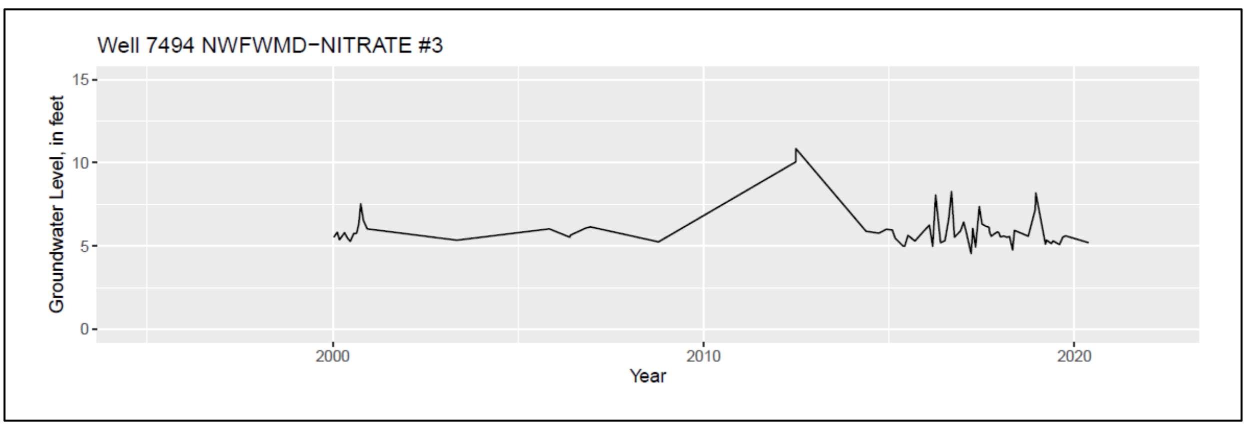

Figure 48. Mean Daily Aquifer Level at Monitor Well NWFID 7494 – Nitrate #3

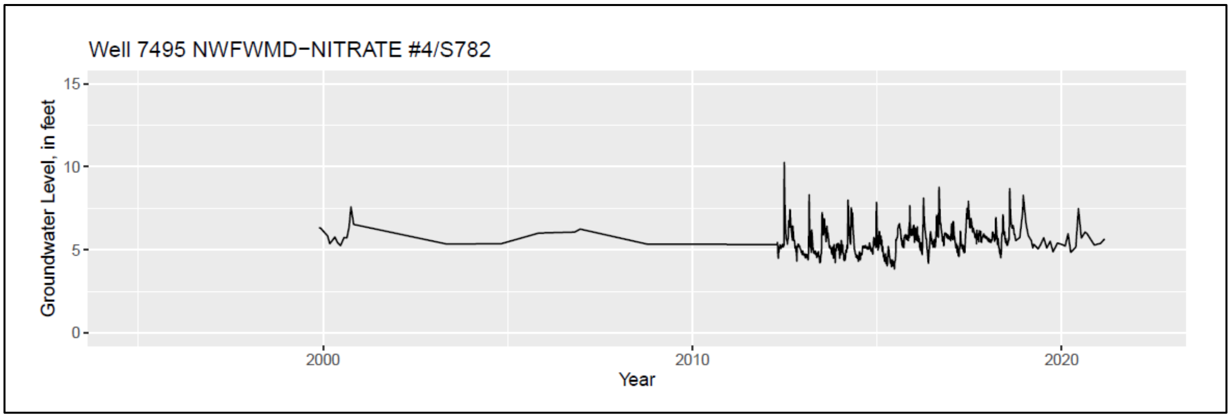

Figure 49. Mean Daily Aquifer Levels at Monitor Well NWFID 7495 – Nitrate #4

2.10 Wakulla Spring Baseline Time Series Selection

The period of record between May 10, 1997, and December 31, 2019, was available for consideration as a baseline time series of continuous data for Wakulla Spring discharge. Manual discharge measurements were not considered for baseline flows since their collection dates could not be verified as being collected randomly and the extensive data gaps present which in some cases extended nearly 20 years. As previously described, the period prior to hydrilla removal (2002) was an impacted system and was likely not representative of the general conditions in the Wakulla River, particularly in relation to the stage-discharge relationship. As a result, the Wakulla River stage and discharge data observed between 1997 and 2002 was determined to not be representative of natural or unimpacted conditions. Furthermore, discharge estimates from the USGS Station 02327022 are required for input into the HEC-RAS model and these flows could not be reliably estimated prior to October 23, 2004, due to a changing volume of water added to the Wakulla River between the spring vent and Shadeville Road. As a result, Wakulla River and Wakulla Spring flows prior to October 23, 2004, were not considered further for MFL evaluation. As a result, the period of flows identified for Wakulla Spring MFL analysis extends from October 23, 2004, through December 31, 2019. The period of record for Wakulla Spring flows used in MFL analysis is presented in Figure 50 and Figure 51. During this time, spring flows averaged 575 cfs and ranged between 168 cfs and 2,086 cfs.

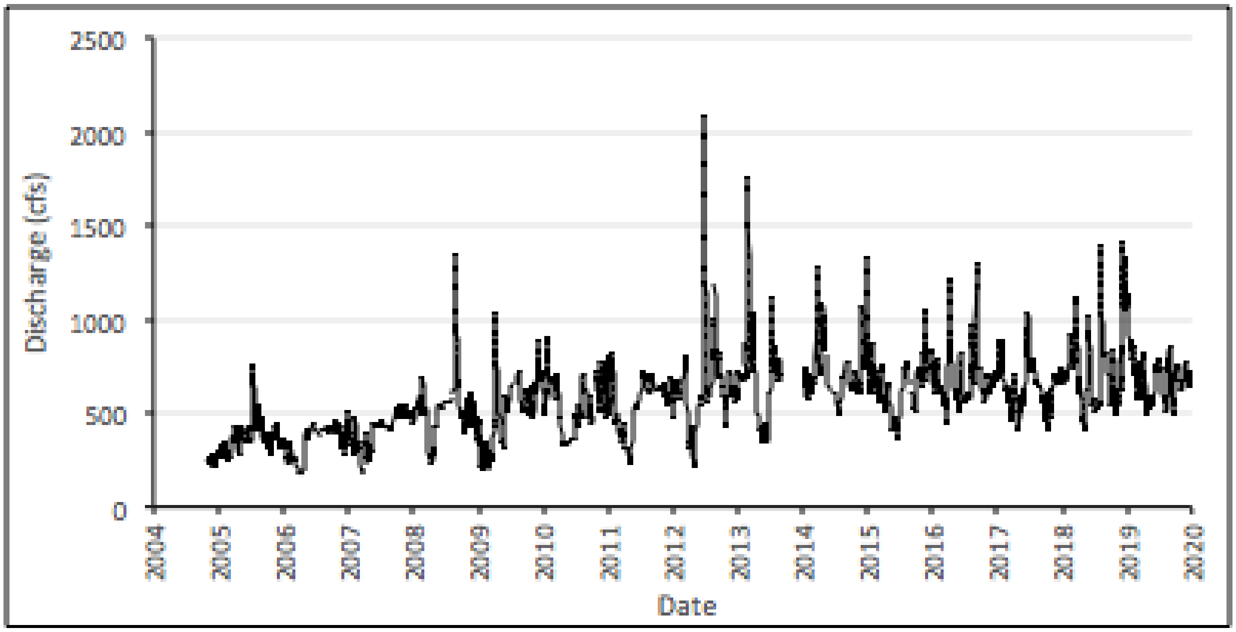

Figure 50: Average Daily Flows for Wakulla Spring (October 23, 2004through December 31, 2019)

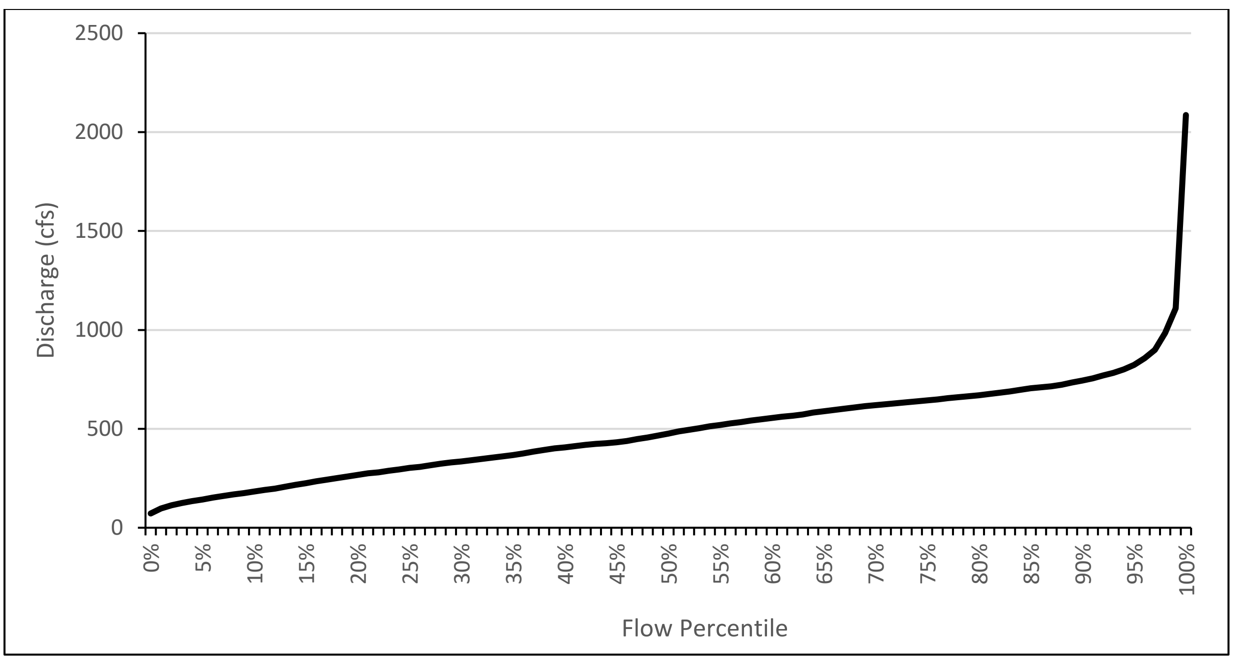

Figure 51: Flow Frequency Curve for Wakulla Spring (October 23, 2004 through December 31, 2009)

2.11 Tidal Influence on the Wakulla River

Due to its proximity to Apalachee Bay and the Gulf of Mexico, stage and discharge in the Wakulla River is tidally influenced. The most downstream location of the Wakulla River at the St. Marks River confluence (i.e., River Station 0.0) is extremely tidal, with water surface elevations fluctuating by up to approximately 4 ft (Figure 52). Downstream boundary conditions represent the observed water surface elevations present at the downstream extent of the study area (i.e., the confluence of the Wakulla and St. Marks Rivers). The influence of tides (downstream t boundary conditions) diminishes moving upstream to the Wakulla Spring pool (River station 48252.78) where water levels generally fluctuate by less than 0.2 ft between the 95 percent exceedance and 5 percent exceedance downstream boundary conditions. Tidally-influenced downstream boundary conditions become more important than spring flow in determining water surface elevations downstream of approximate river station 26000 which is near the Shadeville Road bridge and the USGS Wakulla River near Crawfordville station 02327022 (River Station 32483.62).

Wakulla River flow varies considerably according to tide and location on the river. Near the confluence of the rivers, river flow varies considerably due to tidal fluctuations (Figure 53). During one complete tidal cycle on August 23, 2017, peak outflow (falling tide) and inflow (rising tide) Wakulla River discharge ranged from approximately 4500 cfs to -3500 cfs with a net outflow of 695 cfs. Approximately 3.2 miles downstream from the Wakulla Spring vent at USGS station 02327022 (Wakulla River Near Crawfordville Florida) river flow ranged from 822 cfs to 203 cfs on August 23, 2017.

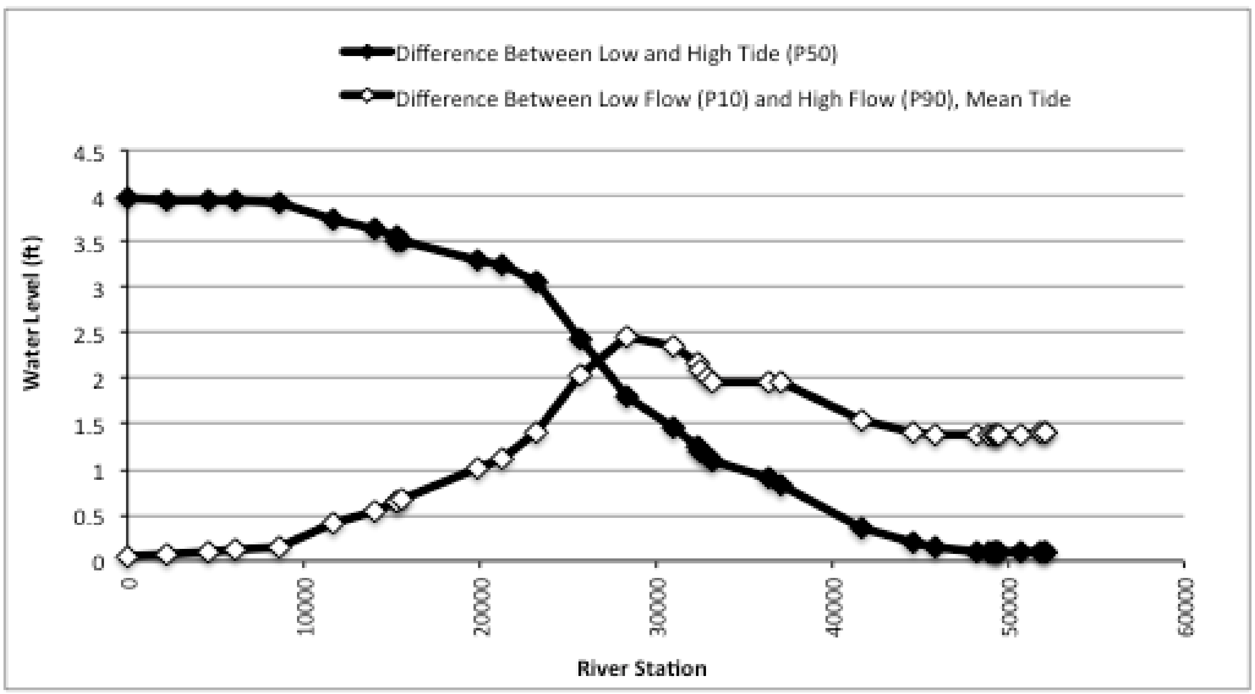

Figure 52: Range of Water Level Variability Between Low and High Downstream Boundary Conditions and Between the 10 percent and 90 percent Spring Flows as Modeled Using HEC-RAS Output

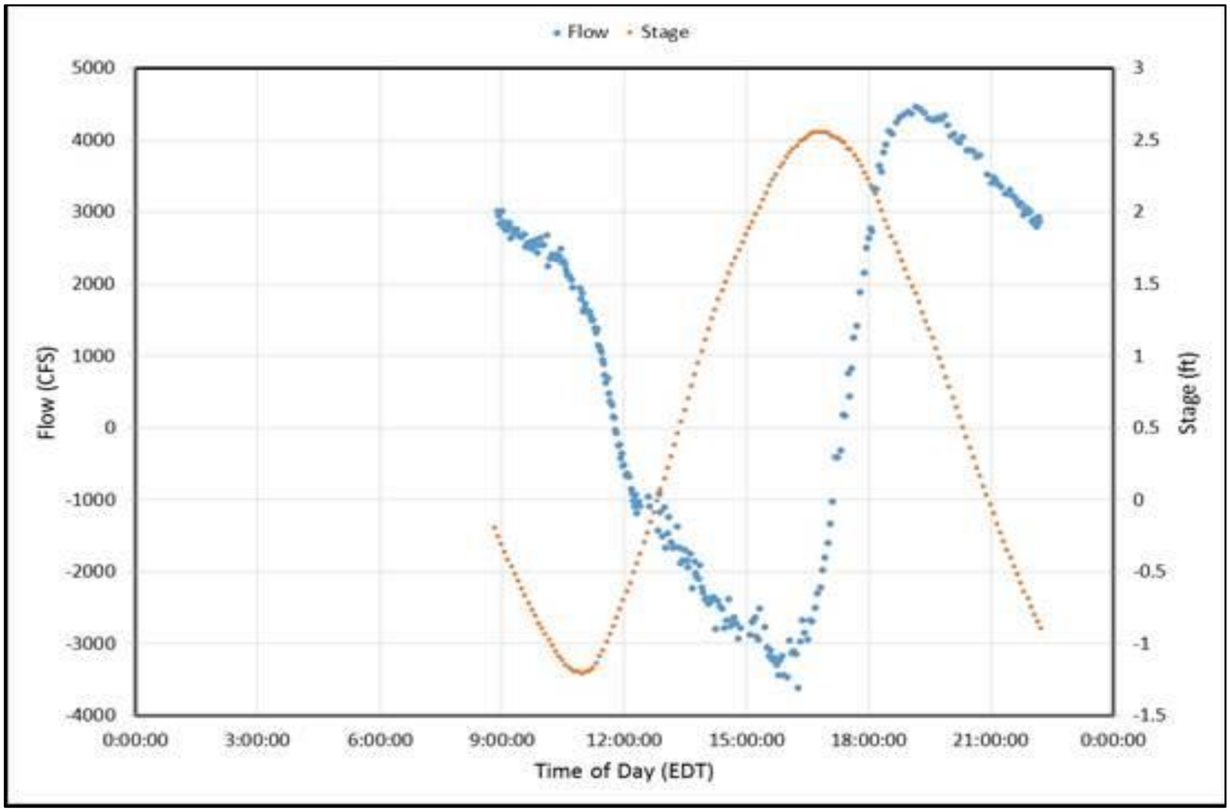

Figure 53: Stage and Discharge Measured on the Wakulla River Near the confluence with the St. Marks River During One Complete Tidal Cycle on August 23, 2017. Figure reproduced from ATM (2017).

2.12 Sally Ward Spring Discharge

Discrete discharge measurements were collected using either an acoustic doppler current profiler (ADCP) or an acoustic doppler current (ADC) meter along the Sally Ward Spring run (between the spring vent and confluence with the Wakulla River). No additional surface water inputs were present at the time of discrete discharge measurements and flows were within the spring run banks. A total of 96 manual discharge measurements have been taken between October 22, 1997, and October 19, 2019 (Figure 54).

Continuous stage and velocity from Sally Ward Spring is monitored at a pedestrian bridge approximately 0.5 miles downstream from the spring vent near the confluence with the Wakulla River (Figure 31). Measurements are taken at 15-minute intervals and began on December 2, 2016, continuing through present. Continuous discharge at Sally Ward Spring is estimated using the index velocity method described by Levesque and Oberg (2012). Unlike Wakulla Spring, discharge at Sally Ward Spring is minimally tidally influenced and as a result tidally filtering the discharge data was not necessary.

Approximately 0.75 miles to the northwest is Indian Spring. Indian Spring has an average daily discharge of 0.59 cfs making it a 4th magnitude spring. Discharge from Indian Spring is relatively small (<1 cfs) and is hydrologically isolated from Sally Ward Spring during normal conditions. However, during periods of excessive rainfall, a slough connecting the two springs becomes inundated and surface water drains into the Sally Ward Spring pool where it combines with Sally Ward Spring discharge. Continuous monitoring of surface discharges entering the Sally Ward spring pool from the Indian Spring slough are monitored with a continuous recorder located at the County Road 61 bridge over the slough (Figure 31). Discharge measurements are collected at hourly intervals beginning on December 18, 2014 and continue through present. Discharge measurements were estimated using the index velocity method described by Levesque and Oberg (2012).

In order to determine the volume of water discharging from Sally Ward Spring, discharge flowing into the Sally Ward spring pool (as measured at the CR 61 bridge using the index velocity method) was subtracted from that measured at the Sally Ward Spring run pedestrian bridge (Figure 55). This provided a more accurate estimate of discharge from Sally Ward Spring (Figure 55). Between December 1, 2016, and September 10, 2019 contributions from the Indian Spring run accounted for an average of 2.7 percent (median 0 percent, range 0 percent to 76 percent) of the flow measured at the Sally Ward discharge monitoring station.

The Sally Ward Spring continuous discharge period of record contained a total 223 days of missing values. Multiple regression models using other data sources were investigated as potential methods for infilling data gaps in order to produce a continuous daily discharge time series for MFL determination. After review, no method produced satisfactory results and no gap infilling was conducted to extend the Sally Ward period of record flows. Additional details are provided in Appendix A.

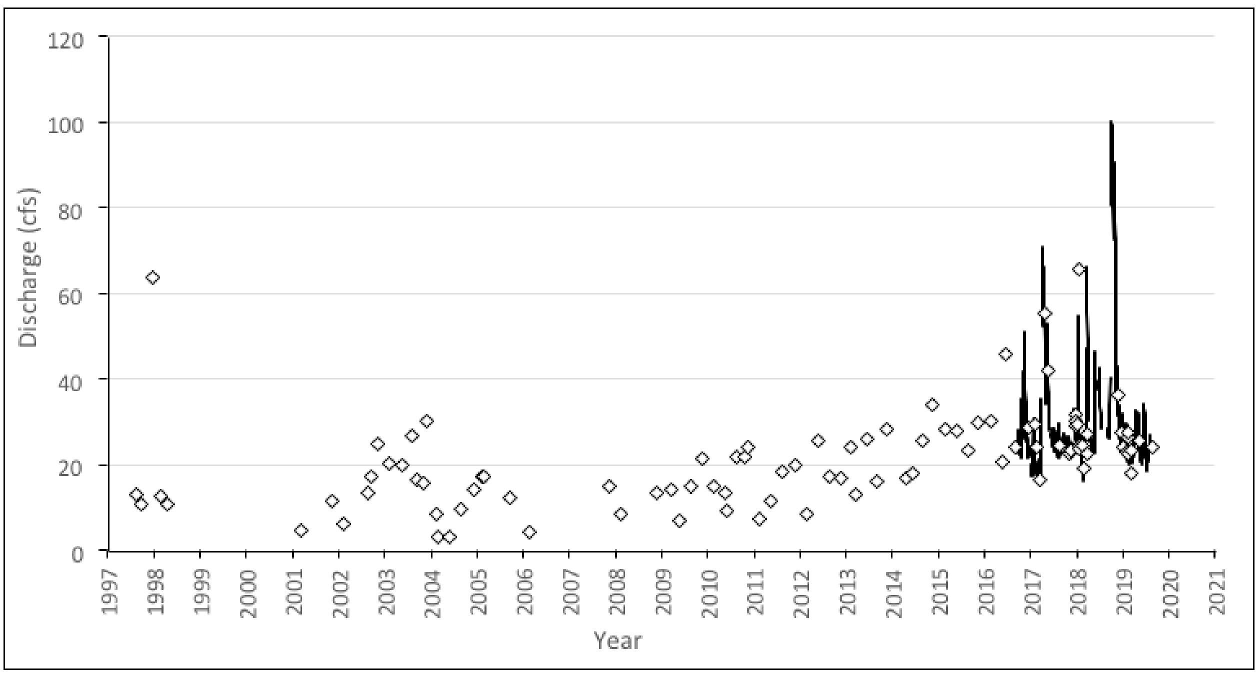

Figure 54: Available Sally Ward Spring Discharge Data

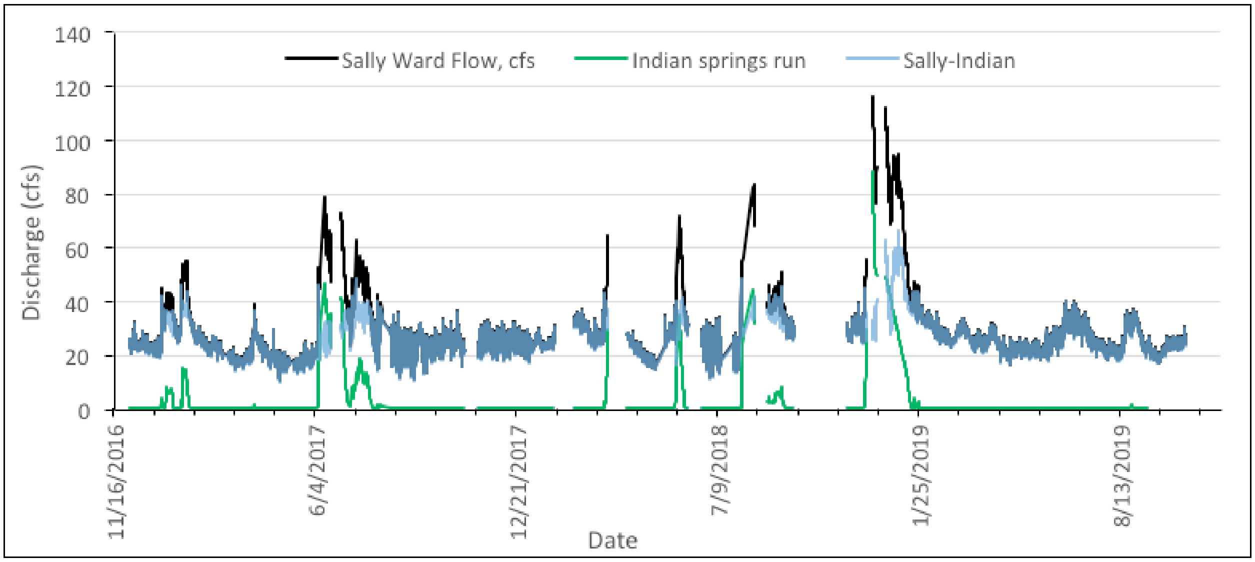

Figure 55: Sally Ward Spring Run, Indian Spring Slough, and Sally Ward Spring Discharge

2.13 Trends in Sally Ward Discharge and Spring Run Hydrodynamics

As with Wakulla Spring, Sally Ward Spring displays an increasing trend in discharge between 1997 and 2019 (Figure 54). Elevated levels of hydrilla in the Sally Ward Spring run have been reported by District staff when conducting discrete measurements which may have caused a similar damming effect and increased water levels while reducing spring discharge. In addition, stages along the Sally Ward Spring run are likely experiencing a backwater effect from the Wakulla River. As a result, stages in the Sally Ward Spring run are affected by stages in the Wakulla River.

The Sally Ward Spring run was hydrologically altered when it was dredged to a depth of approximately 5 ft prior to 1972. The spring run is relatively straight with spoil from the previous dredging efforts deposited on the bank. This spoil has since been recolonized with native vegetation. At the spring run stages greater than 6.44 ft NAVD88, which occur infrequently during large rainfall events, water may leave the channel and enter the floodplain where it can bypass the velocity sensor and not be accounted for in spring discharge estimates. For the period of record where Sally Ward Spring run stage data is available (January 9, 2015 through December 31, 2019), daily average spring run stages exceeded 6.44 ft NAVD88 approximately 3.7 percent of the time. In addition, when spring run discharge leaves the channel it is unknown whether this flow returns to the Sally Ward Spring run or is discharged directly into the Wakulla River or spring pool. As a result, Sally Ward flows rarely extend into the floodplain and index velocity discharge measurements are not estimated when spring run stages exceed 6.44 ft NAVD88. A surveyed measuring point to determine stage in the Sally Ward Spring run was not available prior to 2015 and as a result long-term changes in stage were not able to be investigated.

2.14 Sally Ward Baseline Time-Series Selection

The period of record available for Sally Ward Spring Baseline Time Series selection included discrete measurements from 1997 through 2019, and index velocity estimates from December 1, 2016 through December 31, 2019. It was determined that for Sally Ward Spring, discrete discharge measurements comprise the most appropriate time period. The discrete measurements provided a better range of Sally Ward Spring flows and included some lower flows observed during the early portion of the increasing discharge trend. In addition, this period provided an overlapping time period with the Wakulla Spring baseline flow time series and downstream measurements of the combined Wakulla Spring, Sally Ward Spring, and additional pickup flows in the Wakulla River. Due to potential stage and discharge impacts associated with Hydrilla and the previously described Wakulla MFL analysis time period, measurements between October 23, 2004 and December 31, 2019 were selected for MFL analysis. During this time period, Sally Ward Spring flow averaged 23 cfs and ranged between 4 cfs and 66 cfs (Figure 56 and Figure 57).

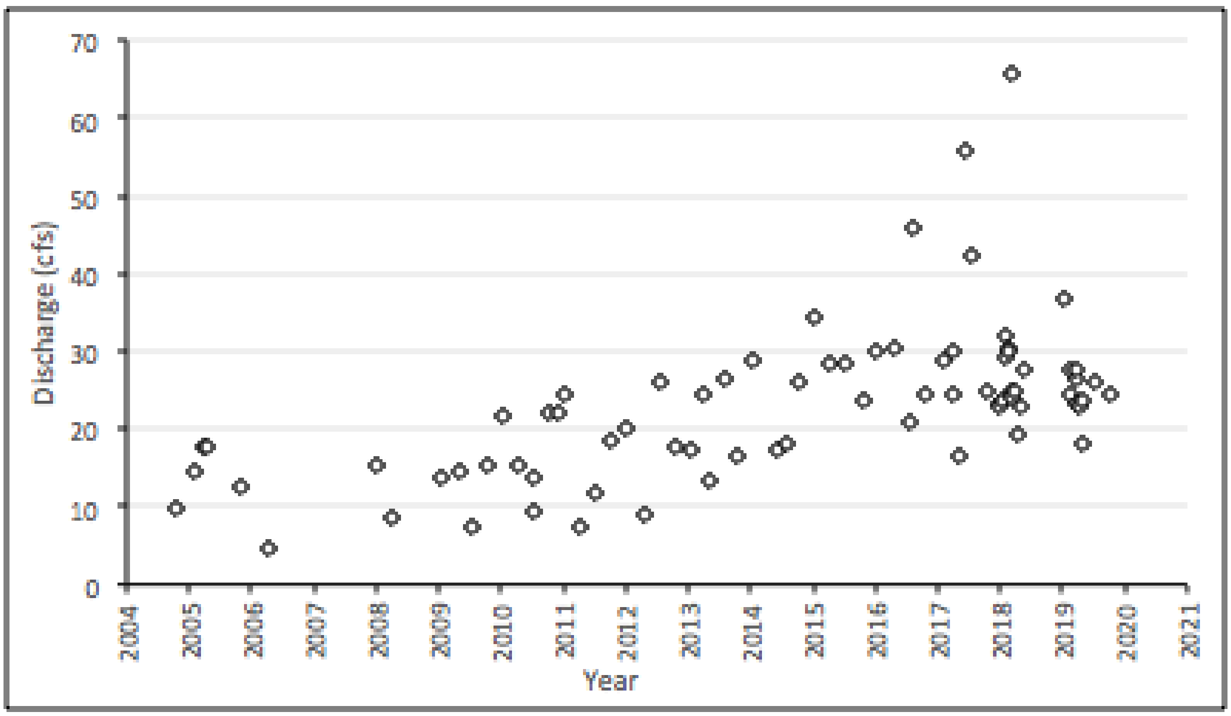

Figure 56: Sally Ward Spring Baseline Time Series Flows (Discrete Measurements 2004 – 2019)

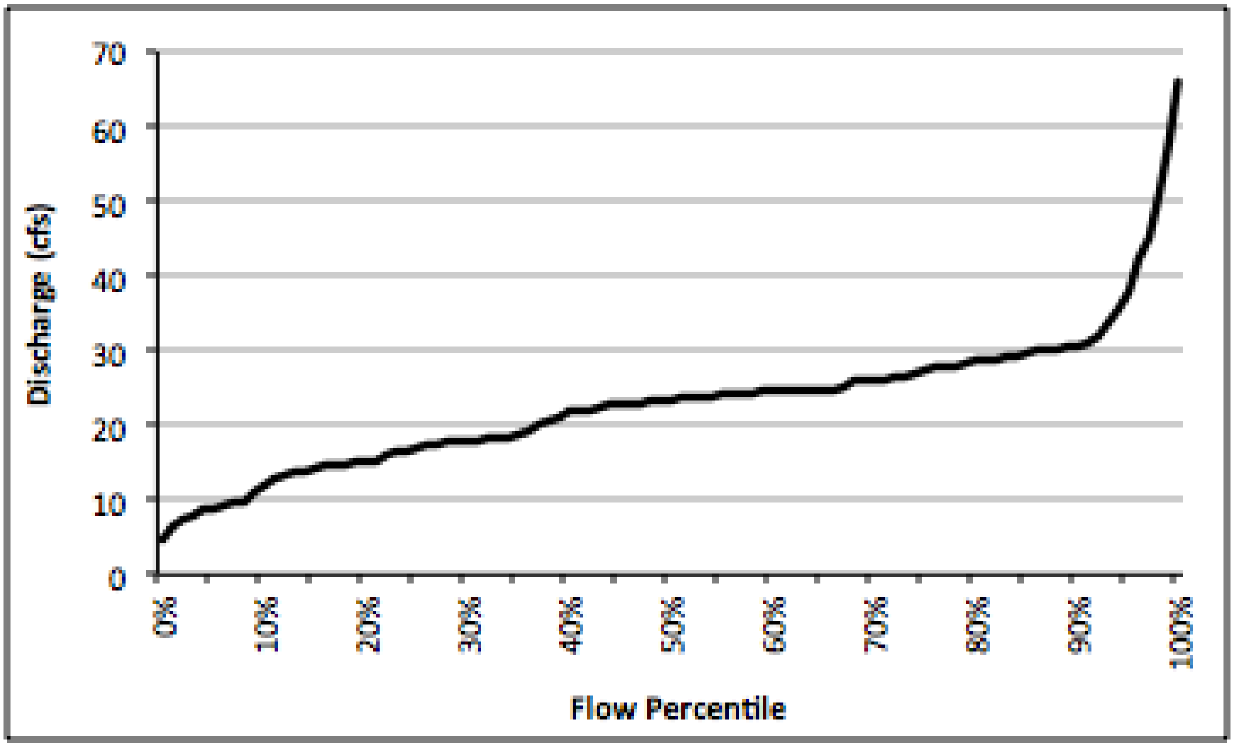

Figure 57: Sally Ward Spring Baseline Time Series Flow Duration Curve (Discrete Measurements 2004-2019)

3 Water Resource Values

The following section presents the consideration of WRVs utilized in the MFL evaluation of Wakulla and Sally Ward springs and the metrics designed to maintain and protect the ecology and water resources of the system. Quantitative data analyses and the methodology for determining the minimum flows that are protective of WRV metrics are provided in Sections 3 and 4.

Section 62-40.473, Florida Administrative Code, lists ten environmental or water resource values (WRVs) that must be considered in the establishment of MFLs (Table 1). While all listed WRVs must be considered, not all may be appropriate for establishing minimum flows for Wakulla and Sally Ward Springs. To determine which WRVs were most appropriate for the Wakulla River, District staff reviewed each WRV based upon three criteria:

1- Potential for significant harm to the WRV as a result of spring flow reductions
2- Relevance to the Wakulla River or Sally Ward Spring run
3- Measurable, quantifiable and can be characterized with available data

All WRVs are discussed below with respect to the three criteria listed above.

3.1 Recreation In and On the Water

The Wakulla River is designated as an Outstanding Florida Water under Florida Administrative Code (Section 62-302.700) and is used for recreation. The Edward Ball Wakulla Springs State Park offers a wide range of recreational opportunities for park attendees including swimming, park sponsored boat tours, and other outdoor activities within state park boundaries. Fishing, scuba diving, canoeing and private boating, while prohibited within the state park, are available to the public downstream of the state park.

3.1.1 Safe Boat Passage

The Wakulla River is utilized by recreational boaters including both Edward Ball Wakulla Springs State Park sponsored tour boats within park boundaries and intensive use by private boat use outside of the park boundaries. Reduced water levels can increase the chances of damage to river substrates (such as prop scarring to SAV habitats) and damage to outboard motors from hard substrates such as the limestone outcroppings present along many parts of the Wakulla River. The intensive recreational boat use along portions of the Wakulla River makes safe boat passage an important MFL metric. Boat use along the Sally Ward Spring run is not permitted. For the Wakulla Spring minimum flow determination, three separate boat passage metrics were utilized to account for different uses along the Wakulla River.

Power Boats – Private boat use is prohibited within the boundaries of the Edward Ball Wakulla Springs State Park; however, the park provides river tours between the spring vent to approximately 1.0 miles downstream. The river tour boats depart the boat dock and travel downstream along the right riverbank (south side of river) and returns upstream along the left riverbank (north side of the river). Along both banks where the boat tour operates are deeper water levels as a result of the structural alterations previously described in Section 1.3.4. The State Park utilizes multiple identical pontoon boats to conduct river tours. When a tour boat was removed from the water for maintenance, the distance between the algae line on the boat and the bottom of the motor was measured to be 3.0 ft. The depth from water line to the bottom of the motor was unable to be assessed using a boat loaded with passengers due to depth and safety restrictions. As a result, a metric of 3.0 ft of water depth across two continuous 20 ft widths along the established tour boat route was used as the safe boat passage metric within the State Park.

Private boat use is allowed below the Shadeville Road bridge. For private recreational boat use in this region, a minimum water depth of 2.0 ft across a continuous channel width of 30 ft was used as the metric to evaluate safe boat passage. This metric has been used in previous MFL assessments and approved by scientific peer review (NWFWMD 2019, SRWMD 2016a).

Canoe/Kayaks - The lower Wakulla River is commonly used for canoeing and kayaking. A privately-owned canoe/kayak rental business located at the intersection of the Wakulla River and the U.S. Hwy 98 bridge is a popular destination for recreational users. The extensive use of the lower Wakulla River for canoeing/kayaking makes safe canoe and kayak passage an appropriate metric for this system.

A minimum thalweg depth of 1.5 ft was used as the metric for safe canoe/kayak passage, similar to previous MFL evaluations (SRWMD 2013, NWFWMD 2019). This metric was not assessed within the boundaries of the Edward Ball Wakulla Springs State Park since recreational canoeing/kayaking is prohibited within park boundaries.

3.2 Fish and Wildlife Habitat and the Passage of Fish

Approximately 3.2 miles of the Wakulla River are within the Edward Ball Wakulla Springs State Park. In addition, the St. Marks National Wildlife Refuge line portions of the Wakulla River south of U.S. Hwy 98. The numerous wildlife and extensive natural vegetation communities make Fish and Wildlife Habitat and the Passage of Fish a relevant WRV.

3.2.1 Fish Passage

The Wakulla River provides habitat to numerous recreationally and commercially important fish species such as largemouth bass (Table 7). Maintaining fish passage during low flow conditions is important to allow fish physical access up and/or downstream a river to areas of deeper water to escape predation or to access food sources and/or spawning habitat. Little information is available concerning the requirements for fish passage for warm water species. Multiple MFL assessments have used a water depth of either 0.6 ft or 0.8 ft across as much as 25 percent of the river width as a fish passage criterion (SRWMD 2016, SWFWMD 2017a). These depths were initially devised to protect anadromous fish (salmon and large trout) passage in the Pacific Northwest (Stalnaker and Arnette 1976) and represented the best available data at the time. In 2002, the SWFWMD determined that 0.6 ft was most representative of the body depth of most individuals of the largest fish species known to inhabit the Peace River (largemouth bass, *Microptera salmoides*). A screening of the fish species known to inhabit the freshwater portion of the Wakulla River (Table 7) revealed that largemouth bass and long-nose gar (*Lepisosteus osseus*) were the fish species capable of reaching the largest body depth. While a fish depth of 0.6 ft has been established and accepted as a minimum depth for largemouth bass, no such depth is available for long-nose gar. However, conversations with FWC biologists indicated that the 0.6 ft used for largemouth bass should be protective of long-nose gar passage as well (Eric Nagid, FWC personal communication). As a result, a minimum thalweg depth of 0.6 ft was utilized in this study as the minimum depth required for fish passage. No minimum channel width was used for this metric since largemouth bass and long-nose gar do not gather in large spawning migrations which require a large cross-sectional area for moving upstream or downstream. Other species of greatest conservation need which are documented in the Wakulla River, such as Suwannee bass, have body depths less than largemouth bass and the metric depth of 0.6 ft should be protective of these species passage as well. This metric was assessed at all channel transect locations along the Wakulla River and Sally Ward Spring run.

The FWC has reported that striped bass, *Morone saxatilis*, have been observed in the St. Marks River. To our knowledge, however, no striped bass have been documented in the Wakulla River by scientific collections or other verified methods. As a result, striped bass were not utilized for the fish passage metric. However, their passage should be protected by other passage metrics such as safe canoe/kayak passage (1.5 ft depth) and safe manatee passage (3.8 ft depth, described below) in the event that this species enters the spring run.

3.2.2 Manatee Passage and Thermal Refuge

The Florida manatee is listed as federally designated threatened species under the Endangered Species Act of 1973. Unlike other springs further south, manatee do not have a long, documented history of using Wakulla Spring. However, manatees have been consistently utilizing Wakulla Spring and its spring run since 2006, making manatee habitat relevant for MFL establishment. Wakulla Spring has recently been listed as a primary winter habitat for refuge from cold water temperatures (Valade et al. 2020).

Manatee use in the Wakulla River has been reported year-round since 2006. While in the river, manatee potentially migrate between the spring pool and downstream portions of the river (Figure 58). A minimum water depth needed for manatees to cross shallow areas has not been established and additional research is needed. Conversations with FWC biologist indicated that manatee can easily cross shallow areas with more than 2.5 ft of water depth (FWC personal communication). Rouhani et al. (2007) described an average manatee depth and width of 3.8 ft for an average adult for use in the establishment of the minimum flow regime for Blue Spring in Volusia County, Florida for use as a thermal refuge criteria. While a water depth of 3.8 ft is an overestimation of the depth of water needed for manatees crossing shallow areas, this depth was used for consistency with the thermal refuge evaluation (described below) since this depth is based upon the size of an average manatee. In addition, a minimum channel width of 3.8 ft was used for manatee passage. This is overly conservative for the protection of manatee movements along the Wakulla River for foraging, warm-water refuge, and other uses and provides for more water than manatee are thought to need.

Previous research has shown that manatee passage can be affected by tides. During high tides when water levels are deeper, manatees may have access to channels and upstream areas that are too shallow to cross during lower tides (Hartman 1979, Zoodsma 1991). Additional research has shown that manatees in southeast Georgia traveled more often during mid to high tides compared with low tides (Rappucci et al. 2012). To account for these behaviors, manatee passage was assessed using the average daily high water level observed throughout the year.

Florida manatee are susceptible to cold stress during winter months when water temperatures fall below 18°C to 20°C for extended periods or below 10°C to 12°C for periods less than a few hours (Bossart et al. 2002). During extremely cold weather, manatees are often observed congregated in and near the Wakulla Spring pool near sunrise, however individuals have been observed approximately one mile downstream during freezing (< 0°C) temperatures (NWFWMD, personal observation). As the air temperature warms, manatees may begin migrating downstream before returning to the spring pool when air temperatures decline again. Wakulla Spring has recently been designated as a primary warm water refuge (Valade et al. 2020), as increased numbers of manatees have been observed overwintering since the winter of 2007/2008. However, Wakulla Spring does not have high thermal refuge quality as the temperature of water being discharged from the spring falls below 20°C during severe conditions (Valade et al. 2020).

Many previously established MFLs in Florida have used two temperature thresholds for thermal refuge, chronic and acute temperature criteria (Rouhani et al. 2006, SJRWMD 2007, SWFWMD 2008, SWFWMD 2012a, SWFWMD 2012b, SWFWMD 2017a). The chronic stress criteria states that water temperatures must not fall below 20°C (68°F) for more than three days (72 hours), and the acute stress criteria states that water temperatures must no fall below 15°C (59°F) for more than four hours (Rouhani et al. 2007). For the current MFL evaluation, the District utilized the chronic and acute temperature criteria described above based upon previous research and consistency with other MFL evaluations (Rouhani et al. 2006, SJRWMD 2007, SWFWMD 2008, SWFWMD 2012a, SWFWMD 2012b, SWFWMD 2017a). This warm-water refuge is for the protection of manatees from cold temperatures associated with the cold air temperatures common during the winter in north Florida. It is designed solely as a refuge from cold temperatures and holds no assumptions of manatee foraging habitat or food availability. Information concerning manatee food availability and other parameters which would be needed to determine a true carrying capacity for the Wakulla River are unavailable.

Wakulla Spring is unique among Florida springs in that the temperature of water being discharged from the spring regularly and naturally falls below 20°C but has not been recorded below 19°C during the winter months when manatees are using the spring as a thermal refuge (Figure 26). These temperature variations may be a result of the surface water inputs to the Floridan aquifer reaching the spring described in Section 1.5.

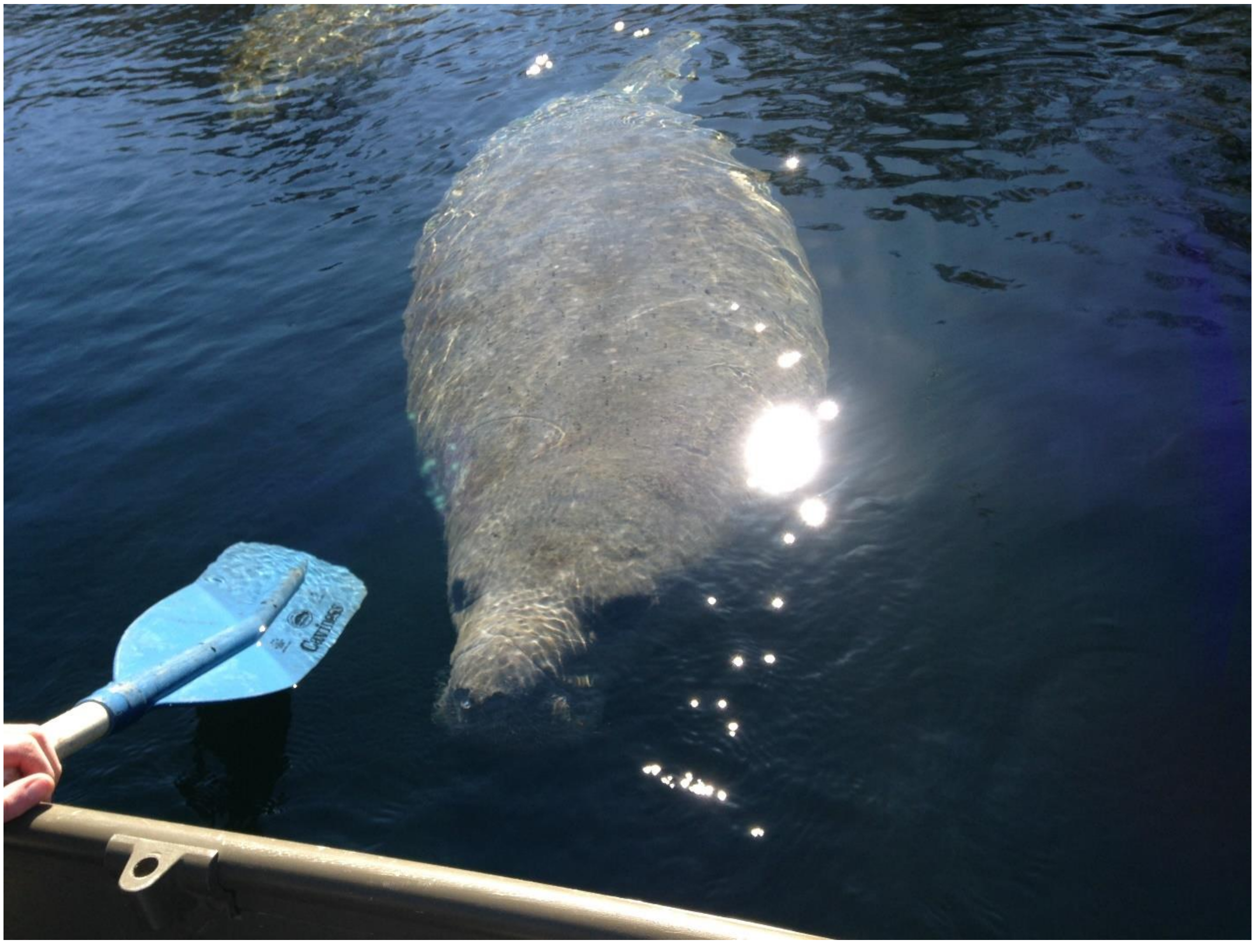

Figure 58: Manatee at the Wakulla Spring Vent on January 18, 2018 (Tallahassee Minimum Air Temperature <-6.7 °C, U.S. Climate Data 2018)

3.2.3 Instream Woody Habitat Inundation

Submerged woody habitat has been identified as being important habitat and food for invertebrate species in streams of the southeastern United States (Benke et al. 1984, Benke et al. 1985). These macroinvertebrates then provide food for larger fauna including the recreationally important sunfishes and largemouth bass. In addition, woody habitat alters streamflow characteristics and helps create multiple habitat types including pools and bars habitat (Abbe and Montgomery 1996).

Two types of instream woody habitat were observed along the Wakulla River. Dead woody debris consists of tree stumps and fallen logs/branches present and inundated along the edge of the river channel. Live roots include tree roots, cypress knees, etc. found along the river edge that are routinely inundated by river flow or have become exposed due to erosion from water flow. Dead woody debris often tends to be found deeper in the river channel and at a lower elevation than live roots.

Elevations (NAVD88) for dead woody debris and live roots were available at three locations along the Wakulla River (NWFWMD 2016). At least ten elevations for each habitat type were collected at each sample location and average together to determine the mean elevation at each transect. The analysis of this data and conclusions regarding its usefulness are further discussed in Section 5.1.2.

3.2.4 Floodplain Vegetation Inundation

The presence, survival, and reproduction of wetland tree species are dependent in large part on the depth and frequency of inundation (Ewel 1990). The numerous wildlife species which utilize the Wakulla River and its watershed rely heavily on the river's adjacent floodplain for their survival.

The inundation of floodplain habitats has been used as WRV metrics in prior established MFLs for river systems and was evaluated for its appropriateness as a metric in this study (SRWMD 2016a, SRWMD 2016C, NWFWMD 2019). During the Peer Review of the St. Marks River Rise MFL Technical Assessment (NWFWMD 2019), the panel recommended that the use of individual communities such as those described in RPI (2016) be reconsidered in future MFL evaluations due to the small sample size used to describe the community types. In response to this comment riparian communities were treated as a single unit and individual vegetation community types were not used. Wetland edges were delineated in the field across the river and from upland to upland. Land elevation points within the ten floodplain transects were surveyed by a licensed surveyor and analyzed to determine the percent of elevations which were at or below that elevation and could be considered to be inundated at a specified water surface elevation. Water surface elevations at each transect were determined which would inundate 5 percent, 25 percent, 50 percent, and 75 percent of the floodplain elevations and were analyzed for MFL determination. Details of floodplain community elevations and analysis of inundation frequencies and riverine wetland hydrology are provided in Section 5.1.2.

3.2.5 Other Fish and Wildlife Habitat Considerations

Physical habitat models such as Physical Habitat Simulation (PHABSIM) and the System for Environmental Flows Analysis (SEFA) relate changes in flow to usable habitat by aquatic species and were considered for use in minimum flow determination. Preliminary field work was performed to identify suitable transects and characterize velocities and substrates along the Wakulla River. The field investigation revealed that Wakulla River is tidally influenced and characterized by dense vegetation in areas. These characteristics precluded the development of reliable relationships among channel profiles, velocities and substrates (Gore 2015). In recent years, existing and additional modeling types have progressed and may be capable of accurately modeling changes to instream habitat in a system like the Wakulla River during future reevaluations. For the current MFL evaluation, multiple alternative habitat metrics including estuarine habitats (reduced salinity), floodplain habitats, instream woody habitats, and fish and manatee passage are included as metrics in this minimum flow evaluation to address and protect the range of flows supporting aquatic ecosystems.

Hydric soils are created when organic material in various stages of decomposition accumulates due to anaerobic conditions which prevent decomposition (Mitsch and Gosselink 2007). Anaerobic conditions occur during periods of extended soil saturation or inundation, which occur in the floodplain and edges of the river where flow is restricted. Processes that maintain floodplain inundation are anticipated to also protect the formation and preservation of hydric soils.

3.3 Estuarine Resources

Estuaries are aquatic habitats located where freshwater mixes with saline marine waters and are defined as having waters of reduced salinity. FNAI defines estuaries and marine waters as having salinities greater than 0.5 ppt (FNAI 2010). Estuarine zones are characterized by highly fluctuating, but overall reduced, salinity levels. Estuaries are extremely important to both vegetation and wildlife, many species of which have evolved to thrive primarily in waters with highly variable salinity. The extent of estuarine waters in the Wakulla River varies depending on sea level, tidal flux, and freshwater discharge from Wakulla and Sally Ward springs, and to a much lesser extent discharge from the St. Marks River.

3.3.1 Estuarine Habitats

Estuarine habitats are present in the portion of the Wakulla River downstream of the U.S. 98 bridge. Salinities is this area generally range from 0.5 to 3 parts per thousand (ppt). Relationships between spring flow reductions and changes in estuarine zones are important to the system and can be modeled and quantified. As freshwater discharges from the springs are reduced, the volume, bottom surface area, or linear extent of shoreline habitat of different oligohaline zones (salinities 0.5 ppt through 3 ppt) can change and move further inland altering the balance between freshwater and habitats. While many species of fish and invertebrates are adapted to the fluctuating ranges of salinity found in estuaries, many cannot tolerate wide fluctuations in salinity. In addition, many freshwater species are not capable of surviving extended periods of increased salinity which can arise from reductions in freshwater flow. As a result, the volume, bottom surface area, and/or linear extent of shoreline habitat of oligohaline zones were identified as metrics for the Estuarine Resources WRV.

Previous research has documented multiple biologically relevant oligohaline zones (<0.5 parts per thousand (ppt) salinity, <2 ppt, <5 ppt, <10 ppt, <15 ppt, etc.) which have been used to set multiple MFLs (SRWMD 2016, SWFWMD 2017a). Many fish populations in the estuaries of Florida's coast of the Gulf of Mexico have shown distinct transition points at waters with salinities of 0 ppt, 2 ppt, 5 ppt, and 15 ppt (SWFWMD 2006; 2007, 2008a, 2008b, 2011; WRA 2005, 2006). Salinities less than 10 ppt are important for the recruitment of multiple fish species (Rogers et al. 1984). Salinity is also a controlling factor in the distribution of many vegetation species. American eelgrass (*Vallisneria americana)*, which is an extremely important species of submerged aquatic vegetation throughout the Wakulla River, is capable of surviving in salinities less than 10 to 15 ppt; however, salinities less than 3 ppt were required for active growth (French and Moore 2003, Haller et al. 1974). Many other littoral species common to the Wakulla River require salinities less than 2 to 3 ppt for survival and growth including bulltongue arrowhead (*Sagittaria lancifolia*), duck potato (*Sagittaria latifolia*), pickerelweed (*Pontederia cordata*), sawgrass (*Cladium jamaicense*), red ludwigia (*Ludwigia repens*), and tupelo (*Nyssa sylvatica*) (Clewell et al. 1999, Delesalle and Blum 1994, McCarron et al. 1998, Penfound and Hathaway 1938, Pezeshki et al. 1987). Near the confluence with the St. Marks River, the forested riparian communities are replaced by sawgrass habitats

(NWFWMD 2016), indicating an increasing average salinity, which is consistent with measured salinities in this area.

Monthly in-situ, vertical water quality profiles collected at 0.5-mile increments during data collection efforts for hydrodynamic model calibration were used to characterize the average salinity conditions in the Wakulla River (See Section 2.2 Hydrodynamic and Water Quality Data Collection). Data collected from all sample depths (0.5-meter increments from surface to substrate) during a single month were averaged to calculate the monthly average and all samples for a given station were averaged to determine a station average. Mean salinity ranges were observed from a high value of approximately 2.95 ppt near the confluence of the Wakulla River with the St. Marks River (W-1) declining to 0.13 ppt at station W-9 (approximately 0.9 miles upstream of US Hwy 98) (Figure 59 and Figure 31). Increased salinities (>0.5 ppt) were observed on average from the confluence with the St. Marks River to approximately 1 to 1.5 miles upstream between stations W3 and W4. The mean oligohaline habitats observed in the Wakulla River of <0.5 ppt, <1 ppt, <2 ppt, and <3 ppt were used in the analysis to assess effects of potential spring flow reductions. The different biota inhabiting these habitats justifies the use of multiple metrics for each salinity zone. For example, fish species often tend to utilize the entire water column (I.e., volume), while benthic invertebrates utilize the bottom substrate (I.e., surface area), and shoreline vegetation requires a length of shoreline (I.e., length of shoreline). As a result, oligohaline zones of <0.5 ppt, <1 ppt, <2 ppt, and <3 ppt were assessed using the volume, bottom surface area, and shoreline length of habitat were used as the metrics for this WRV. The range of Wakulla River flows sampled during water quality profiles ranged from 411 cfs during March 2017 to 1097 cfs during January 2017.

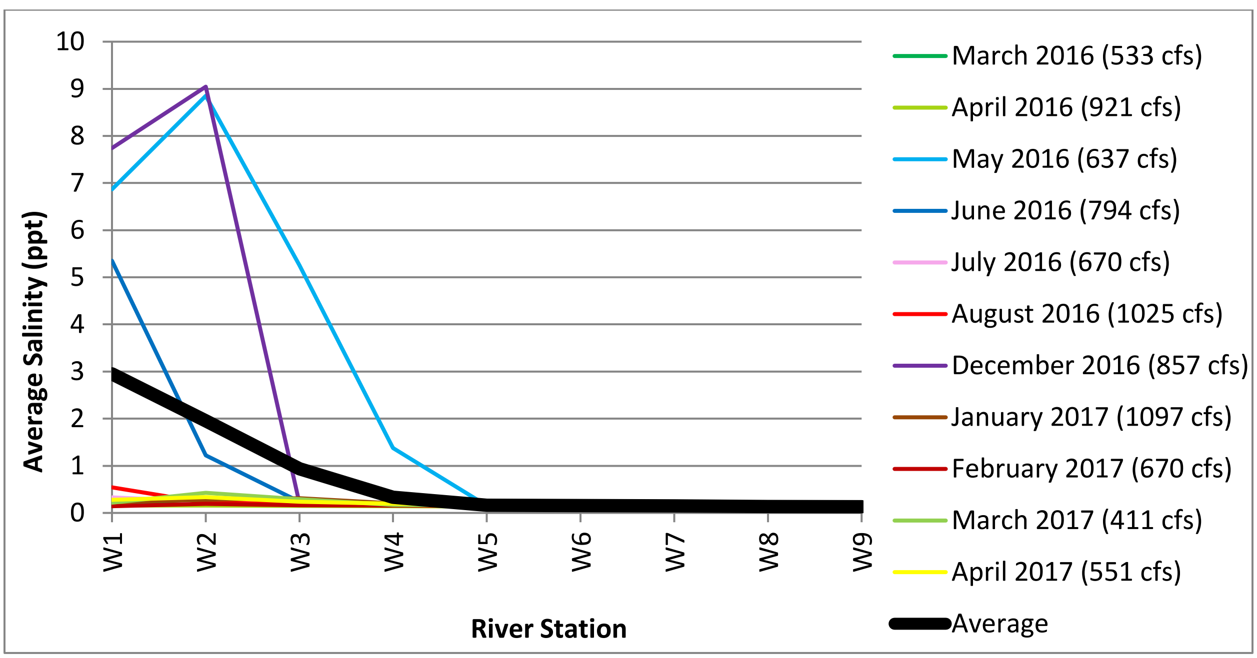

Figure 59: Mean Salinity Observed During In-Situ Water Quality Profile Monitoring Along the Wakulla River. Locations of River Stations are Depicted in Figure 30.

3.4 Transfer of Detrital Material

Detrital material is comprised of dead organic material (largely vegetation) in the process of decomposition. Plant detritus comprises a large portion of the food base in aquatic and wetland ecosystems. Detritus arises from littoral and submerged aquatic vegetation both along the Wakulla River, in addition to sources entering nearby swallets, which is then transported to and discharged at Wakulla Spring. Springwater, in general, is typically low in detrital material (McCabe 1998). The transfer of detrital material from the floodplain into the Wakulla River relies on stormwater runoff and out of bank flows associated with high flow events. River discharge then transports detritus downstream to the lower St. Marks River and ultimately into Apalachee Bay. Little quantifiable data is available regarding the transport of detrital material in the Wakulla River or its relationship to flow characteristics. In addition, spring water is typically very low in detritus. As a result, this WRV was unable to be quantified as a metric.

3.5 Maintenance of Freshwater Storage and Supply

Maintaining long-term freshwater storage for non-consumptive uses and environmental resources is the prime objective for establishing a MFL flow regime. There are no individual water use permits for surface water withdrawals on the Wakulla River. Freshwater storage and supply for the natural system is addressed as part of the overall minimum flow regime, which protects water availability for multiple WRVs.

3.6 Aesthetic and Scenic Attributes

Aesthetic and scenic attributes refer to passive uses of the river such as nature viewing, hiking, and photography. These uses are one of the main reasons for the popularity of the Wakulla River and state park for recreational uses. Active recreational uses are described in Section 3.1. The vegetation (instream and riparian) and wildlife are addressed under WRV2 Fish and Wildlife Habitats and the Passage of Fish.

Previous MFLs have described an increase in filamentous algal cover in rivers as a decrease in the aesthetics of a system (SRWMD 2013). The relationship between algal cover and water velocity has been described as a subsidy-stress relationship where changes in water velocity can promote algal growth through increased nutrient uptake, but also impede algal growth through shearing (Horner and Welch 1981, Stevenson 1996, Biggs et al. 1998, King 2012). However, little information exists concerning the relationship of flow and algal cover in the Wakulla River, making this potential metric unable to be reliably quantified during the current MFL evaluation. Specific, detailed information on the location and densities of submerged aquatic vegetation are both unavailable at present. In addition, analysis of the relationship between water velocity and algal coverage may be impeded by changing river hydraulics such as the extensive channeling and ineffective flow areas present along much of the Wakulla River described in Section 2.6. Increased water velocities have an unknown effect on the ability of desirable submerged aquatic vegetation to become established and increase in cover. Water velocities in the Wakulla River have also increased through time as is evident by the increasing spring discharge previously described.

Future work and data collection are needed to better understand the complex relationship between velocity, submerged aquatic vegetation, and filamentous algae in the Wakulla River.

Similar to excessive algal cover, nuisance and exotic vegetation can decrease the aesthetics of an aquatic system. Currently, little nuisance and exotic vegetation exists along the Wakulla River, although hydrilla, *Hydrilla verticillata*, was once prevalent near the spring pool. The increase in hydrilla coincided with elevated nitrate, NO_3, concentrations at the spring. Hydrilla prevalence has been reduced significantly following targeted efforts to reduce nitrate concentrations in the Wakulla Spring GWCA in combination with grazing by manatees and numerous herbicide treatments. Little information exists concerning the relationship of flow and nuisance and exotic vegetation cover in the Wakulla River, making this potential metric unable to be reliably quantified during the present MFL evaluation. Available information concerning nuisance/exotic vegetation and Wakulla River flow velocities and will be reviewed prior to Wakulla and Sally Ward Springs MFL reevaluation.

In recent years, reduced water clarity in Wakulla Spring and a decrease in the number of days that glass bottom boat tours have been conducted near the spring vent have been reported. Currently, limited data are available for water quality parameters such as fluorescent dissolved organic material, chlorophyll a, and turbidity. Available data indicate that water clarity is inversely related to spring discharge with high water clarity correlated with reduced spring discharge (Section 1.6). As previously discussed, water clarity at Wakulla Spring is complex. However, available data indicate that reported declines in water clarity since 1995 are unrelated to groundwater withdrawals, which have remained relatively constant during this same time period.

Another metric that has been used for aesthetic and scenic value is the change in water depth, which can affect the appearance and scenic value of a waterbody. Although the change in water depth was not explicitly used as an aesthetic and scenic value metric in this MFL evaluation, the proposed minimum flow is anticipated to result in a minimal change in water depths, as discussed in section 5.1.2.

3.7 Filtration and Absorption of Nutrients and Other Pollutants

Nutrients are taken up by aquatic plants (Reddy and De Busk 1985) where they are stored, and in some cases transported out of the aquatic system. Floodplains and wetland soils also provide areas for nitrogen mineralization and denitrification (Koschorreck and Darwich 2003, Kellogg et al. 2010). Information concerning the filtration and absorption of nutrients and other pollutants is currently unavailable for the Wakulla River and Sally Ward Spring run. As a result, this metric was unable to be quantified.

3.8 Sediment Loads

Data directly relating sediment loads to spring flow for this system is not available, preventing direct quantification of this metric as related to minimum flows from the Wakulla and Sally Ward springs. However, while sediment transport can occur during all flows, net sediment transport in a river is often a function of the frequency and intensity of flow and flood stages (Wolman and Miller 1960). Information concerning sediment size and transport downstream is currently unavailable for the Wakulla River and Sally Ward Spring run. As a result, this metric was unable to be quantified.

3.9 Water Quality

Current water quality in the Wakulla River (including the Sally Ward Spring run) is generally good. Nitrate levels in Wakulla Spring tripled between the 1970s through the 1990s (Chelette et al. 2002). The Florida Department of Environmental Protection has adopted a statewide Total Maximum Daily Load (TMDL) of 0.35 mg/l for nitrate and implemented a Basin Management Action Plan (BMAP) for the Upper Wakulla River and Wakulla Spring which identifies specific actions required to reduce pollutant loads (DEP 2018). Nitrate levels at Wakulla Spring have currently been reduced to near the TMDL criteria of 0.35 mg/L (Section 1.6). Multiple corrective actions have been implemented to reduce nitrate at Wakulla Spring. Since nutrients leading to reduced water quality arise from surface actions, the protection of water quality is best achieved through restorative activities located at pollution sources and not through spring discharge. Water quality data was considered and utilized in the MFL determination. Quantitative analysis of water quality data and relationships with spring discharge are presented in Section 1.6 Water Quality.

3.10 Navigation

This WRV refers to the navigation of commercial vessels within the study area. The Wakulla River is not used for commercial navigation making the Navigation WRV inappropriate for the Wakulla and Sally Ward springs minimum flows determination.

3.11 Selection of Water Resource Values

After carefully considering all ten WRVs, four were utilized for further MFL analysis. The four WRVs determined to be most appropriate for the establishment of minimum spring flows are:

- Recreation In and On the Water
- Fish and Wildlife Habitat and the Passage of Fish
- Estuarine Resources
- Water Quality

4 Models Used in Minimum Flow Determination

In order to relate the WRVs and associated metrics to changes in spring flow from Wakulla and Sally Ward springs, extensive data collection and modeling efforts were performed. Three different models were developed for MFL assessment including a Hydraulic Engineering Centers River Analysis System (HEC-RAS) model for assessing stage/discharge-based WRVs and two separate Environmental Fluid Dynamics Code (EFDC) models for assessing manatee thermal refuge and estuarine habitat. An EFDC model was developed for assessing manatee thermal refuge near the Wakulla Spring pool and an EFDC model was developed for assessing salinity-flow relationships and potential changes in oligohaline habitats near the City of St. Marks. Data collection, development of the baseline spring flows, and model selection and development are described below.

4.1 HEC-RAS Model Development and Calibration

The Hydrologic Engineering Centers River Analysis System (HEC-RAS) model is a widely used one-dimensional model for hydraulic analysis of river channels and associated floodplains. The stream channel geometry and properties are represented by a series of attributed cross-sections. The HEC-RAS model enables the calculation of water surface profiles for steady and unsteady (transient) flow profiles. Calculations are based on computed energy losses between adjacent cross-sections.

A combined HEC-RAS model of the Wakulla River and St. Marks River developed for the St. Marks River Rise MFL determination was updated and expanded for the Wakulla Spring and Sally Ward Spring MFL evaluation, using HEC-RAS version 5.0.7. Details of the HEC-RAS modeling effort for the St. Marks River Rise can be found in Appendix D. The development, calibration, validation, and modeling scenarios of the HEC-RAS model utilized for this evaluation are described in detail in Appendix D of this report.

The District contracted with Applied Technology and Management, Inc. (ATM) to update an existing HEC-RAS model that was used in the determination of the St. Marks River Rise minimum flow. Subsequent model updates consisted of adding in a reach which includes the Sally Ward Spring run and updating in-channel cross section geometry with data collected during a bathymetric survey along the Wakulla River and Sally Ward Spring run in August 2019 following Hurricane Michael. A total of 12 cross-sections were added or refined in the model along the Wakulla River, based on review of collected bathymetric data. Additional cross-sections were included to better represent shallow and braided areas in the upper portion of the Wakulla River above the Shadeville Road bridge. A total of eight surveyed cross-sections and the pedestrian bridge that spans Sally Ward Spring run were added to represent the Sally Ward Spring run. Available LiDAR data was used to extend the transects in the model into the adjacent floodplain as needed to fully encompass the potential inundation area. A review of the survey data revealed that in some locations, changes in the river channel profile occurred following Hurricane Michael in October 2018 and after the extremely high flows present during November and December 2018, due to scouring and deposition of sediment. A total of 104 cross-sections were included in the final model, including 42 cross-sections on the Wakulla River and Sally Ward Spring run (Figure 60), 52 cross-sections on the St. Marks River above the confluence with the Wakulla River, and 10 cross-sections below the confluence. A map of the entire HEC-RAS model domain can be found in Appendix D.

Boundary conditions for the St. Marks River/Wakulla River/Sally Ward Spring run HEC-RAS model consisted of the upstream flows from the St. Marks River Rise, Wakulla Spring, and Sally Ward Spring; downstream stage on the St. Marks River near the Gulf of Mexico; and internal lateral inflows (both uniformly distributed and point inflows) on both rivers.

Upstream inflows for the Wakulla River were derived from the Wakulla Spring and Sally Ward Spring flow time series described in Section 2 Hydrology. Upstream inflows for the St. Marks River were derived from the St. Marks at Newport USGS Station 02326900. Diffuse groundwater inflow, contributions from smaller springs located along the Wakulla River, and surface water inputs are represented as lateral inflows (reach pickup) in the HEC-RAS model. Lateral pickup along the Wakulla River between the spring vents and the Edward Ball Wakulla Springs State Park boundary at Shadeville Rd was estimated by subtracting the combined tidally filtered flow from the Wakulla Spring vent flow and Sally Ward Spring run from USGS Station 02327022 tidally filtered flow data. Lateral pickup along the Wakulla River below Shadeville Rd. and for the St. Marks River was estimated based on net flow measurements taken along the Wakulla and St. Marks rivers near the confluence, as well as a net flow measurement taken below the confluence to determine total net flow at that location. Details regarding these calculations can be found in Appendix D.

Downstream stage boundary conditions were based on tidal predictions at the St. Marks Lighthouse provided by the National Oceanographic and Atmospheric Administration (NOAA). Stage measurements were taken at Station HD-3 located at the Wakulla/St. Marks River confluence; however, issues were identified with some measurements following Hurricane Michael. As a result, stage at HD-3 was not appropriate to use as a boundary condition as the model was calibrated to post-Michael conditions. The lighthouse at the St. Marks National Wildlife Refuge is the closest location with tidal information after Hurricane Michael.

Model Calibration and Validation – The updated HEC-RAS model was calibrated to observed stages and flows by adjusting channel friction (Manning's n) and incorporating ineffective flow areas in the channel based upon field observations and review of aerial images to account for effects of vegetation on flow. Stage and flow calibration data was available at several monitoring stations including:

- USGS 02327000 Wakulla Spring Nr Crawfordville
- USGS 02327022 Wakulla River Nr Crawfordville
- NWFWMD Station 010822 (Boat Tram)
- NWFWMD Station 000774 Sally Ward Spring Run
- USGS 02326900 St. Marks River Nr Newport

The model was calibrated as a transient model using a data simulation period from December 24, 2018, through September 8, 2019. This period of data reflects changes in channel characteristics and stage-discharge relationships observed after Hurricane Michael. Additional details regarding the HEC-RAS model calibration approach and results can be found in Appendix D. Model calibration results show that generally stage predictions are within 0.2 to 0.3 ft, except at USGS station 02327022 located at the downstream boundary of the state park. The predicted and observed flow duration curves match well at this location, indicating that stage differences at this location appear to be primarily a result of timing differences between the observed and predicted stages. Considering that predicted tidal values were used at the downstream boundary condition, the transient model was shown to be a good predictor of water levels across low, medium, and high flow conditions. Statistical measures of model performance for the calibration period comparing simulated and observed time series are shown in Table 17.

The period of September 10, 2019, through January 22, 2020, served as the model validation period, which included Tropical Storm Nestor which landed on October 19, 2019, near Apalachicola, Florida. During October and November 2019, the model underpredicted stages at all calibration locations and is likely a result of tidal timing and the use of predicted tides at the downstream boundary condition. Model results converged again during December 2019 and matched observed stages well for the remainder of the verification period. This indicates that the model predicted stage well as the system recovered from Tropical Storm Nestor. Statistical measures of model performance for the entire simulation period, comparing simulated and observed time series are shown in Table 18. Additional details regarding the HEC-RAS model verification can be found in Appendix D.

The calibrated HEC-RAS model was converted to steady-state to evaluate critical flows and stages for water resource values and support the determination of minimum flows for Wakulla Spring and Sally Ward Spring for the baseline flow period from October 23, 2004- December 31, 2019. The record of field measurements at the USGS 02327022 gage, located in the middle portion of the Wakulla River, was used to assess how well the steady-state model predictions captured observed flow-stage dynamics. The USGS has made 144 field measurements of flow and stage from 2005 to April 2020 with 10 field measurements occurring following the passage of Hurricane Michael in October 2018. A comparison of predicted rating curves at Shadeville Road under various downstream tidal boundary scenarios from the steady state model were compared to the observed field measurements at the USGS 02327022 gage (Figure 61). Minor adjustments were made to Manning's "n" coefficients until the range of observations was largely contained by the median, mean daily high, and mean daily high winter downstream stage boundary scenarios and the median downstream boundary scenario corresponded to the central tendency of the range of observations based on visual inspection of Figure 61. Computation of calibration performance metrics is not suitable for comparing steady-state model output with observed measurements at Shadeville Road since this model output does not correspond directly to specific occurrences in time when measurements were made.

Based on this comparison, the steady-state model captures typical conditions the river system has experienced over the 2004-2019 period of record. Therefore, the constructed Wakulla River steady-state model is considered suitable for use in MFL determinations and the associated assessment of water resource values (WRVs). Details regarding the development and utilization of the steady state HEC-RAS model are presented in Appendix D.

Table 17: Summary Statistics of Model Performance – St. Marks River/Wakulla River HEC-RAS Model Final Calibration, December 24, 2018 through September 8, 2019 (Based on one-hour simulated and observed time series).

River	Station	Statistics	Mean (ft-NAVD88)	Max (ft-NAVD88)	Min (ft-NAVD88)	R^2	RMSE	RMSE/Range %	PBIAS	RSR
Sally Ward Spring	SWS	Obs	5.23	6.41	4.48					
		Sim	5.22	6.49	4.63	0.958	0.11	5.9	-0.298	0.304
		Diff	-0.01	0.08	0.15					
Wakulla River	2327000	Obs	4.90	6.04	4.15					
		Sim	4.92	6.17	4.27	0.936	0.13	7.0	0.375	0.359
		Diff	0.02	0.13	0.12					
	Boat Tram	Obs	4.45	5.47	3.73					
		Sim	4.42	5.77	3.76	0.937	0.19	10.9	1.165	0.579
		Diff	-0.03	0.35	0.03					
	2327022 (Stage)	Obs	2.08	4.42	0.32					
		Sim	2.22	3.92	0.14	0.790	0.44	10.8	6.682	0.732
		Diff	0.14	-0.5	-0.18					
	2327022 (Flow)	Obs	780.4	1600.0	116.0					
		Sim	789.3	1506.7	289.6	0.933	85.23	5.7	1.663	0.365
		Diff	8.9	-93.3	173.6					

Table 18: Summary Statistics of Model Performance – St. Marks River/Wakulla River HEC-RAS Model Full Simulation Period, December 24, 2018 through January 22, 2020 (Based on one-hour simulated and observed time series).

River	**Station**	**Statistics**	**Mean (ft, NAVD88)**	**Max (ft, NAVD88)**	**Min (ft, NAVD88)**	**R^2**	**RMSE**	**RMSE/ Range%**	**PBIAS**	**RSR**
Sally Ward Spring	SWS	Obs	5.23	6.41	4.48					
		Sim	5.17	6.49	4.60	0.916	0.15	7.7%	-1.122	0.458
		Diff	-0.06	0.08	0.12					
Wakulla River	2327000	Obs	4.90	6.04	4.15					
		Sim	4.89	6.17	4.25	0.870	0.14	7.3%	-0.187	0.431
		Diff	-0.01	0.13	0.10					
	Boat Tram	Obs	4.45	5.47	3.73					
		Sim	4.42	5.77	3.74	0.902	0.18	10.6%	0.278	0.559
		Diff	-0.03	0.30	0.01					
	2327022 (Stage)	Obs	2.17	5.02	0.32					
		Sim	2.23	3.92	0.14	0.786	0.40	8.6%	2.390	0.666
		Diff	0.06	-1.1	-0.18					
	2327022 (Flow, cfs)	Obs	781.8	1610.0	116.0					
		Sim	788.4	1506.7	289.6	0.924	80.3	5.4%	1.177	0.385
		Diff	6.6	-103.3	173.6					

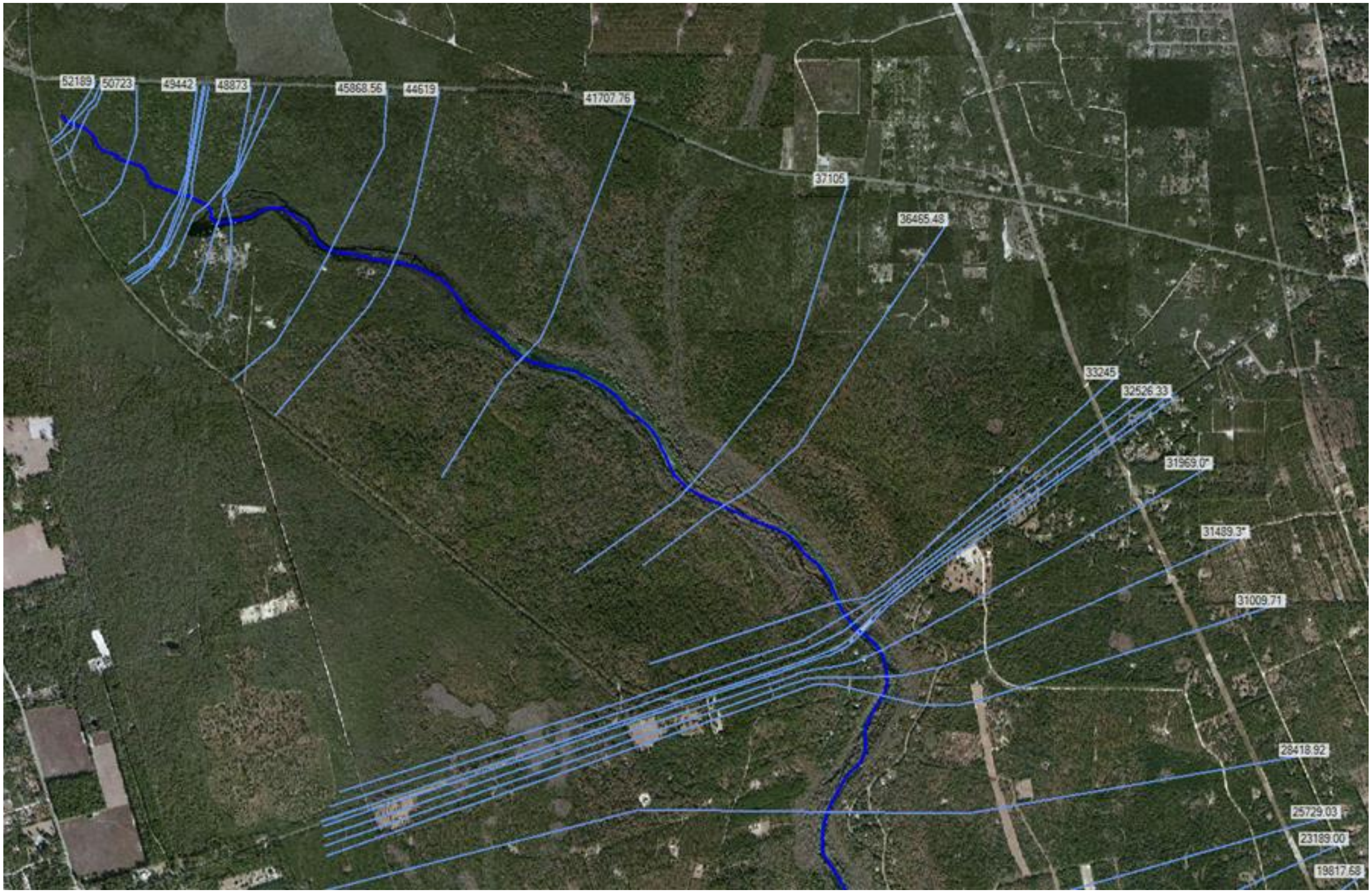

Figure 60: HEC-RAS Model Geometry and Transect Sites for the Wakulla River and Sally Ward Spring Run.

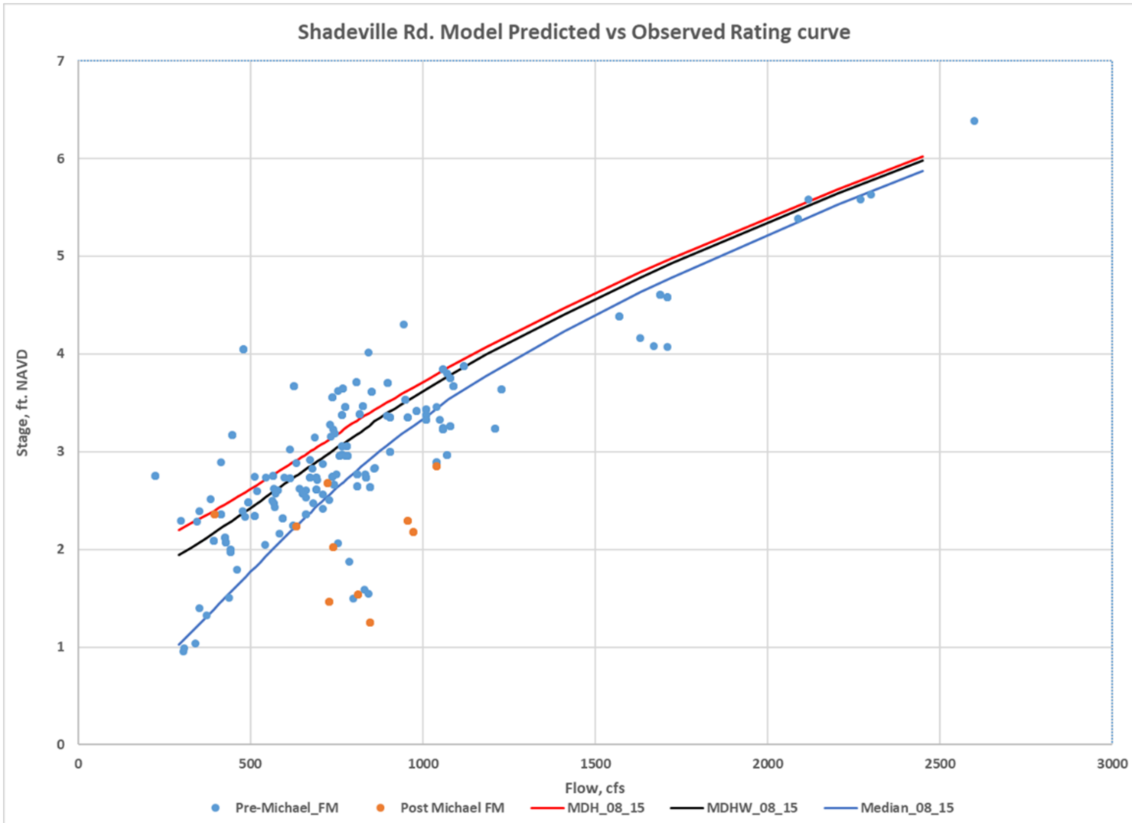

Figure 61: Comparison of Simulated Rating Curves and Field Measurements at USGS 02327022 for Specified Boundary Elevations

4.2 Estuarine EFDC Modeling

The District contracted with Janicki Environmental, Inc. to develop an EFDC model of the estuarine areas for the Wakulla River and St. Marks River systems. The EFDC model was used to characterize the impacts of spring flow reductions on WRV 3 (Estuarine Resources) metrics. A summary of the EFDC model development, calibration, and results is provided below. Additional details of EFDC model development, calibration, and flow reduction scenarios can be found in Appendix B and Appendix E.

4.2.1 Model Development and Calibration

The estuarine EFDC model extends from the St. Marks and Wakulla rivers at each of the U.S. Highway 98 bridges downstream to the mouth of the St. Marks River in Apalachee Bay. The study area for the Wakulla River extends from the U.S. Highway 98 bridge to the Wakulla River and St. Marks River confluence (Figure 62). The Wakulla River and St. Marks River reaches included in the model encompass the oligohaline portion of the Wakulla River and St. Marks River as well as the transition between fresh and oligohaline waters. Data were collected to support EFDC model development, implementation, and calibration. In addition to stage and flow data collected by the USGS along the Wakulla and St. Marks rivers, continuous water level, temperature, and specific conductivity data were collected from five hydrodynamic (HD) monitoring stations (Section 2.2, Figure 31, Table 12). Water surface elevation, water temperature, and specific conductivity data were collected at five-minute intervals at each site. Offshore boundary conditions were based on predicted water surface elevations at the St. Marks Lighthouse as provided by NOAA. Upstream boundary conditions were set using data from stations HD-1 (St. Marks River at U.S. 98) and HD-2 (Wakulla River at U.S. 98) (Figure 31). Model grid bathymetry for the St. Marks and Wakulla rivers upstream of the mouth of the St. Marks River (HD-5) was determined using elevation cross-sections collected during 2016 combined with aerial photography. Offshore of the St. Marks River mouth, bathymetry data was taken from the Florida Shelf Habitat (FLaSH) mapping study (Robbins et al. 2007). River discharge data from the St. Marks River Near Newport station (station 02326900) and 02327022 (Wakulla River near Crawfordville) were used as flow inputs. Flows from the St. Marks River Rise were reduced by 7.3 percent based on the established minimum flow for the St. Marks River Rise to ensure that recommended MFLs from Wakulla and Sally Ward springs would not produce significant harm when combined with the St. Marks River Rise adopted MFL. Additional input data files and sources are described in Appendix E.

The period between May 11, 2017, and July 19, 2017, was selected as the best available data for model calibration (i.e., based on boundary condition Stations HD-1, HD-2, and HD-5). In addition to water level, temperature, and specific conductivity data collected at the five “HD” monitoring stations, additional data obtained from the National Weather Service, University of South Florida, and USGS were included as described in Appendix E. Additional tests of the EFDC model’s responsiveness to forcing conditions were conducted by comparing measured to modeled water mass flux, salinity, and temperature data. All comparisons indicated that the EDFC model was appropriately calibrated and capable of simulating water surface elevations, temperature, salinity, and mass flux in the estuarine portion of the St. Marks River (Table 19). Specific details regarding EFDC model development and calibration can be found in Appendix B and Appendix E.

Wakulla River flows measured at USGS Station 02327022 (Wakulla River Near Crawfordville, Fl.) were selected to be used for the estuarine EFDC model input. These flows were selected on account of containing flows from Wakulla, Sally Ward, and other smaller springs in addition to other surface water inputs. It has been shown that downstream of USGS station 023237022 additional inflows to the Wakulla River are negligible (ATM 2017). Flows at this station extend from October 23, 2004, through present. Due to the long EFDC model simulation run time and the long duration of the baseline time period, a smaller time period was required for model input. A subset period was then selected that is most representative of the range and distribution of flows for the entire period of a flow period. The subset time period between December 1, 2007, through October 4, 2010, was determined to be representative of the entire flow distribution of the Wakulla River period of record and was selected as the baseline time period to be used in modeling efforts (Table 19, Figure 63, Figure 64).

In 2019, the NWFWMD established a minimum flow for the St. Marks River Rise which specified that long-term average spring flows must not fall below 419 cfs (7.3 percent allowable spring flow reduction). To ensure that cumulative spring flow reductions from Wakulla Spring, Sally Ward Spring, and the St. Marks River Rise would not impact estuarine habitats, flows from the St Marks River Rise were reduced by 7.3

percent for the model simulation period. Details of baseline time series selection for the Estuarine EFDC model can be found in Appendix B.

Although the EFDC model includes portions of both the Wakulla and St. Marks rivers, the focus of this study was on the evaluation of potential spring flow reductions from the Wakulla and Sally Ward springs. The oligohaline zones to be protected were selected based on salinity data collected along the Wakulla River as described in Section 2.2. Freshwater habitats, such as those found in the majority of the upper reaches of the Wakulla River, are generally viewed as having a salinity of 0 ppt; however, some dissolved salts are naturally present in water discharging from the springs. For much of the year the salinity in the Wakulla River upstream of the City of St. Marks is low (<1.0 ppt); however, higher salinity waters can encroach upriver during periods of reduced river discharge (May, June, and December 2016) (Figure 59). Most of the Wakulla River shoreline consists of freshwater forested swamps and floodplain habitats where salinities are below 0.5 ppt (NWFWMD 2016). Freshwater habitats extended from the Wakulla and Sally Ward springs down to profile Station W-5 during all vertical profile sampling events (Figure 59). The oligohaline zones included in the analysis include <0.5 ppt, <1 ppt, <2 ppt, and <3 ppt. Oligohaline zones were investigated in three different ways including the length of shoreline, surface area of bottom habitat, and the water volume. Results of the Estuarine Resources MFL assessment are provided in Section 5.2.

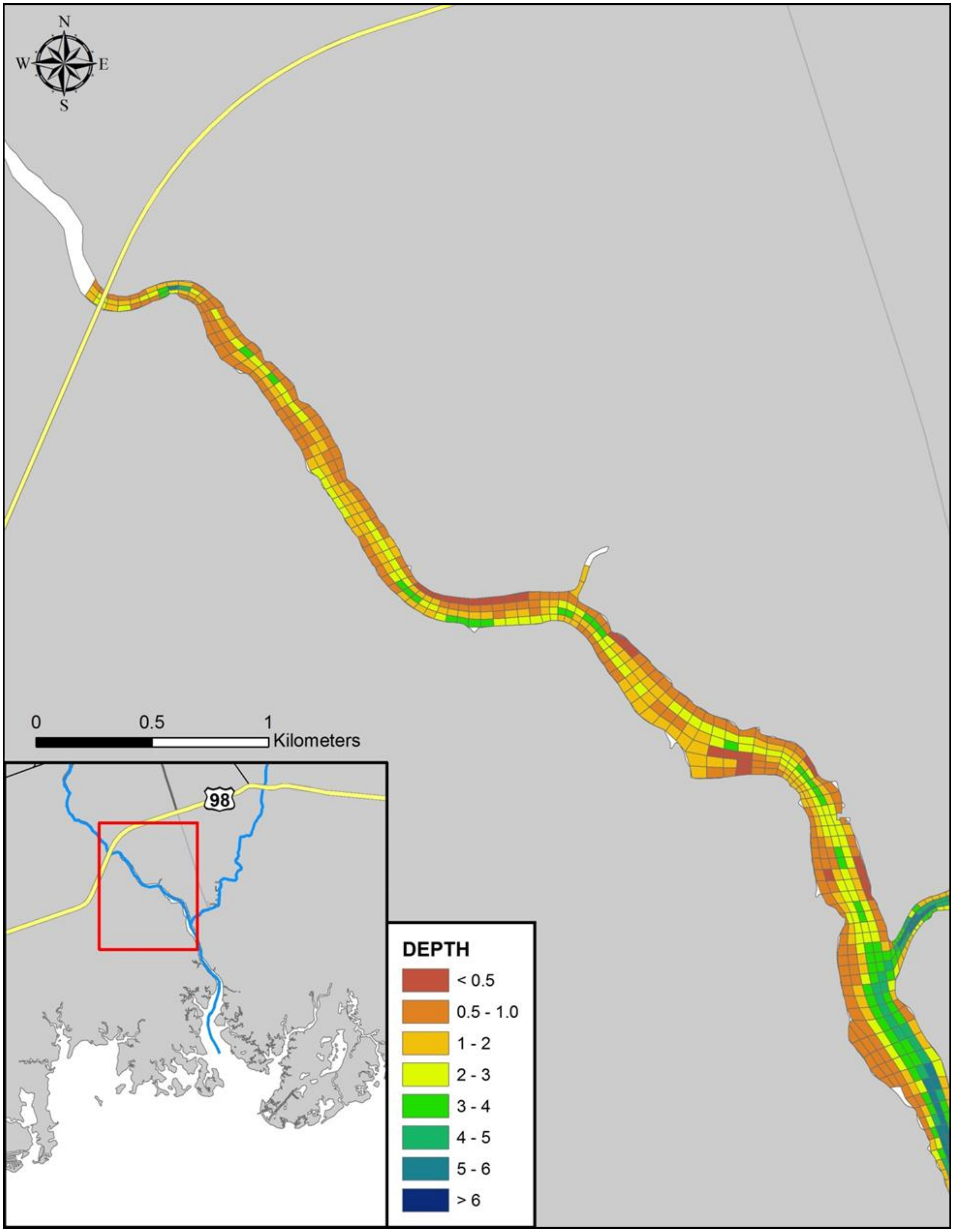

Figure 62: EFDC Model Domain of the Wakulla River Study Area.

Table 19: Comparison of Estuarine EFDC Model Full Period of Record and Modeling Subset Flows.

Flow Percentile	Wakulla River Near Shadeville Road Flows(cfs)	
	Full POR (October 23, 2004 through December 31, 2019	Modeling Subset (January 1, 2008 through December 31, 2010)
5	384	354
10	421	396
25	531	496
50	673	673
75	818	788
90	964	923
95	1104	1027
Mean	700	676

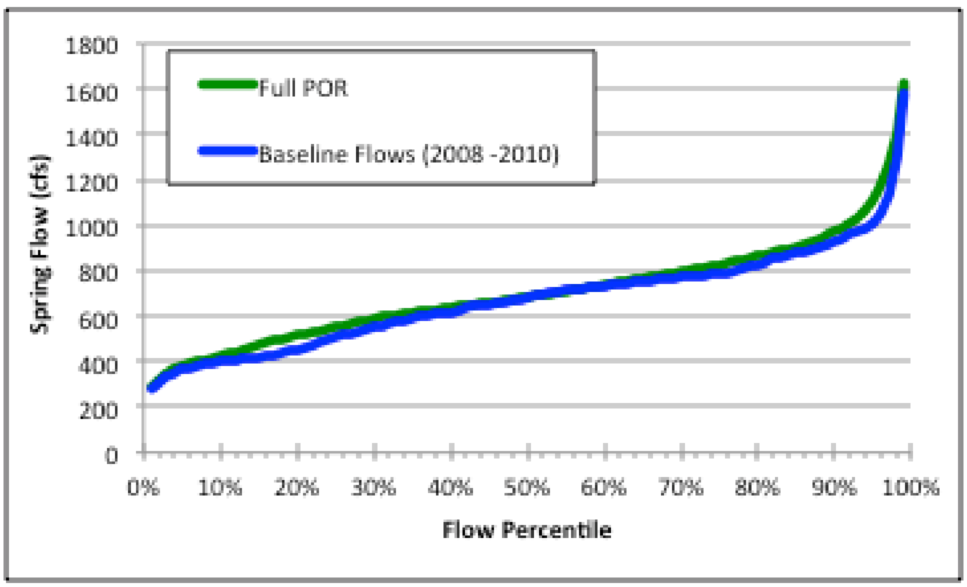

Figure 63: Flow Frequency Curves for the Full Period of Record and Model Subset Flows Used in Estuarine EFDC Model Analysis.

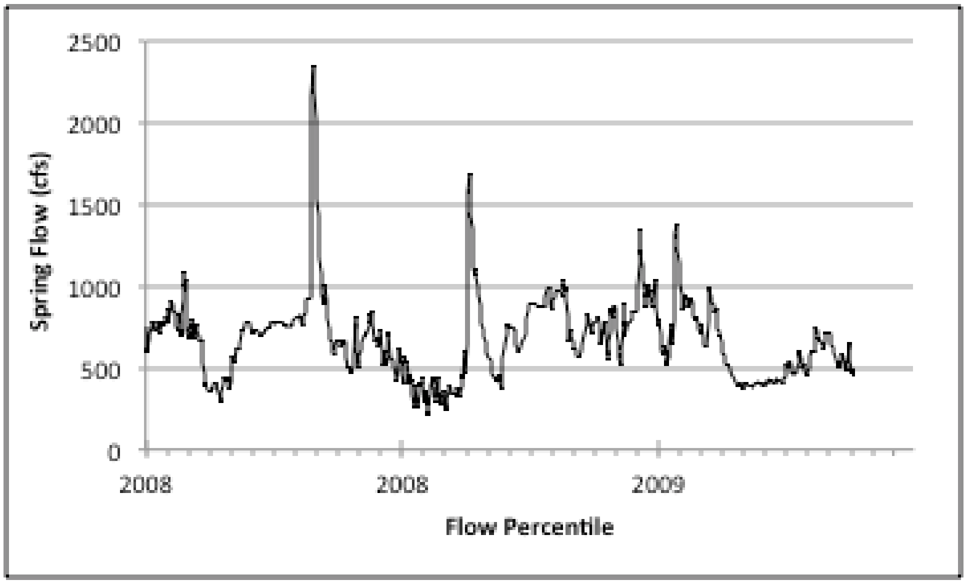

Figure 64: Estuarine EFDC Model Baseline Time Series.

Table 20: Estuarine EFDC Model Calibration Results for Salinity.

Calibration Point	ME (ppt)	MAE (ppt)	RMSE (ppt)	R2
HD-5 Surface	0.4	2.5	3.5	0.50
HD-4 Surface	0.2	1.7	2.6	0.30
HD- 5 Bottom	1.9	3.0	4.2	0.63
HD-4 Bottom	3.6	4.8	5.8	0.27
HD-3 Bottom	-0.1	0.1	0.7	0.12

4.3 EFDC Modeling and Manatee Thermal Refuge Evaluation (Thermal Model)

Previous minimum flow evaluations have used different modeling approaches to assess the availability of manatee thermal refuge. Many studies (Blue Spring, Homosassa River, Chassahowitzka River, Weekie Wachee) have utilized an EFDC model (Rouhani et al. 2007, SWFWMD 2008, SWFWMD 2012a, SWFWMD 2012b), although other models have also been used (SWFWMD 2017a, SRWMD 2006, SWFWMD 2004). Due to observed lateral differences in water temperature across the Wakulla River during freeze events, an EFDC model was determined to be most appropriate for manatee thermal refuge modeling since this model can account for variations in temperature laterally, vertically, and longitudinally.

The District contracted with Janicki Environmental, Inc. and Applied Technology and Management, Inc. to develop an EFDC model for the Wakulla Spring pool and spring run for a downstream portion of the river extending approximately 0.6 miles downstream from the Wakulla Spring main vent (Thermal Model). The development and implementation of the thermal model is summarized below. Additional details of thermal model development, calibration, and flow reduction scenarios can be found in Appendix C.

4.3.1 Model Development and Calibration

The thermal model extends from the Wakulla Spring main vent to the Wakulla Boat Tram located approximately 0.6 miles downstream (Figure 65). This stretch of the river includes the spring pool and immediate spring run where manatees have been observed by District staff during freezing air temperatures during 2017 to 2020. Data were collected to support EFDC model development, implementation, and calibration. Continuous stage, flow, and water temperature data have been collected at the Wakulla Spring main vent, Sally Ward Spring run bridge, and the Wakulla River Boat Tram station as previously described (Table 12). Local air temperature was obtained from the Tallahassee Regional Airport (NOAA 2020b). In addition, two temporary CTD sensors (conductivity, temperature, depth) were installed on either side of the river just downstream of the large bend in the river and below where the Sally Ward Spring run joins with the main river. These sensors collected continuous data and were used for additional model calibration/verification. Vertical and horizontal thermal profiles of the model domain were collected during the coldest days of the year during the winter months between 2017 and 2020. Thermal profiles were collected from surface to bottom at a minimum of three locations at five points across the river. Thermal profile data was used for additional model calibration.

Upstream boundary conditions were set using data from the Wakulla Spring main vent and Sally Ward Spring run, while downstream boundary conditions were set using Wakulla River Boat Tram station data. Initial model grid bathymetry was determined using acoustic doppler velocity meter depth recordings combined with water levels determined from surveyed benchmarks. Additional input data files and sources are described in Appendix C.

Following Hurricane Michael in October 2018, the stage discharge relationship changed in the model domain and as a result stages were unable to be appropriately calibrated among multiple years. As a result, the period between December 1, 2019, and March 1, 2020, was selected as the best available data for model calibration. This period was selected as it was the best representation of the system in its current state. Model calibration results showed that the EDFC model was appropriately calibrated and capable of simulating water surface elevations and temperature in the upper portion of the Wakulla River. Specific details regarding Thermal EFDC model development and calibration can be found in Table 21, Figure 66, Figure 67, Figure 68, Appendix C. The Wakulla at Sally Ward Spring Run Mouth represents a location where water from the Sally Ward Spring run mixes with water from the Wakulla River. The water temperature at this location is affected by the discharge volumes of the Wakulla River and Sally Ward Spring run in addition to the water temperatures of both locations. Water temperatures at this location are subject to larger daily fluctuations associated with air temperatures and the relatively slow velocities along the Sally Ward Spring run. Water flowing from the Sally Ward Spring run remains concentrated in a narrow excavated area along the left edge of water. Since this water can be colder than Wakulla River water and remains isolated, these grid cells were removed from the analysis and not included.

Due to the EFDC model simulation run time and the long duration of the baseline time period spring flows, smaller time periods were required for model input to assess the effects of flow reductions. Four separate time periods were selected for this purpose which spanned the range of Wakulla Spring vent flows and temperatures, in addition to including a significant cold period where reduced air temperatures could potentially affect the amount of available manatee thermal refuge. All subsets selected occurred between November and March when manatees are most likely to use Wakulla Spring as a thermal refuge between the winters of 2006/2007 and 2019/2020. These winter periods were selected as they are the winters when manatees have been documented using Wakulla Spring during winter months. Prior to the winter of 2006/2007 manatees had not been documented near the Wakulla Spring vent for extended periods of time. Winter periods were selected when manatees were known to be present in the Wakulla River since it is unknown why manatees were not present in the Wakulla Spring area prior to 2006/2007. Manatee use of Wakulla Spring may have been limited by hydraulic and atmospheric conditions and including these conditions in the analysis may represent a protection of conditions not suitable for manatees. Winter periods were then selected that contained 1- a wide range of Wakulla Spring vent discharges, 2- concurrent spring vent discharges and vent temperature measurements, 3- relative cold spring vent water temperatures (<20°C). Based upon the selection criteria described above, four periods selected for analysis are:

1- February 9, 2013 through March 31, 2013
2- November 14, 2014 through March 31, 2015
3- November 6, 2017 through March 31, 2018
4- November 1, 2018 through March 31, 2019

Simulations of baseline conditions and reduced spring flow were made for each of the time periods selected. An initial spring flow reduction scenario of 30 percent was used to assess the responsiveness of the model and bracket the spring flows corresponding with a 15 percent reduction in available manatee thermal area. A 30 percent initial spring flow reduction scenario was selected as this was considered an extreme value beyond which spring flow reductions were considered unlikely. Subsequent spring flow reductions are used to determine what spring flow reduction would result in a 15 percent thermal area reduction if necessary. Additional details concerning thermal EFDC model development and calibration can be found in Appendix C. Thermal EFDC model MFL scenario results can be found in Section 5.1.2.

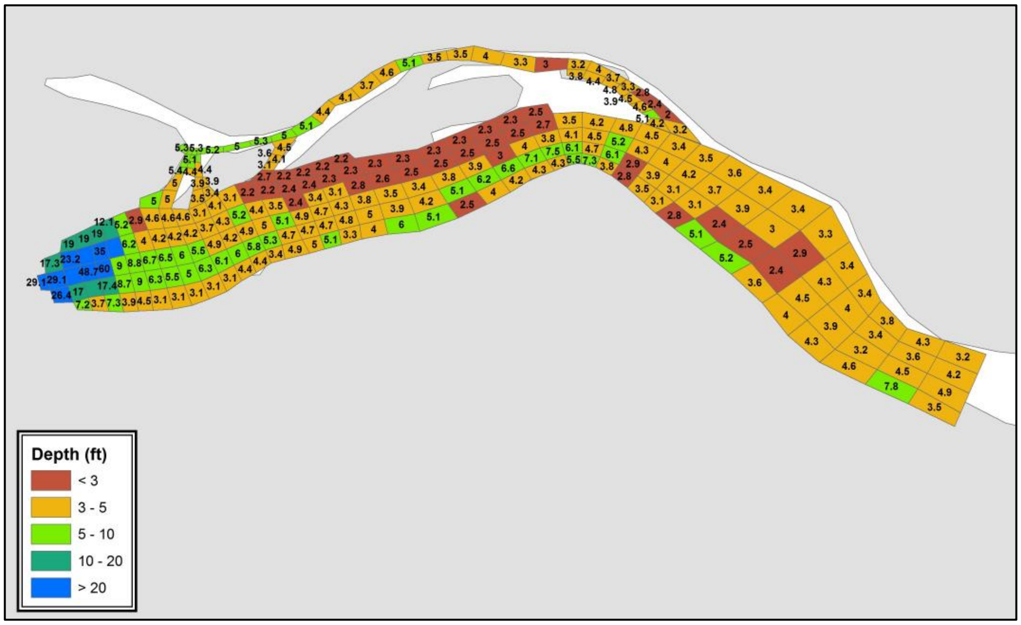

Figure 65: Wakulla Spring Manatee Thermal Refuge EFDC Model Domain and Grid Cell Depths.

Table 21: Thermal EFDC Model Calibration Results. Calibration point locations are depicted on Figure 30.

Calibration Point	R2	RMSE	ME	MAE
Wakulla Boat Dock	0.44	0.11	0.10	0.10
Wakulla at Bend	0.88	0.03	-0.01	0.03
Wakulla at Sally Ward Run Mouth	0.95	0.25	0.09	0.20

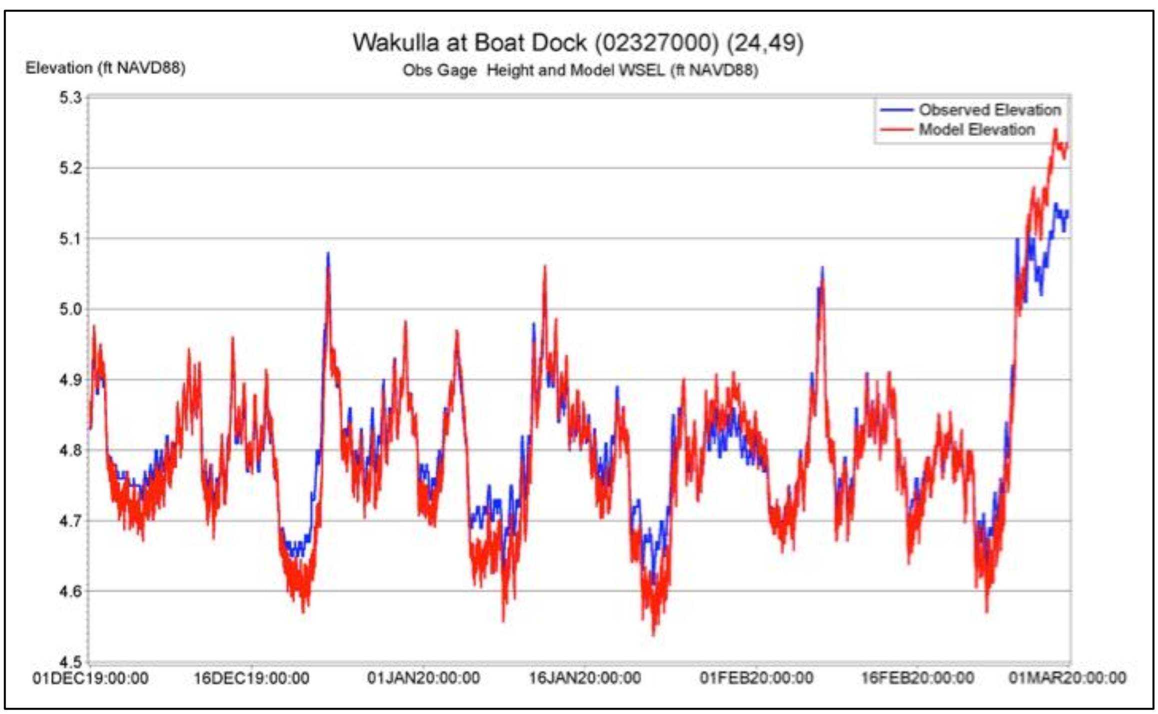

Figure 66: Thermal EFDC Model Calibration Results, Observed vs. Predicted Wakulla River Stage at the Wakulla Boat Dock.

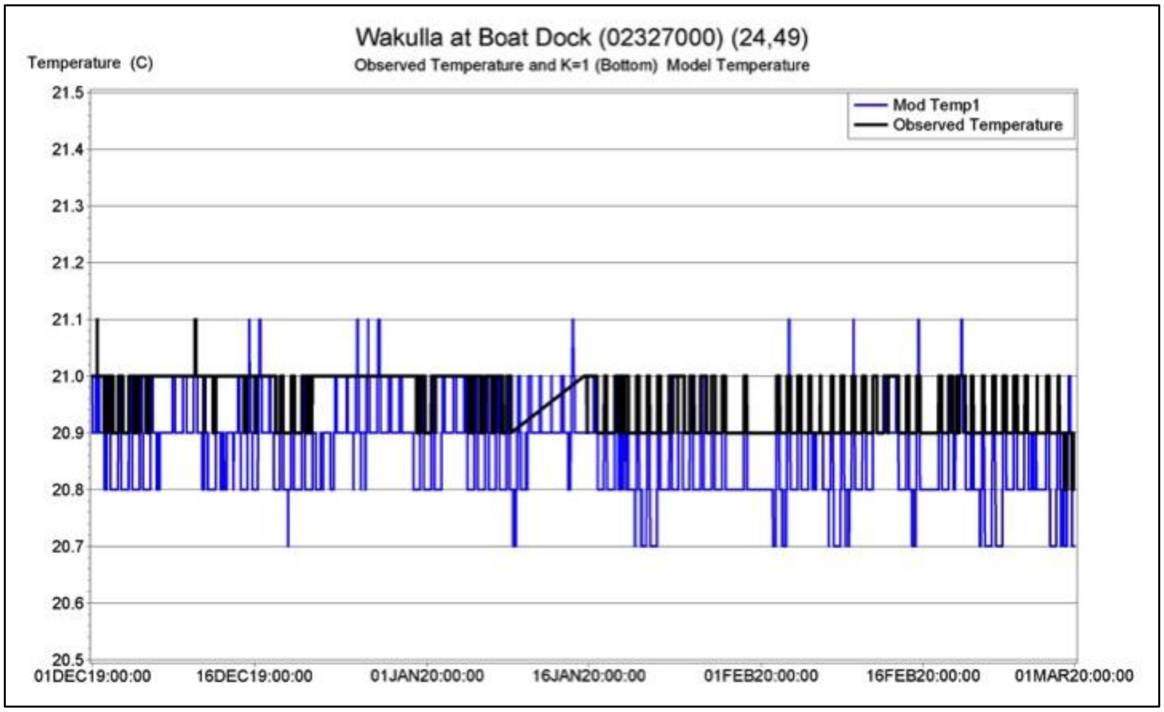

Figure 67: Thermal EFDC Model Calibration Results, Observed vs. Predicted Temperature at the Wakulla Boat Dock.

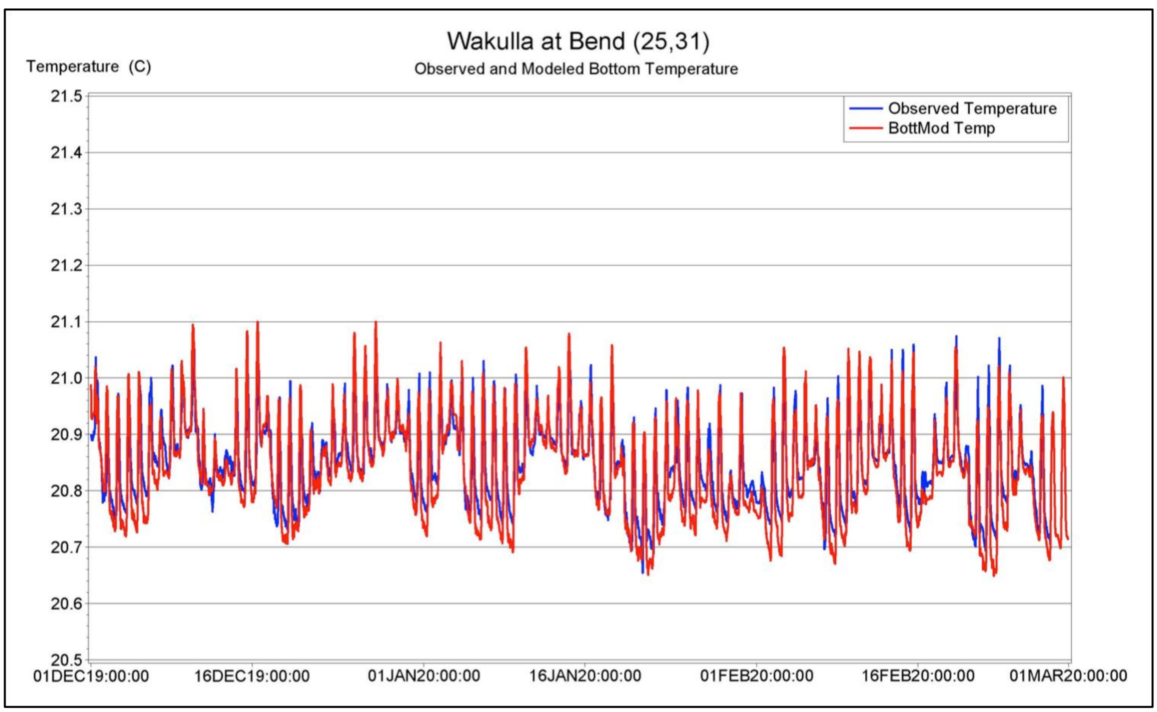

Figure 68: Thermal EFDC Model Calibration Results, Observed vs. Predicted Temperature at the Wakulla River Bend.

4.4 Consideration of Instream Habitat Models

Instream physical habitat models such as Physical Habitat Simulation (PHABSIM) and the System for Environmental Flows Analysis (SEFA), which relate changes in flow to usable habitat by aquatic species, were considered for use in determining minimum flows for the Wakulla River. A PHABSIM or SEFA simulation model utilizes site-specific instream measurements at fixed intervals across a series of transects at locations of interest along a river. Site-specific measurements include open-channel flow characteristics (water surface elevation, depth and velocity), substrate composition, refuge/cover distribution, and species-specific habitat suitability criteria (Gore 2015).

Preliminary field work was performed to identify suitable transects and characterize velocities and substrates along the Wakulla River during September 2015. Field investigations revealed that large portions of the Wakulla River are significantly influenced by tide, in addition to submerged aquatic vegetation, including filamentous algae, along the much of the spring run, which precluded the development of reliable relationships among channel profiles, velocities and substrates (Gore 2015).

Models capable of modeling instream habitat are continually being updated and refined and while at the time of this technical assessment's preparation, suitable models were not available (Gore 2015) this may not be the case during future MFL (re)evaluations. As part of the District's adaptive management policy for MFLs, the use of instream habitat models will be reconsidered during the Wakulla and Sally Ward Spring MFL reevaluation.

5 Evaluation of Water Resource Values and Results

This section describes the evaluation and results of the Water Resource Value metrics described in Section 3.

5.1 HEC-RAS Model WRV Evaluation

For the purposes of evaluating the effects of spring flow reductions on MFL WRVs, a steady-state version of the calibrated HEC-RAS model was used. Unless otherwise stated, median downstream water level boundary conditions (e.g., tidal boundary conditions) were used in WRV analyses.

The period of flow record between October 23, 2004, and December 31, 2019, for the Wakulla and Sally Ward springs was used as the baseline time series to assess metrics evaluated with the HEC-RAS model (WRV 1 Recreation In and On the Water and WRV 2 Fish and Wildlife Habitats and the Passage of Fish). The methodology and results for each WRV metric are described below. The methodology used to determine the spring flow reduction associated with a 15 percent reduction in the frequency of occurrence for each WRV metrics is described below. A 15 percent reduction in the percent of time in a WRV metric has been observed has been implemented as the protection standard for numerous MFL assessments throughout Florida and is also used in this assessment.

<u>Minimum Flow Determination Methodology</u>

1. Determine critical elevation (e.g., river stage associated with sufficient depth) for the metric at each transect.
2. Using the HEC-RAS model output (water surface elevation, river flow, and exceedance frequency), determine the exceedance frequency of critical river flow at each transect associated with the critical elevation determined in step 1. The exceedance frequency indicates the percentage of time that the critical elevation is attained or exceeded.
    - When the critical elevation was bracketed by two exceedance frequencies, the exceedance frequency for the critical elevation was determined using a linear relationship based on the difference between the water surface elevations.
3. Using the exceedance frequency from step 2, determine the critical spring flow at Wakulla and Sally Ward Spring.
4. Determine the average number of days per year the critical spring flow at Wakulla and Sally Ward Spring was achieved based on the exceedance frequency.
5. Reduce the number of days the critical flow at the spring was achieved by 15 percent.
6. Determine the exceedance frequency associated with the reduced number of days and determine the associated flow at Wakulla and Sally Ward Spring.
7. Calculate the allowable reduction in spring flow (cfs) associated with the reduced frequency of inundation by subtracting the flow determined in step 6 from that in step 3.
8. Determine the allowable spring flow reduction using the result from step 7.

5.1.1 WRV1 Recreation In and On the Water

Two metrics were utilized to assess the effects of Wakulla and Sally Ward Spring flow reductions on WRV 1, Recreation In and On the Water. These metrics include the safe passage of power boats in two separate areas of the river (the Edward Ball Wakulla Springs State Park boat tour area and downstream of Shadeville Road) and the safe passage of canoes and kayaks downstream of Shadeville Road. As discussed in Section 2.11, below river station 26000 water depths in the Wakulla River are driven by tidal fluctuations rather than changes in spring flow. In addition, these areas of the Wakulla River are relatively deep and depth for public motorboat use is not limited. As a result, although results are presented in Figure 69 and Figure 70, Recreation metrics were not considered downstream of transect 26000.

5.1.1.1 Safe Boat Passage

Multiple safe boat passage metrics were used. The Edward Ball Wakulla Springs State Park boat tour runs from the Wakulla Spring pool downstream approximately 1.0 miles. Public access to the Wakulla River is limited to below the Shadeville Road bridge to the confluence with the St. Marks River.

Safe Motorized Boat Passage – The critical depth for the safe passage of motorized boats metric was a minimum channel depth of 2.0 ft across a 30 ft continuous channel width. The motorized boat passage metric was assessed at each HEC-RAS model transect where recreational, public boat access is allowed, between river station 32448.65 (Shadeville Road) and river station 61.68 (confluence with St. Marks River) (Figure 69). The critical depth for the metric was first calculated by determining the highest elevation (NAVD 88, ft) across the deepest 30 ft portion of channel width (maximum substrate elevation) (Table 22). The water depth required for the metric (2.0 ft) was added to the maximum substrate elevation to obtain the critical elevation. The critical elevation was then compared with HEC-RAS modeling results to determine the flow percentile and river discharge associated with the critical elevation. Safe motorized boat passage was assessed using a median downstream boundary condition.

As can be seen in Figure 69 and Table 22, safe motorized boat passage was possible under all modeled spring flow scenarios as the critical depth for this metric was exceeded at all transects during even the lowest modeled flows (99 percent exceedance) under median downstream boundary conditions. For example, transect 32448.65 displayed a maximum substrate elevation of -2.38 ft (NAVD 88) and a critical elevation of -0.38 ft NAVD 88 (i.e., -2.38 ft + 2.0 ft). Under the lowest modeled flows (99 percent Exceedance), water surface elevations at transect 32448.65 were 1.03 ft (NAVD 88), which exceeded the critical elevation by 1.41 ft. As a result, this metric at this transect was determined to not be limiting. The five transects with the least amount of water depth available over the critical elevation are listed in Table 22. Since flows limiting motorized boat passage were not observed during the baseline time period, this metric was not considered further for MFL analysis.

Safe Canoe/Kayak Passage – The evaluation of safe canoe and kayak passage metric was performed using the same methodology as the analysis of safe motorized boat passage. The critical depth (NAVD 88) for the safe passage of canoe/kayak vessels was determined by adding 1.5 ft to the thalweg elevation (maximum substrate elevation) for each transect (Figure 70 and Table 22). This metric was assessed at all locations where public canoeing and kayaking is allowed, i.e., downstream of the Shadeville Road bridge (River Station 32448.65).

Safe canoe and kayak passage was possible at all river stations examined at all flows under median downstream boundary conditions. Transect 32448.65 was the most limiting transect, with a maximum substrate elevation of -3.45 ft (NAVD 88) and a critical elevation of -1.95 ft (NAVD 88). The minimum modeled water depth (99 percent exceedance) was 1.03 ft which exceeded the critical depth by 2.98 ft (Figure 70). The five transects with the least amount of water depth available over the critical elevation are listed in Table 22. Since flows limiting motorized boat passage were not observed during the baseline time period, this metric was not considered further for MFL analysis.

State Park Boat Tour Passage – The Wakulla Springs State Park river tour boat operates along a set route of approximately 1.9-mile loop. The tour boat leaves the boat dock and travels approximately 0.8 miles downstream along the right edge of water before crossing the river and returning upstream along the left edge of water. The tour traverses the Wakulla Spring pool before returning to the boat dock.

The critical water depth for the safe state park tour boat passage is 3.0 ft. The safe passage depth was determined by measuring the vertical distance between visible water lines on tour boats and the bottom of the motor. To account for the established tour boat route which has been structurally changed through excavation as described in Section 1.3.4, a minimum water depth of 3.0 ft across two continuous 20 ft channel widths was used, one along the right edge of the river and one along the left edge of the river. A continuous width of 30 ft, as was used in the recreational boat passage metric, was not utilized since two tour boats will not be passing each other in the same portion of the river. This metric was assessed at all river station transects located within the established tour boat route (i.e., River Stations 48252.78, 45868.56, and 44619).

Wakulla Springs State Park tour boat operation was possible at all modeled flows at the three river stations present in the range of the tour boat route (48252.78, 45868.56, and 44619) (Table 22). Transect 44619 was the most limiting transect, with a maximum substrate elevation of 0.1 ft (NAVD 88) and a critical elevation of 3.1 ft (NAVD 88). The minimum modeled water depth (99 percent exceedance) was 3.28 ft which exceeded the critical depth by 0.18 ft. The three transects present along the tour boat route and the results of the analysis are listed in Table 22. Since flows limiting state park boat tour boat passage were not observed during the baseline time period, this metric was not considered further for MFL analysis.

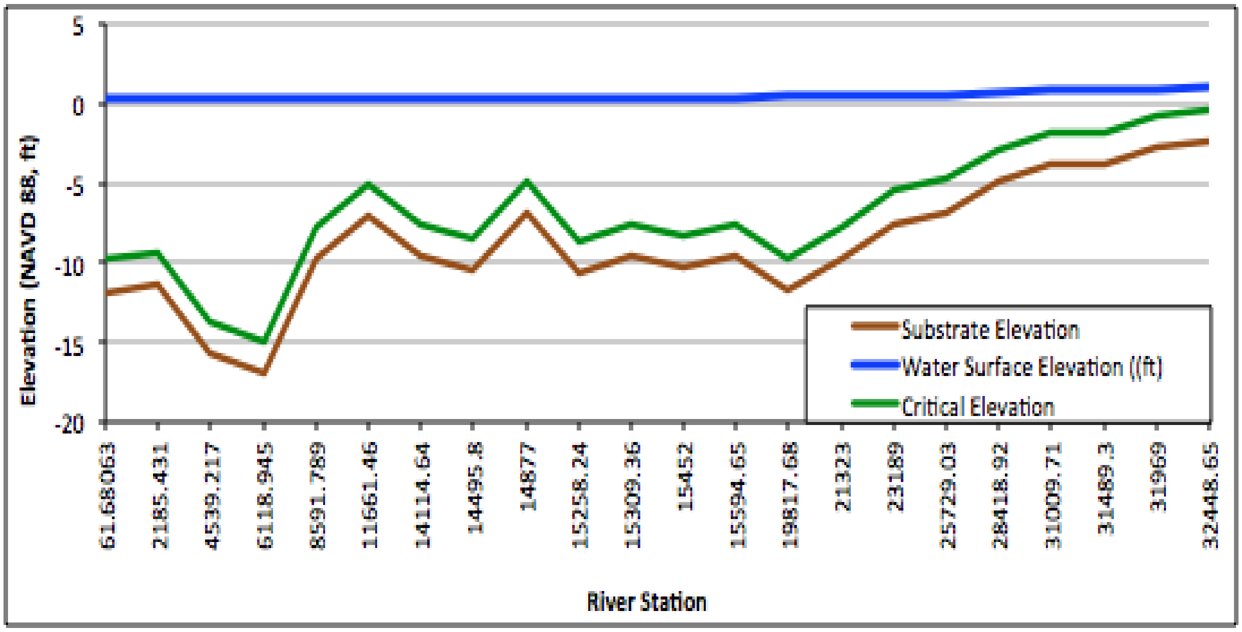

Figure 69: Substrate Elevation, Critical, and Water Surface Elevations (99 Percent Exceedance) Across Transects for Safe Power Boat Passage Metric.

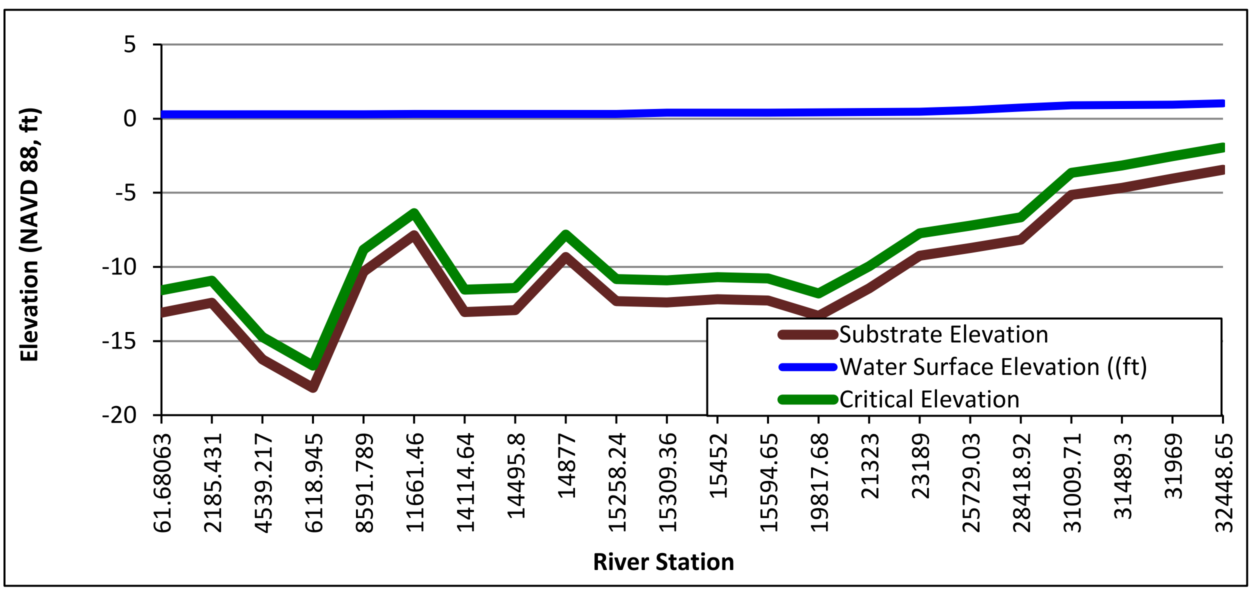

Figure 70: Thalweg, Critical, and Water Surface Elevations (99 Percent Exceedance) Across Transects for Safe Canoe/Kayak Passage Metric. *The 99 Percent Exceedance is the lowest flow modeled.

Table 22: Critical Elevation and Modeling Results for Metrics Associated with Recreation In and On the Water.

Metric					Model Results		
Metric Name	River Station (ft)	Maximum Substrate Elevation (NAVD88)	Water Depth for Metric (ft)	Critical Elevation (Water Surface) (NAVD88)	Percent Exceedance	Water Surface Elevation (NAVD 88)	River Flow (cfs)
Safe Power Boat Passage	32448.65	-2.38	2.0	-0.38	99	1.03	293
	31009.71	-4.14	2.0	-2.14	99	0.90	293
	28418.92	-5.4	2.0	-3.4	99	0.74	293
	25729.03	-6.51	2.0	-4.51	99	0.57	293
	23189	-7.42	2.0	-5.42	99	0.46	293
Safe Canoe/Kayak Passage	32448.65	-3.45	1.5	-1.95	99	1.03	293
	31009.71	-5.2	1.5	-3.7	99	0.90	293
	11661.46	-7.87	1.5	-6.37	99	0.31	293
	28418.92	-8.16	1.5	-6.66	99	0.74	293
	25729.03	-8.72	1.5	-7.22	99	0.57	293
Wakulla Tour Boat Passage	48252.78	-0.79	3.0	2.21	99	3.82	206
	45868.56	-1.0	3.0	2.0	99	3.56	221
	44619	0.1	3.0	3.1	99	3.28	228

5.1.2 WRV2 Fish and Wildlife Habitats and the Passage of Fish

Many floral and faunal species are known to inhabit the Wakulla River. As a result, multiple habitat-based metrics were evaluated to protect the Wakulla River and Sally Ward Spring runs and their floodplain. These metrics were designed to protect habitats inundated across a range of flows.

Fish Passage

Based upon documented fish species occurrence data for the Wakulla River and Sally Ward Spring runs, largemouth bass, *Microptera salmoides*, was determined to be the largest bodied species that could potentially have passage affected by reduced spring flows (Table 7). Analysis completed by the SWFWMD (SWFWMD 2002), determined a critical depth of 0.6 ft above the thalweg to be appropriate for *M. salmoides* passage across shallow areas. The thalweg location is defined as the lowest elevation along the channel. This metric was assessed at all HEC-RAS transects along the Wakulla River and Sally Ward Spring runs to determine where water depths were potentially limiting. The depth required for fish passage was calculated by adding 0.6 ft to the thalweg elevation (Figure 71, Table 23).

Safe fish passage was possible at all river stations at all flows. Transect 41707.76 was the most limiting transect, with a maximum substrate elevation of 0.1 ft (NAVD 88) and a critical elevation of 0.7 ft (NAVD 88). The minimum modeled water depth (99 percent exceedance) was 2.78 ft which exceeded the critical depth by 2.08 ft (Figure 71). The five transects with the least amount of water depth available over the critical elevation are listed in Table 23. Since flows limiting safe fish passage were not observed during the baseline time period, this metric was not considered further for MFL analysis.

Similar results were observed along the Sally Ward Spring run. Transect 48873 was the most limiting transect, with a maximum substrate elevation of 1.06 ft (NAVD 88) and a critical elevation of 1.66 ft (NAVD 88). The minimum modeled water depth (99 percent exceedance) was 3.84 ft which exceeded the critical depth by 2.78 ft during median downstream boundary conditions (Figure 71). The five transects with the least amount of water depth available over the critical elevation are listed in Table 23. The water surface elevation at each transect is 3.84 ft NAVD 88, which is to be expected due to the short distance between the transects (569 ft) and the backwater effects from the Wakulla River determining stage in this portion of the Sally Ward Spring run. Since flows limiting safe fish passage along the Sally Ward Spring run were not observed during the baseline time period, this metric was not considered further for MFL analysis.

While largemouth bass, and potentially long-nose gar, are the deepest bodied fish documented in the Wakulla River and Sally Ward Spring run system, the Florida Fish and Wildlife Conservation Commission has expressed concern that striped bass, *Morone saxatilis*, may utilize the Wakulla River (Ted Hoehn, personal communication, Eric Nagid, personal communication). As described above, even at the lowest modeled flow at the most limiting transect, a 2 ft water depth threshold at the thalweg which has been recommended by the FWC for the metric, was always achieved along the Wakulla River (FWC 2019e).

Table 23: Results of Fish Passage Evaluation. Results include the five transects with the least amount of water depth present above the critical elevation.

Metric					Model Results		
River Stretch	**River Station (ft)**	**Maximum Substrate Elevation (NAVD88)**	**Metric Depth (ft)**	**Critical Stage (Water Surface) Elevation (NAVD88)**	**Percent Exceedance**	**Water Surface Elevation (ft, NAVD88)**	**River Flow (cfs)**
Wakulla River	41707.76	0.1	0.60	0.7	99	2.78	245
	32448.65	-3.45	0.60	-2.9	99	1.03	293
	32910.27	-3.33	0.60	-2.7	99	1.21	293
	32526.33	-3.43	0.60	-2.8	99	1.15	293
	48252.78	-1.53	0.60	-0.9	99	3.82	208
Sally Ward Spring Run	48873	1.06	0.60	1.66	99	3.84	6.71
	49332	0.94	0.60	1.54	99	3.84	6.71
	49370	0.94	0.60	1.54	99	3.84	6.71
	49206	0.75	0.60	1.35	99	3.84	6.71
	49442	0.56	0.60	1.16	99	3.84	6.71

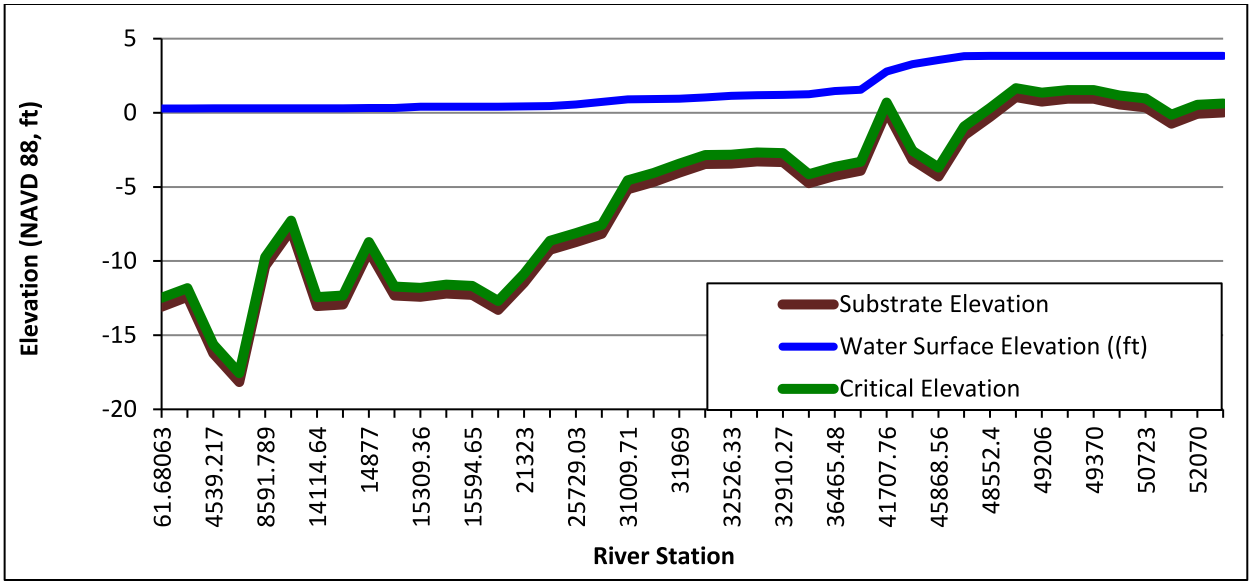

Figure 71: Critical Elevation and Minimum Modeled Water Levels for Safe Fish Passage Along the Wakulla River. *The 99 Percent Exceedance is the lowest flow modeled.

Florida Manatee

Two evaluations were conducted related to Florida manatee: safe manatee passage and thermal refuge availability.

Safe Manatee Passage – Manatee passage is not known to be a limiting factor along the Wakulla River. A safe manatee passage depth of 3.8 ft water depth across a 3.8 ft minimum channel width (described in section 3.2.2) is used to ensure manatee passage along the Wakulla River. Manatee passage was assessed at all river stations located in the Wakulla River throughout the year. Manatee do not regularly enter the Sally Ward Spring run and the Sally Ward spring pool does not serve as a thermal refuge (Valade et al. 2020). The critical water surface elevation associated with the safe manatee passage along the Wakulla River was determined by first identifying the maximum channel elevation (i.e., survey point) located in the deepest portion of the river channel with a minimum of 3.8 ft channel width at each river station (HEC-RAS transect) (Table 24). A minimum water depth of 3.8 ft was added to this elevation to obtain the critical water surface elevation. Consistent with other peer reviewed MFL determinations for tidally influenced systems (SWFWMD 2008, SWFWMD 2012A, SWFWMD 2012B, SWFWMD 2017a), this was assessed using a mean daily water surface elevation during a high downstream boundary condition. Prior work and telemetry data collected at the Crystal River/King's Bay system indicated that manatees take advantage of tidal conditions, with movements more likely to occur during high tide and water levels (Little et al. 2019). The high downstream boundary condition was based on the best available data, which was the average daily high water level for the period of record flows at station HD-3 (downstream boundary condition) between April 22, 2008, and December 31, 2015. Reliable stage data at station HD-3 was not available after December 31, 2015 as low water levels were not recorded.

Along the Wakulla River, water depths of 3.8 ft were not exceeded during all flows at a single transect, River Station 41707.76 (Table 24, Figure 72). This river station is located downstream of the Wakulla River/Sally Ward Spring Run and flows at this station are comprised of discharge from both springs. At this transect, a water depth of 3.8 ft resulted in a critical elevation of 4.04 ft NAVD 88, which is associated with a total river flow of 560 cfs. This river flow corresponds to a combined spring flow of 520 cfs and was met or exceeded 66 percent of the time (Table 24, Table 25). The remaining 40 cfs of river flow at this location is associated with lateral groundwater pickup and surface water inputs between the springs and transect 41707.76. A 15 percent reduction results in a combined spring flow reduction of 59 cfs or an average overall reduction in water levels of less than 1.7 inches. Conversations with FWC staff have indicated that manatees are capable of safely crossing shallow areas with water depths above 2.5 ft (FWC, personal communication), significantly less than the 3.8 ft used. Water depths at River Station 41707.76 were never observed below 2.9 ft during the entire period of record flows. Because water depths along Transect 41707.76 exceeded 2.5 ft even after a reduction of less than 1.7 inches, access to the Wakulla Spring pool by manatees will not be impeded by a flow reduction of 59 cfs.

Transect 41707.76 is located along a known shallow area of the Wakulla River approximately mid-way between Wakulla Spring and the Shadeville Hwy Bridge (Figure 60). This portion of the river is relatively wide (approximately 516 ft between the left edge of water and right edge of water at a transect water surface elevation of 3.9 ft) and shallow (Figure 73). Unlike upstream transects near the spring pool which were artificially excavated (DEP 2004) and downstream transects which are deeper, transect 41707.76 has no deeper channelized areas and the river bottom elevation tends to vary little across the river (Figure 73 and Figure 74).

Little submerged aquatic vegetation is present near this transect. Submerged and emergent vegetation is largely limited to the river edges, however several areas of bullrush (*Scirpus* sp.) and isolated cypress trees are present in the river channel (Figure 75 and Figure 76). The river channel substrate at this transect consists of a layer of sand overlying a limestone substrate at an undetermined depth beneath the sand. River edges with emergent vegetation and floodplains consist of wetland soils. While the river channel substrate consists primarily of sand which may be subject to sediment transport, this section of the river consists of a shallower, unexcavated areas and the minimal change between river surveys conducted during 2015 (Pre-Hurricane Michael) and 2019 (Post-Hurricane Michael) (Figure 73 and Figure 74) suggest that this feature in the river is relatively permanent.

Table 24: Results of the Manatee Passage Minimum Flow Analysis for the Most Limiting Transects Along the Wakulla and Sally Ward Spring System.

Metric					Model Results		
River Stretch	River Station (ft)	Maximum Substrate Elevation (NAVD 88)	Critical Depth (ft)	Critical Stage (Water Surface) Elevation (NAVD 88)	Percent Exceedance	Water Surface Elevation (ft, NAVD 88)	River Flow, cfs
Wakulla River	41707.76	0.24	3.80	4.04	66	4.04	560 cfs
	32718.3	-3.15	3.80	0.65	99	2.29	293 cfs
	31969.0	-2.77	3.80	1.03	99	2.18	293 cfs
	45868.56	-4.0	3.80	-0.2	99	3.7	221 cfs
	48252.78	-1	3.80	2.8	99	3.84	208 cfs

Table 25: Calculation of Allowable Flow Reductions at River Station 41707 at Wakulla and Sally Ward Springs.

Spring	Critical Values			15% Decrease		Change in Days of Inundation and Associated Minimum Flow	
	Critical River Flow (Stage NAVD 88)	Exceedance Frequency	Critical Spring Flow (cfs)	Reduced Exceedance Frequency	Baseline Spring Flow (cfs)	Change in Spring Flow (cfs)	Percent Change
Combined Wakulla and Sally Ward Spring	560 cfs (4.04 ft)	66%	520.20 cfs	56%	579.41 cfs	59.21 cfs	10.2

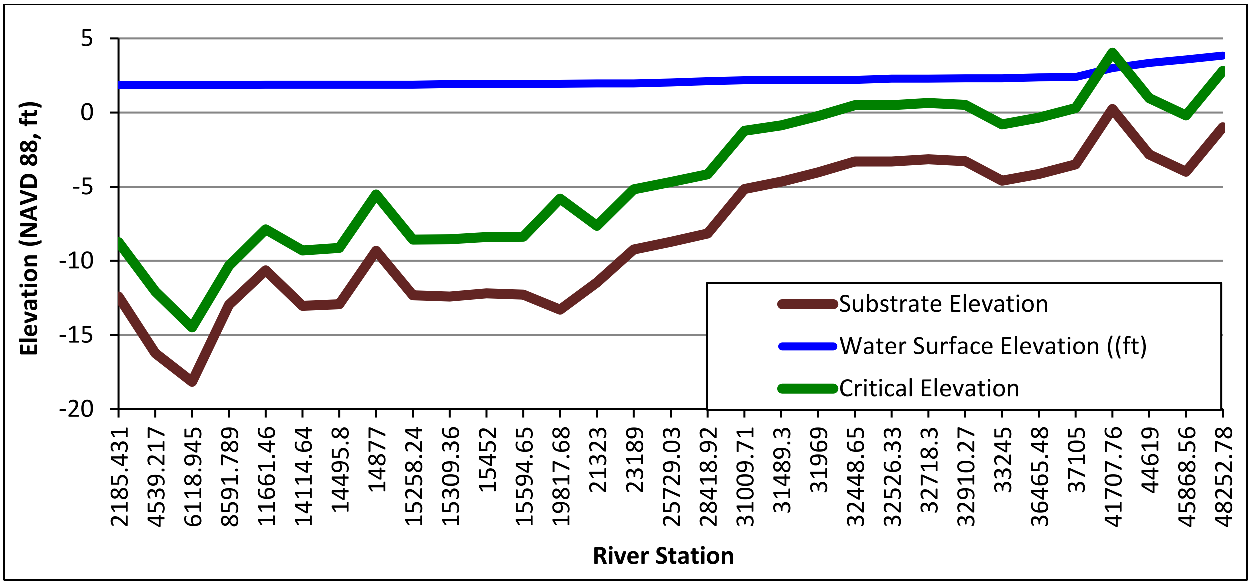

Figure 72: Critical Elevation and Minimum Modeled Water Levels for Manatee Passage Along the Wakulla River.

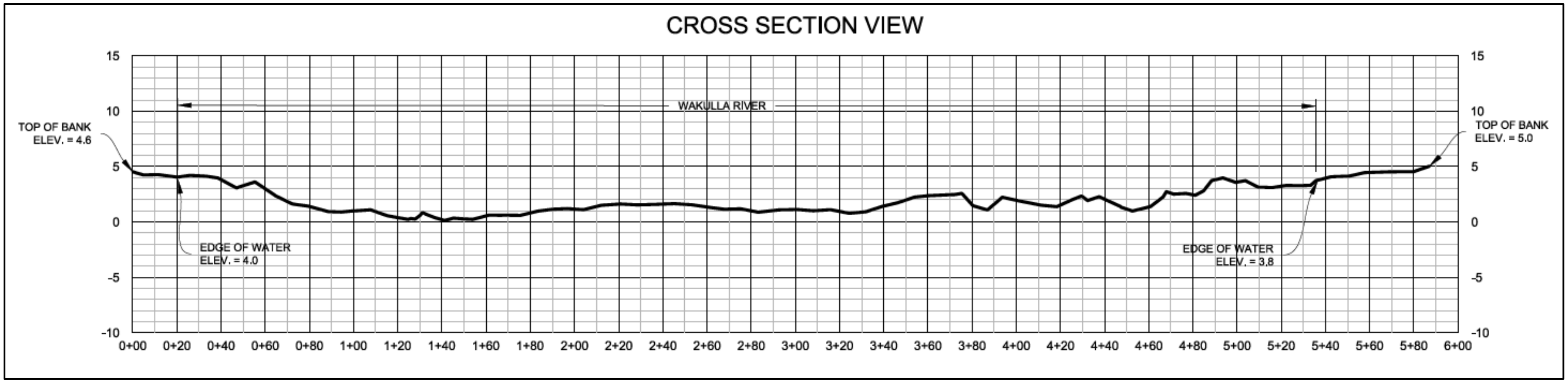

Figure 73: Bathymetric Survey of Wakulla River Transect 41707.76 (W2) conducted by Wantman Group, Inc. on 8/2/2019.

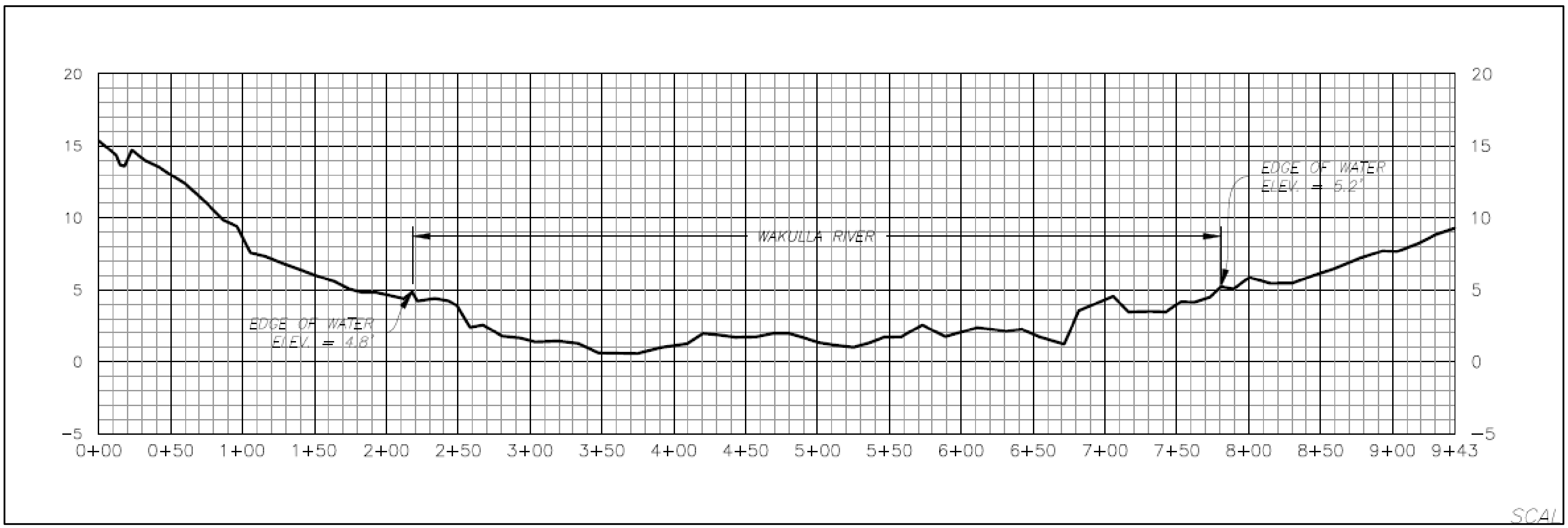

Figure 74: Bathymetric Survey of Wakulla River Transect 41707.76 (W2) from Wantman Group, Inc. Survey Report dated 10/21/2015.

Figure 75: Transect 41707.76 Along the Wakulla River. Photo taken on February 25, 2021 Looking to the Northeast.

Figure 76: Transect 41707.76 and View of Shallow areas of River Upstream and Downstream of the Transect.

Manatee Thermal Refuge – Chronic stress to manatees is reported to occur when water temperatures fall below 20° C for 72 hours or longer (Rouhani et al. 2007). Acute stress is reported to occur when water temperatures drop below 15° C for four hours or longer (Rouhani et al. 2007). During periods where cold water temperatures may result in chronic or acute stress, manatees often seek a warm water refuge until water temperatures increase again. The manatee thermal refuge metric is designed to protect the availability of manatee warm water refuge during the short-term cold weather periods. No assumptions were made concerning the availability of forage and other biological requirements during these short time periods.

The baseline winter periods were reviewed to identify the most limiting periods for thermal refuge based on low water temperature, low spring flows, and low air temperature. Four time periods were identified for which thermal conditions may limit manatee thermal refuge at Wakulla Spring. During the four winter periods evaluated, the area of suitable warm water refuge greater than 3.8 ft in depth that exceeded the chronic stress criteria (>20°C for more than three days) varied considerably from 0 m^2 (0 percent of the study area or no available warm water refuge in the model domain) to 89,227 m^2 (100 percent of the model domain). Most variation was associated with reductions in the temperature of water flowing from the spring vent.

A comparison between baseline and conditions associated with a 30 percent reduction in spring flows indicates that during 41 days of the 458-day record, the 30 percent flow reduction scenario resulted in greater surface area of water of ≥20°C than was simulated to occur under measured Wakulla Spring flows. In other words, the amount of thermal refuge increased under the flow reduction scenario. As previously stated, the temperature of water flowing from the Wakulla Spring vent naturally falls below 20°C for extended periods of time during winter months during which time warm water refuge within the model domain would only exist due to air temperatures raising water temperatures above 20°C. During these periods, reductions in Wakulla River flow should increase the contact time with warmer air temperatures and represent a net increase in warm water refuge. This likely resulted from the inverse relationship between spring discharge and water temperature observed on some occasions during the winter months (Appendix C).

To facilitate a conservative analysis of only those days with reductions in the surface areas with water temperatures ≥20°C, reductions for all days when there was an increase in surface area of ≥20°C due to the flow reduction scenario were set to zero. In addition, all days with no surface area of ≥20°C under baseline conditions were also set to zero. In total, 58 days of the 458 days evaluated either had zero surface area of ≥20°C under baseline (e.g., measured spring flows) or increases in the surface areas of ≥20°C for the 30 percent flow reduction scenario. All remaining days showed a reduction in warm water refuge surface area with reduced spring flows.

When looking at the chronic temperature criteria, which requires that water temperature not fall below 20° C for more than three days (72 hours) and water depths not fall below 3.8 ft, a total of 34 three-day periods were identified where more than 15 percent of the thermal refuge would be lost under a 30 percent reduction in spring flows (Figure 77 and 78, Table 26). The three most limiting periods were February 15-17, 2015, February 16-18, 2015, and February 18-20, 2015 where 5,036 m^2, 7,631 m^2, and

12,365 m² of suitable thermal refuge remained under reduced flow conditions (Table 26). The remaining 31, three-day periods all provided warm water refuge in excess of 12,370 m².

The amount of manatee warm water refuge far exceeds that required for the maximum number of manatees observed in the Wakulla Spring area. The maximum number of manatees observed at Wakulla Spring during winter months was 46 individuals. Using the most limiting three day period and the maximum number of manatees observed at Wakulla Spring, the 5,036 m² of warm water refuge would allow each manatee more than 110 m² (1,178 ft²) of space. For comparison, Rouhani et al. (2007) described the average manatee as requiring approximately 2.65 m² (28.5 ft²). Information concerning determination of manatee carrying capacity such as the availability of manatee forage in the Wakulla River is unavailable and could not be assessed during this MFL evaluation but will be examined during future analyses.

Based upon the description of manatee dimensions provided by Rouhani et al. (2007), sufficient surface area of water >20° C and more than 3.8 ft in depth was present to allow up to 1,900 manatees to congregate near Wakulla Spring during the most limiting three-day period. For comparison, the maximum number of manatees observed at Wakulla Spring during winter months was 46 individuals, and the total estimated winter manatee population for northwest Florida and the west coast of Florida are 270 and 3,339 individuals, respectively (FWC 2020a). Again, these estimates are for short term periods where only water temperature was assumed to be limiting. Considering the relatively small numbers of manatees that use Wakulla Spring as a warm water refuge and the large surface area of thermal refuge remaining under a 30 percent spring flow reduction scenario, this metric was not considered further for MFL establishment.

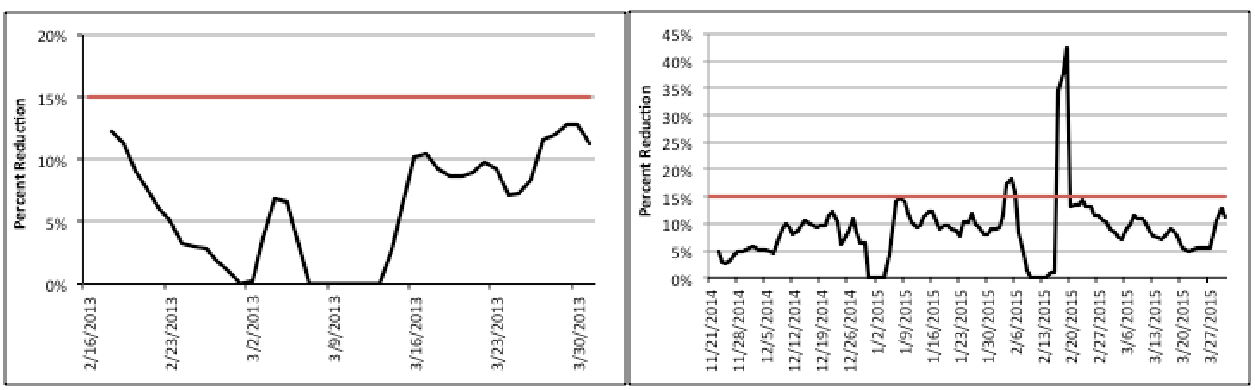

Figure 77: Percent Change in Available Manatee Chronic Thermal Refuge Area Between February 9, 2013 and March 31, 2013 and November 21, 2014 and March 31, 2015.

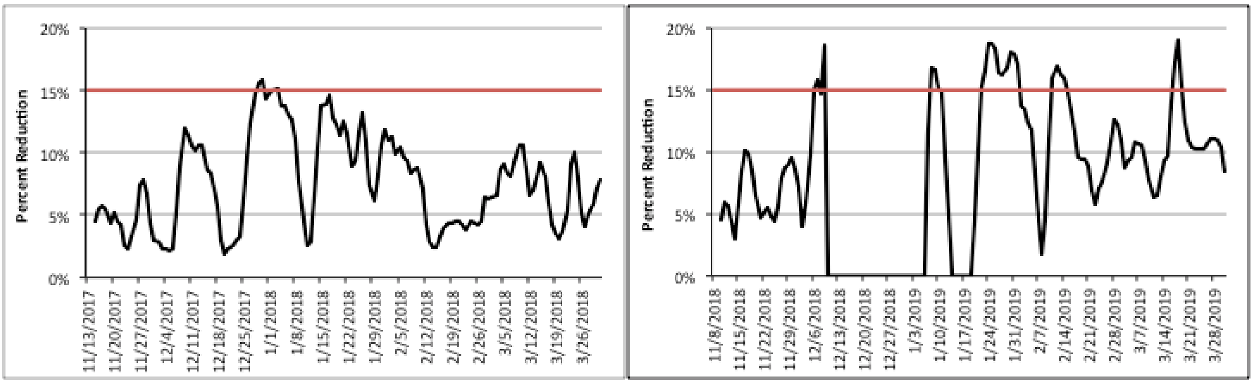

Figure 78: Percent Change in Available Manatee Thermal Refuge Area for Chronic Stress Criteria Between November 13, 2017, and March 31, 2018, and November 8, 2018 and March 31, 2019.

Table 26: Time periods where 30 Percent Spring Flow Reductions Resulted in Greater Than a 15 Percent Reduction in Manatee Thermal Refuge Based on Chronic Stress Criteria.

End Date	Reduced Area (m2)	# Manatees Supported	End Date	Reduced Area (m2)	# Manatees Supported
2/17/2015	5,036	1,900	2/13/2019	24,544	9,262
2/18/2015	7,631	2,879	1/27/2019	25,344	9,564
2/19/2015	12,365	4,666	2/4/2015	25,487	9,618
1/22/2019	12,370	4,668	1/31/2019	26,876	10,142
2/11/2019	18,029	6,803	2/1/2019	27,239	10,279
2/6/2015	18,834	7,107	1/30/2019	27,289	10,298
2/5/2015	21,240	8,015	1/29/2019	27,639	10,430
3/18/2019	21,331	8,049	1/28/2019	28,021	10,574
1/23/2019	22,172	8,367	1/8/2019	30,977	11,690
1/26/2019	22,693	8,563	1/3/2018	33,652	12,699
2/14/2019	23,186	8,749	12/9/2018	34,126	12,878
1/25/2019	23,348	8,810	1/9/2019	36,374	13,726
1/24/2019	23,609	8,909	1/10/2019	36,429	13,747
3/19/2019	23,639	8,920	12/30/2017	37,519	14,158
2/12/2019	23,933	9.031	12/29/2017	38,396	14,489
3/17/2019	23,961	9,042	12/7/2018	65,180	24,596

Shoreline Woody Habitat

Shoreline woody habitats were sampled in 2016 at three floodplain vegetation transects (river stations 44619, 41707.76, and 33245) along the Wakulla River. Elevations were surveyed for two types of woody habitat, dead woody debris, and live roots. Dead woody debris includes twigs, branches, or other dead woody plant material present along and near the shoreline. Elevations were determined for at least 10 samples at each transect and averaged to determine a mean elevation. Sample sizes are relatively small and considerable uncertainty exists regarding whether the measured elevations are representative of the distribution of woody habitat present along the length of the spring run or across the entire river channel along a given transect. As a result, the woody habitats sampled along the Wakulla River were not considered for MFL determination.

Floodplain Vegetation

Elevations (NAVD 88) of riparian floodplain habitat were surveyed at 10 wetland cross-sections along the Wakulla River and the wetland-upland edge was estimated. Three of these transects were determined to have water surface elevations within the channel that varied more in response to changing river flows compared to being driven primarily by downstream tidal boundary conditions (Section 2.11, Figure 34) and were further evaluated for possible use in minimum flow analyses.

Riparian wetlands along the Wakulla River system are classified as "seasonally inundated" and "semi-permanently" flooded (NWI 2014, DEP 2009), which are generally indicative of hydroperiods ranging from several months to most of the year. Riparian wetlands generally become seasonally inundated during periods of high river flows, although wetland vegetation along some rivers and floodplains may be hydrologically maintained by other sources such as direct precipitation, elevated groundwater levels and seepage. Upon reviewing surveyed elevations from field wetland determinations and HEC-RAS model results, it became apparent that the riparian wetlands included in the current MFL evaluation were likely not supported by Wakulla and Sally Ward spring flows. This determination was based upon nearby groundwater levels, surveyed elevations of riparian wetlands, and HEC-RAS model results, as described below.

Although data is limited, water surface elevations in nearby groundwater wells, indicate that the groundwater elevation exceeds the stage in the river and is near the land surface elevation in the vicinity of the Wakulla River Appendix A. These findings are supported by potentiometric surface maps as discussed in Section 1.6 and observations regarding wetland soils described in Section 1.8.2 and detailed in NWFWMD 2016).

Inundation frequencies of floodplain elevations differ from what would be expected based on expected hydroperiods for seasonally inundated or semi-permanent flooded wetlands. In order to achieve inundation of 50 percent of wetland transect 44619, flows in excess of 876 cfs, which represents the eight percent flow exceedance (P92), would be required (Table 27). In other words, on average, approximately 50 percent of the floodplain would be inundated for less than one month a year. These results are even more dramatic when considering transect 41707.76. These findings indicate that direct precipitation and high water-table conditions are maintaining riparian wetlands along the Wakulla River, rather than spring discharge. The potentiometric surface of the Floridan aquifer is higher than the river stage in the vicinity of Sally Ward Spring, Wakulla Spring, and the numerous springs present along the upper portion of the river, which causes aquifer discharge (e.g., spring flow) to occur. Similar results have been observed along other spring runs in Florida (SRWMD 2019).

Table 27: Critical Water Surface Elevations Required to Inundate Ecological Transects Along the Wakulla River. *Water surface elevations are more influenced by tidal fluctuations than changes in spring flow and were not included in analysis.

River Station (Ecological Transect #)	Percentage of Floodplain Inundated (%)	Critical Elevation (NAV88)	Model Elevation (NAVD88)	Percent Exceedance (%)	Flow (cfs)
44619 (W1)	**5%**	4.62	4.62	42	661
	10%	4.73	4.72	34	692
	25%	4.97	4.95	18	772
	50%	5.22	5.21	8	876
	75%	5.66	5.49	4	1003
41707 (W2)	**5%**	4.62	4.62	16	814
	10%	4.80	10	5	878
	25%	5.01	4.96	6	958
	50%	5.74	5.85	1	1417
	75%	6.62	6.57	<1	1796
33245 (W3)	**5%**	2.11	2.12	78	532
	10%	2.67	2.66	48	698
	25%	3.11	3.11	22	846
	50%	3.75	3.68	6	1068
	75%	4.53	4.38	2	1406

5.2 Estuarine EFDC Model WRV Evaluation

Multiple metrics were evaluated for Estuarine Resources including the volume, bottom surface area, and shoreline length for each oligohaline (e.g., low salinity) zone. Volume was considered as a metric to protect fish species habitat, bottom surface area to protect benthic species habitat, and shoreline length for the protection of shoreline floodplain vegetation communities. The period January 1, 2008, through October 4, 2010, is representative of the range and distribution of spring flows that occur during the baseline period and was used to evaluate potential spring flow reductions with the EFDC Model for computational efficiency (WRV 3 Estuarine Resources). Daily St. Marks River Rise spring flows were reduced by 7.3 percent to reflect the established minimum flow for the St. Marks River Rise and ensure that cumulative flow reductions from Wakulla Spring, Sally Ward Spring, and the St. Marks River Rise would not result in significant harm. An initial spring flow reduction of 30 percent was applied to Wakulla and Sally Ward spring flows to help determine the sensitivity of oligohaline habitats to spring flow reduction. This flow reduction was assumed to be high, beyond which any flow reductions would be unlikely. Additional flow reduction scenarios were conducted, if needed, to determine the allowable spring flow reductions that result in a 15 percent change in the metrics described above.

Changes in oligohaline zones were shown to be relatively insensitive to reductions in spring flow. A modeled spring flow reduction scenario of 30 percent resulted in changes in volume, bottom surface area, and shoreline length below the designated 15 percent change threshold. The volume and bottom surface area of lowest salinity habitats ($\leq$0.5 ppt) displayed the largest reduction in both average (12.39 percent and 12.09 percent, respectively) and median (14.57 percent and 13.75 percent, respectively) conditions (Table 28, Table 29). It should also be noted that the percent change in habitat for the 0.5 ppt metric is likely a vast underestimation of the available freshwater habitat in the Wakulla and Sally Ward System. This percent change represents only the change in volume, surface area, or shoreline length present within the Estuarine EFDC Model domain, which extends from the confluence with the St. Marks River to approximately the U.S. Hwy. 98 bridge (Figure 62). The rest of the system is comprised of freshwater habitats (<0.5 ppt) and if these portions of the system were included, the percent change would be considerably lower. Because no metric associated with oligohaline zones displayed a change of 15 percent or larger for a 30 percent reduction in spring flow, this metric was not used to determine minimum flows for Wakulla and Sally Ward springs. Details of EFDC flow reduction scenarios are provided in Appendix B.

Several details concerning the Wakulla and Sally Ward spring runs may help explain the lack of sensitivity of the spring run to reductions in spring flow. Salinity near the confluence of the St. Marks and Wakulla rivers are highly affected by tidal variations (Xiao et al. 2014). In addition, Wakulla and Sally Ward spring flow represents only a portion of the freshwater flowing into the estuary. The St. Marks River, numerous other small springs and diffuse groundwater flows contribute as well.

Table 28: Estuarine Metrics for Each Oligohaline Zone Under Baseline Conditions.

Parameter	**Oligohaline Zone**	**Water Volume (m^3)**	**Bottom Surface Area (m^2)**	**Shoreline Length (m)**
Median of Average Daily Values	**≤ 0.5 ppt**	852,478	531,063	9,675
	≤ 1 ppt	909,925	572,130	9,863
	≤ 2 ppt	962,175	606,943	9,863
	≤ 3 ppt	985,616	637,361	9,863
	≤ 4 ppt	1,000,799	646,681	9,863
Mean of Average Daily Values	**≤ 0.5 ppt**	856,784	543,519	9,484
	≤ 1 ppt	908,724	574,115	9,822
	≤ 2 ppt	962,390	610,836	9,942
	≤ 3 ppt	990,803	633,882	9,952
	≤ 4 ppt	1,007,191	648,546	9,955

Table 29: Estuarine Metrics for Each Oligohaline Zone for a 30 Percent Reduction from Baseline Conditions in Spring Flows.

Parameter	Oligohaline Zone	Water Volume		Bottom Surface Area		Shoreline Length	
		m^3	Percent Reduction	m^2	Percent Reduction	m	Percent Reduction
Median of Average Daily Values	**≤ 0.5 ppt**	124,223	14.57	72,997	13.75	805	8.32
	≤ 1 ppt	103,651	11.39	72,471	12.67	290	2.94
	≤ 2 ppt	62,363	6.48	44,879	7.40	0	0.00
	≤ 3 ppt	37,686	3.82	39,379	6.18	0	0.00
	≤ 4 ppt	30,399	3.04	26,522	4.10	0	0.00
Average of Average Daily Values	**≤ 0.5 ppt**	106,144	12.39	65,710	12.09	709	7.47
	≤ 1 ppt	92,690	10.20	61,019	10.63	399	4.06
	≤ 2 ppt	64,591	6.71	45,041	7.37	66	0.67
	≤ 3 ppt	47,106	4.75	32,740	5.17	12	0.12
	≤ 4 ppt	34,579	3.43	24,494	3.78	3	0.03

5.3 Water Quality

The potential for the withdrawals to cause significant harm to water quality by reducing spring flows was evaluated. Based on analysis shown in this section, recommended minimum flows for Wakulla Spring are not expected to cause significant harm to water quality or impair the designated use of the spring run. In addition, this WRV should be further protected by WRVs such as Fish and Wildlife Habitat and the Passage of Fish (Floodplain Vegetation) which will ensure vegetation is maintained to help uptake, store, and transform nutrients.

To assess if a statistically significant change in nitrate concentration would occur from a proposed Wakulla Spring flow reduction due to changes in dilution, a 95 percent confidence interval of the difference in predicted nitrate concentration between baseline time period average flow of 575 cfs and a proposed allowable 15 percent flow reduction flow of 86 cfs (to 489 cfs) was estimated. Note that serial correlation (temporal autocorrelation) was evident in the residuals shown in Section 1.6, indicating the potential for underestimating the width of a confidence interval for the estimated difference in nitrate concentration. Helsel and Hirsch (1992) note that selecting a subset of the dataset is an appropriate method for removing the effects of serial correlation. Examination of the residuals indicated that subsetting the data by randomly sampling approximately one fourth of the available 192 unique daily nitrate concentration values would yield samples of residuals that did not generally exhibit serial correlation. Therefore, a resampling approach was implemented using R statistical software, in which 10,000 subsets of approximately one fourth (45 of 192) of the available residuals shown in Section 1.6 (reflecting time-corrected nitrate concentrations) were randomly sampled and used to generate a set of 10,000 estimated differences in nitrate concentration at flows of 575 and 489 cfs. The upper and lower limits of a 95 percent confidence interval for the difference in nitrate concentration at flows of 575 cfs and 489 cfs was then estimated by computing the percentiles at probabilities of 0.975 and 0.025, respectively. This resulted in an estimated 95 percent confidence interval with upper and lower limits of approximately 0.038 and -0.005, respectively.

Because this confidence interval includes zero, the potential change in nitrate concentration from MFL implementation (e.g., an allowable spring flow reduction) does not appear to be statistically significant at a 95 percent level of confidence. In other words, no quantifiable change in nitrate is projected to occur. This is likely due to the significant variability displayed in time adjusted nitrate residuals versus flow, as described in Section 1.6.

5.4 Effects of Sea Level Rise

Measured sea level at locations globally have indicated that in many areas, including the Gulf of Mexico, sea levels are rising. Rising sea levels, which provide downstream boundary conditions, have the potential to affect both the stage-discharge relationship and availability of estuarine habitats. To help determine whether observed and potential future changes in the ecology of the Wakulla River are resulting from changes in spring flow or rising sea levels, additional model scenarios were run using best estimates of current, observed sea level rise rates. An MFL is not intended to mitigate the effects of coastal sea level rise on spring flows, water clarity, or any of the WRVs previously described.

The effects of sea level rise were assessed by including an additional scenario using both HEC-RAS and Estuarine EFDC models. The thermal EFDC model is upstream of the anticipated impacts associated with sea level rise and as a result, the effects of potential sea level rise were not quantified. This scenario was completed by adjusting the offshore boundary condition to sea levels predicted through 2040. Sea level rise predictions from 2020 through 2040 were obtained from the National Oceanographic and Atmospheric Association (2020). The mean sea level rise of 2.38 mm/year was calculated using the average of the median NOAA projections for sea level rise at Apalachicola, Florida (2.56 mm/year) and Cedar Key, Florida (2.19 mm/year). This calculated projection accumulates to a sea level rise of 47.5 mm (1.9 inches, 0.16 ft) by 2040. Although data indicates that the rate of sea level rise has increased during recent year, the long-term projected rate was used for this analysis. The effects of sea level rise were quantified on water surface elevations between the confluence and Wakulla Spring using the HEC-RAS model, while changes in oligohaline zones between the confluence and U.S. Highway 98 bridge were quantified using the EFDC model. Changes in river water surface elevation were assessed by increasing the water surface offshore boundary condition of both models by 1.9 inches (0.16 ft).

Changes in sea level resulted in changes in water surface elevations of 0.16 ft near the confluence to 0.0 ft near Wakulla Spring and 0.0 ft near Sally Ward Spring (Figure 79). During low downstream boundary conditions changes were relatively constant and reflected changes in the boundary conditions from River Station 61.7 (confluence with the St. Marks River) to River Station 8591.8. During median and high downstream boundary conditions this trend extended further upstream to River Station 23189 (upstream of the U.S. Highway 98 crossing of the Wakulla River). During low downstream boundary conditions, the effects of sea level rise diminished steadily upstream of River Station 8591.8 to near River Station 44619. During median and high downstream boundary conditions, the effects of increased sea level were detected upstream to approximately River Station 41707.76. The effects of sea level rise were not detected at Wakulla Spring (River Station 48252.78) or Sally Ward Spring (River Station 52189.0) under any downstream boundary condition. Details of the effects of sea level rise on water surface elevations along the River Rise spring run can be found in Appendix D.

The effects of sea level rise on oligohaline zones were most manifested on the bottom surface area metric (Table 30). The oligohaline zones of <0.5 ppt and <1.0 ppt were the most sensitive. Bottom surface area displayed the largest loss of habitat for both average and median daily salinity conditions. An increase in sea level of 1.9 inches translated into a loss in the bottom surface area of the <0.5 ppt oligohaline zone compared to the baseline time period. Similar results were observed for the <1.0 ppt. The average volume and shoreline length of oligohaline zone loss were less sensitive. Details of the effects of sea level rise on salinity in the River Rise spring run can be found in Appendix B.

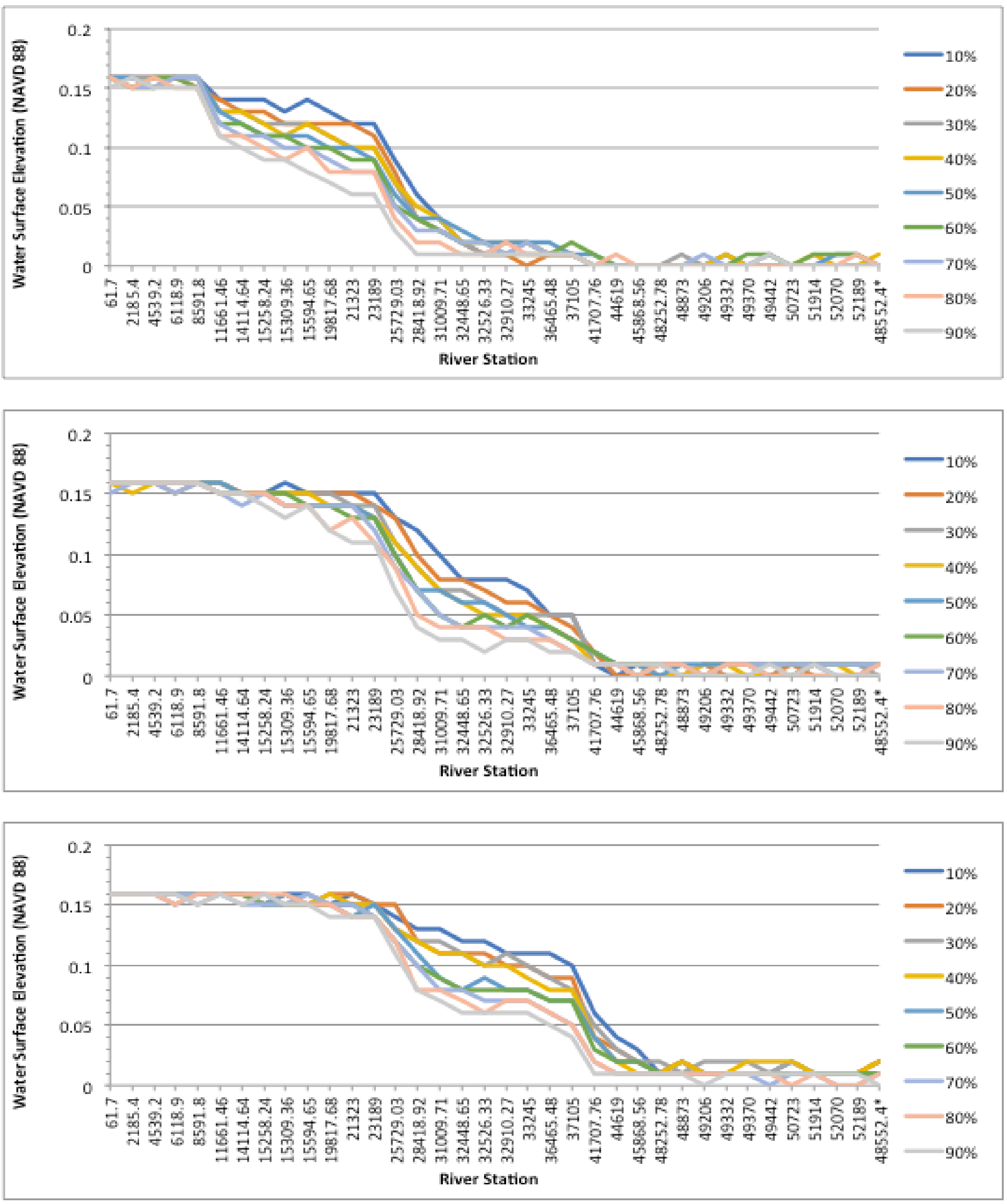

Figure 79: Change in Water Surface Elevation Along the HEC-RAS Model River Stations Associated with a 0.16 ft (1.9 inch) Rise in Sea Level During Low, Median, and High Downstream Boundary Conditions.

Table 30: Changes in Estuarine Metrics Associated with a 1.9 inch Increase in Sea Level by 2040.

Parameter	Oligohaline Zone	Water Volume		Bottom Surface Area		Shoreline Length	
		m^3	Percent Reduction	m^2	Percent Reduction	m	Percent Reduction
Median of Average Daily Values	**≤ 0.5 ppt**	19,690	2.31	25,914	4.89	59	0.61
	≤ 1 ppt	5,549	0.61	35,207	6.16	0	0.00
	≤ 2 ppt	-7,453	-0.77	9,329	1.54	0	0.00
	≤ 3 ppt	-14,219	-1.56	21,985	3.45	0	0.00
	≤ 4 ppt	-15,619	-1.90	7,466	1.15	0	0.00
Average of Average Daily Values	**≤ 0.5 ppt**	9,565	1.13	28,368	5.28	58	0.62
	≤ 1 ppt	4,101	0.46	25,665	4.52	-14	-0.15
	≤ 2 ppt	-4,630	-0.49	17,744	2.93	-11	-0.11
	≤ 3 ppt	-10,639	-1.08	13,065	2.08	-2	-0.02
	≤ 4 ppt	-15,250	-1.53	10,764	1.68	0	0.00

6 Recommended Minimum Flows

The most limiting metrics across the range of flows were utilized to develop the recommended minimum flows for the Wakulla and Sally Ward springs system. Allowable reductions in spring flow corresponding to a 15 percent reduction in inundation frequency (e.g., time) was determined for each WRV metric. Safe manatee passage at Wakulla River transect 41707.76 allowed for a flow reduction of 59.21 cfs (38.3 mgd). This transect is located downstream of the Wakulla River and Sally Ward Spring run confluence and flows at this location are comprised of flows from both springs. Other WRV metrics tested were either insensitive to spring flow reductions (Estuarine Resources), had metric conditions met during all flows (Boat and Fish Passage), or the amount of available thermal refuge remaining after extreme spring flow reductions far exceeded the known use of the metric (Manatee Thermal Refuge).

The recommended minimum flow is an allowable reduction in the combined flow from Wakulla and Sally Ward springs. The single most limiting metric was used to determine allowable spring flow reduction. This most limiting allowable flow reduction can be applied equivalently to the range of observed combined spring flows. Setting the minimum flow at the combined average baseline spring flow provides for adequate protection of Wakulla and Sally Ward spring over the range of observed spring flows. The recommended minimum flow is an allowable flow reduction of 59 cfs from the combined Wakulla Spring and Sally Ward average baseline spring flow of 598 cfs. This translates in an allowable reduction of 9.9 percent of the combined average baseline spring flow.

The minimum flow described above was developed using the most conservative metric and the most limiting transect included in the analysis. This transect is located within the Edward Ball Wakulla Springs State Park approximately 1.5 miles downstream from the Wakulla Spring pool. This transect is located in portion of the Wakulla River which is relatively shallow compared to the upstream area which has been excavated for tour boat use and areas downstream of Shadeville Hwy which contain naturally deep areas across the river.

7 Adaptive Management

The District is committed to taking an adaptive management approach to the Wakulla and Sally Ward Springs MFL assessment. Multiple efforts have already been implemented prior to the completion of this MFL technical assessment and adaptive management includes, but is not limited to:

1- Continued data collection of 30 wells that have been constructed or instrumented with data loggers to increase the spatial and temporal resolution of groundwater level data,
2- Review and/or enhance as appropriate available models used for MFL Technical Assessments,
3- Continue to evaluate changes in river flows and hydraulics, including scouring and deposition,
4- Review availability of instream habitat models and consider their appropriateness for future MFL evaluations, and
5- Review additional data concerning salinity in the Wakulla Spring, Wakulla River, and the Spring Creek Spring Group as it becomes available.
6- Review available quantitative data concerning manatee ecology and thermal needs at Wakulla Spring.

Additional available data will be incorporated into future MFL reevaluations as appropriate and changes to MFL metrics may be considered.

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9 Appendices

9.1 Appendix A: Draft Wakulla and Sally Ward Springs: Development of Composite Discharge and Baseline Time Series Technical Memorandum

9.2 Appendix B: Wakulla Spring MFL: Hydrodynamic Model for MFL Evaluation of the Estuarine River

9.3 Appendix C: Wakulla Spring MFL Hydrodynamic Model for Thermal Refuge Evaluation

9.4 Appendix D: Update and Calibration of the Hydrologic Engineering Centers River Analysis System (HEC-RAS) Model Wakulla River System and Development of the Wakulla River System Hydrologic Engineering Centers River Analysis System (HEC-RAS) Steady State Model

9.5 Appendix E: Hydrodynamic Model Development and Calibration in Support of St. Marks River Rise MFL Determination