NITRATE LOADING AS AN INDICATOR OF NONPOINT SOURCE POLLUTION IN THE LOWER ST. MARKS-WAKULLA RIVERS WATERSHED

PREPARED BY :

NORTHWEST FLORIDA
WATER MANAGEMENT DISTRICT

APRIL 2002

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AS AN
INDICATOR OF NONPOINT SOURCE POLLUTION
IN THE
LOWER ST. MARKS-WAKULLA RIVERS WATERSHED

Water Resources Special Report 02-1

This project and the preparation of this report were funded in part by a Section 319 Nonpoint Source Management Program grant from the U.S. Environmental Protection Agency (USEPA) through a contract with the Nonpoint Source Management and Water Quality Standards Section of the Florida Department of Environmental Protection. The total cost of the project was $503,700 of which $291,966, or 58 percent was provided by the USEPA.

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ACKNOWLEDGMENTS

The support provided by the Florida Department of Environmental Protection and the U.S. Environmental Protection Agency was invaluable. Eric Livingston, Environmental Administrator, FDEP Bureau of Watershed Management, was instrumental to the success of this project. Rick Copeland and Lyle Hatchett, FDEP Bureau of Watershed Management, served as project managers. The efforts of both of these gentlemen on behalf of the District are gratefully acknowledged. Rick Copeland also reviewed the report.

The authors wish to acknowledge the cooperation and assistance provided by the City of Tallahassee. Bill Leseman, Jay Johnson, Jamie Shakar, John Morrill and Keith Turner and Koren Taylor provided, as they have done on numerous occasions in the past, much-appreciated support and assistance. Frank Evans of the Wakulla County Planning Office provided information on the location of sewer infrastructure in the County. Tom Singleton and Joe Hand of the Florida Department of Environmental Protection provided access to their work in the St. Marks basin as well as relevant consultant reports. Chris Werner and the divers of the Woodville Karst Plain Project shared their data and experience of the caves in the study area.

Peter Krottje and Nick Wooten of the Northwest Florida Water Management District provided valuable data support and assistance. Alan Baker, Gary Miller, Ferdouse Sultana and Karen Kebart provided GIS support and assistance.

On behalf of the City of Tallahassee, Koren Taylor and Jamie Shakar reviewed draft versions of the report. Graham Lewis (NWFWMD), David Toth (SJRWMD), Tom Kwader (URS Corporation and member of Leon County Science Advisory Committee), Kyle Champion (SWFWMD) and Eric DeHaven (SWFWMD) provided outside review.

The cover photograph was taken inside the conduit system looking up at a glass bottom boat floating on the surface of the spring. Daniel Wagner, who graciously agreed to its use, took the photograph.

REVISION June 2003 – As part of the District's lower St. Marks/Wakulla rivers watershed nitrate investigation, water levels were measured in the study area and potentiometric surfaces contoured (report Figures 22 through 24). Three maps were prepared; January 1999, August 1999 and March 2000. One criterion for inclusion on the final map was a surveyed wellhead elevation. Seven measured wells were not surveyed during the study period due to time constraints. Data from these wells were not included in the original contouring efforts. Funding provided by the FDEP Florida Springs Initiative (2002-2003) allowed for two of the unsurveyed wells (NWF ID# 7238 and 7239) to be professionally surveyed to $\pm$0.1 ft, NGVD. Correctly adjusted ground water elevation data from these two well points were inserted into Figures 22 through 24 and the potentiometric surface contours revised accordingly.

INTRODUCTION

Purpose and Scope

This report is being submitted to provide Leon and Wakulla counties, the City of Tallahassee, the Florida Department of Environmental Protection and other interested parties with a means of assessing the risk posed to drinking water wells (existing and proposed) and surface water bodies by NO_3-N contamination. It is the intent of this study to augment the St. Marks River Surface Water Improvement and Management (SWIM) Program in its effort focusing on the restoration and long-term preservation of the St. Marks and Wakulla rivers watershed. This is an integral component of the State of Florida's Watershed Management Program. This work was performed under Florida Department of Environmental Protection (FDEP) Contract Number WM695. Specifically, the scope of this work includes the following activities:

- Relying on an existing USGS-developed numerical model of the Floridan Aquifer, develop a steady-state water budget for the study area. Quantify the horizontal flux into the study area from up-gradient portions of the Floridan Aquifer. Estimate ground water inputs from principal sinking streams. Quantify areally distributed recharge rates to Woodville karst plain. Quantify losses through springs and rivers. Quantify losses to the Gulf of Mexico.

- Develop a project-specific network of approximately 40 existing wells. Develop criteria for including wells in network. Review Northwest Florida Water Management District (NWFWMD) databases for wells suitable for inclusion. Visit well sites and determine their locations via global positioning system (GPS).

- Develop a network of surface water sampling sites comprised of rivers, springs, sinking streams, and sinkholes. In conjunction with DEP, develop criteria for including sites in network, parameter lists and sampling frequency. Site visit and GPS sites.

- Construct a supplemental network of approximately six Floridan Aquifer wells suitable for isotopic sampling. Develop criteria for choosing site locations. Obtain necessary easements. Obtain contractor services and construct wells. Locate wells with GPS.

- Conduct sampling of karst features, springs and sinkholes.

- Sample project-specific network wells for field parameters, major ions, nutrients, silica, and dissolved organic carbon (DOC). The U.S. Geological Survey Water Quality and Research Laboratory in Ocala, FL analyzed samples for major ions. Prepare maps showing the spatial distribution of selected parameters. Prepare corresponding potentiometric-surface map from water-level data collected at time of sample collection. Sample supplemental network twice in one year for the same parameters, as well as isotopes $^{18}O/^{16}O$, D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{3}H/^{3}He$.

- Develop geographic information systems (GIS) coverages of karst features within the study area including, sinkholes, springs, sinking streams, etc.

- Examine all data to delineate areal distribution of NO_3-N, isotopes and other water quality parameters. Perform geochemical modeling using WATEQF and NETPATH. Integrate and interpret geochemical data to determine flow paths, flow rates, ground water ages and NO_3-N flux through the system.

- Compile NO_3-N concentration and load data for the principal input sources to the Floridan Aquifer in study area including stormwater runoff; horizontal flux into study area from up-gradient areas; and effective concentration of rainfall recharge, recharge from wastewater treatment facilities, and leaching from fertilizer application.

- Conduct an inventory of septic tank sites in the study area using available census data, land-use data, areal photographs and Department of Health (DOH) septic tank permitting records. Develop GIS coverages representing current spatial distribution of septic tanks in study area. Based on available literature, develop estimates of NO_3-N loading rates from septic tanks. Combine data on septic tank loading rates with cumulative tank numbers to estimate total load to Floridan Aquifer from this source.

- Develop STELLA application. Perform and document sensitivity analyses. Document usefulness and limitations associated with this approach. Transfer STELLA application to interested local governments. Provide an integrated technology transfer and training program to local decision-makers and affected stakeholders interested in understanding and using the application.

Project deliverables consist of this report and Katz et al. (in preparation). This project and the preparation of this report were funded in part by a Section 319 Nonpoint Source Management Program grant from the U.S. Environmental Protection Agency (USEPA) through a contract with the Nonpoint Source Management and Water Quality Standards Section of the Florida Department of Environmental Protection. The total cost of the project was $503,700 of which $291,966, or 58 percent was provided by the USEPA. The project described here is a component of the District's St. Marks Surface Water Improvement and Management Program. From FY96-97 through FY00-01, expenditures on the St. Marks SWIM program (exclusive of the 319h grant) totaled approximately $574,000.

Area of Investigation

The focus of this study is those portions of Leon and Wakulla counties where the Floridan Aquifer is under either semi-confined or under unconfined conditions (Figure 1). This includes approximately the eastern two-thirds of Leon County and the eastern half of Wakulla County. Tallahassee, Woodville, Crawfordville and St. Marks all lie within the study area. The vast majority of residents in both counties live within the study area. This area was selected because of the relatively good hydraulic connection between the land surface and the underlying Floridan Aquifer. Further, much of the water that flows south to points of discharge either originates in or flows beneath this area. The area identified as being under semi-confined conditions generally coincides with the Tallahassee Hills physiographic subdivision as mapped by Hendry and Sproul (1966), Puri and Vernon (1964) and Brooks (1981). It also corresponds to what Davis (1996) mapped as Floridan Aquifer "overlain but not confined by low-permeability Miocene-and Pliocene age sediments."

The area identified as being under unconfined conditions generally corresponds to what Brooks (1981) mapped as the Lake Munson Hills and Woodville Karst Plain physiographic subdivisions. It also corresponds to the Woodville Karst Plain as mapped by Rupert (1988) and Lane (1986) and to what Davis mapped as where the Floridan Aquifer is "unconfined and the top of the

AREA OF INVESTIGATION

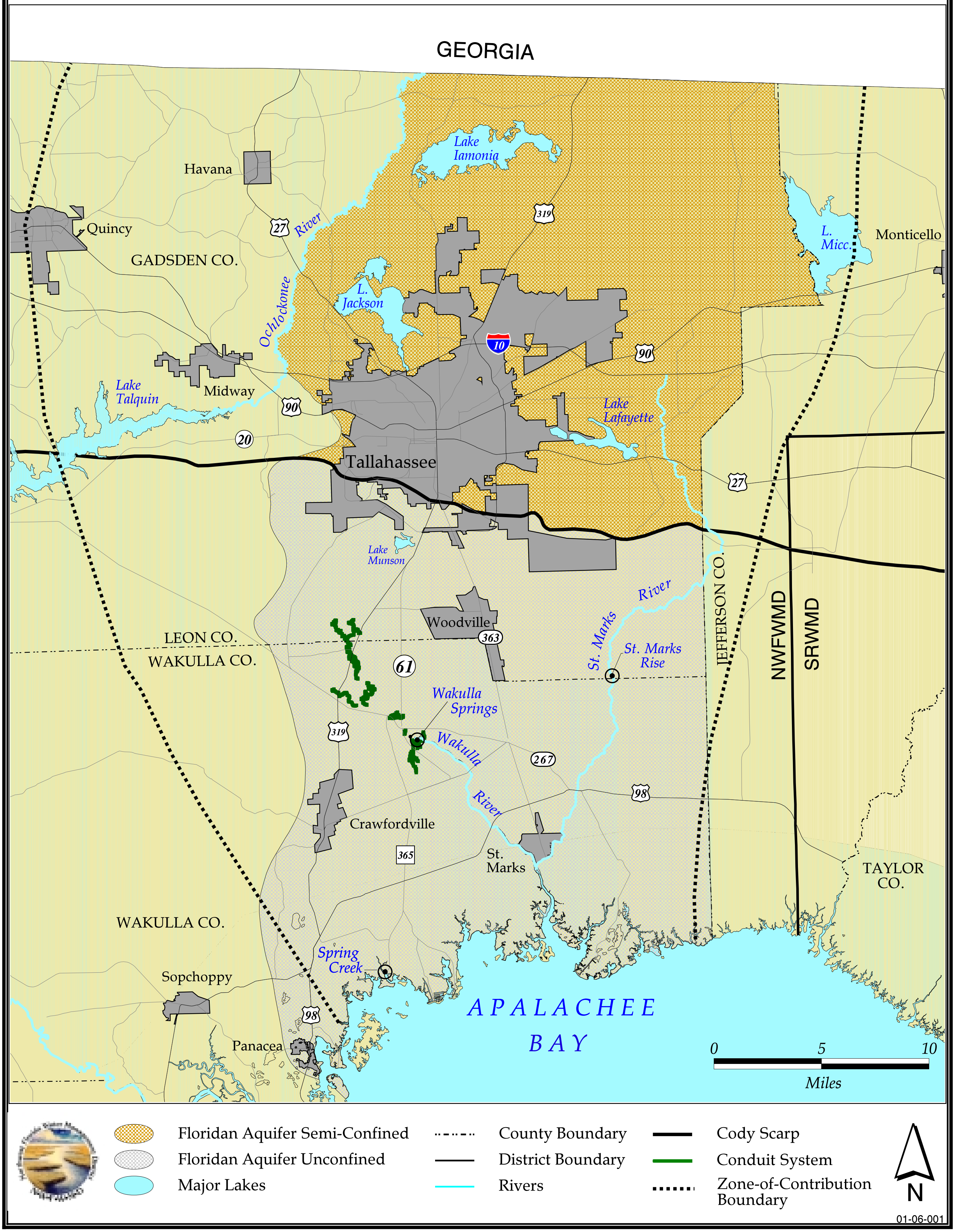


FIGURE 1

aquifer is at (or near) land surface". The boundary between the semi-confined and unconfined areas corresponds to the Cody Scarp, as mapped by Puri and Vernon (1964). The remainder of Leon and Wakulla counties are described by Davis as being under confined conditions.

The study area is imbedded within a larger Floridan Aquifer zone-of-contribution for the significant ground water discharge occurring in Wakulla Springs, the lower St. Marks River and beneath the Gulf of Mexico (Figure 1). Potentiometric surface mapping by Davis (1996) was used to delineate this larger zone-of-contribution. Land use for the coastal Wakulla County Floridan Aquifer zone-of-contribution delineation is provided in Figure 2.

Rainfall

During the study period 1998-2000, rainfall was abnormally low. The 50-year (1951-2000) average annual rainfall at the Tallahassee Airport is 62.6 inches. The 10-year (1991-2000) average annual rainfall declines to 60 inches, reflecting drought conditions during the latter part of this period. Comparisons between the Tallahassee Airport 50-year average annual and yearly totals for 1998, 1999 and 2000 are given in Figure 3. Data from the River Sink rainfall station are only available for 1999 and 2000. During 1998, the airport recorded a deficit of 3.8 inches (6.1 percent of the 50-year average). In 1999, the deficit was 12.5 inches (two-year cumulative deficit of 16.3 inches, or 13.1 percent of two years average rain). During 2000, the deficit was 17.5 inches, yielding a three-year cumulative deficit of 33.8 inches, or 18.0 percent of three years average rain. Not only did dry conditions persist for much of the three-year study period, but also the severity of the drought worsened during the latter half of the period. The persistent lack of rainfall during the study period yielded a lowering of the Floridan Aquifer potentiometric surface, low or no inflows to sinkholes and sinking streams, lower than normal discharge from springs, low lake levels and diminished or nonexistent surface streamflows.

Mean monthly rainfall totals for the 10-year period 1991-2000 were calculated for the Tallahassee Airport. These monthly averages are compared with monthly rainfall during the same period in Figure 4. A ten-year cumulative departure from normal is given in Figure 5. For the entire 36-month period (January 1998 through December 2000), monthly rainfall exceeded the 10-year monthly average in only eight months (February 1998, March 1998, July 1998, September 1998, May 1999, June 1999, August 2000 and September 2000). Two monthly average exceedances are attributable to tropical storms. In September 1998, Hurricane Earl (9/3/1998) dropped 5.07 inches of rain at Tallahassee Airport and Hurricane Georges (9/30/1998) dropped 5.32 inches. In September 2000, Hurricane Gordon (9/18/00) dropped 0.71 inches of rain at the Airport and Tropical Storm Helene (9/22/00) dropped 8.2 inches.

The National Oceanographic and Atmospheric Administration, Drought Information Center has published the weekly U.S. Drought Monitor http://www.drought.noaa.gov/ since May 20, 1999. The study area was classified as being under drought conditions for the entirety of 2000. The beginning of 2000 found the study area under D2 (severe drought) conditions, which persisted for all of January. February was characterized as being at D1 (moderate drought) status. D2 conditions persisted from the end of February until the end of May. From the beginning of June until September 11, the study area was under either D3 (extreme drought) or D4 (exceptional drought) conditions. The D1 conditions that prevailed from September 19 through October 30 were associated with the passage of tropical storms through the area. From the first of November until the end of the year, the study area was again under D2 conditions.

LAND USE CLASSIFICATIONS WITHIN THE ZONE OF CONTRIBUTION

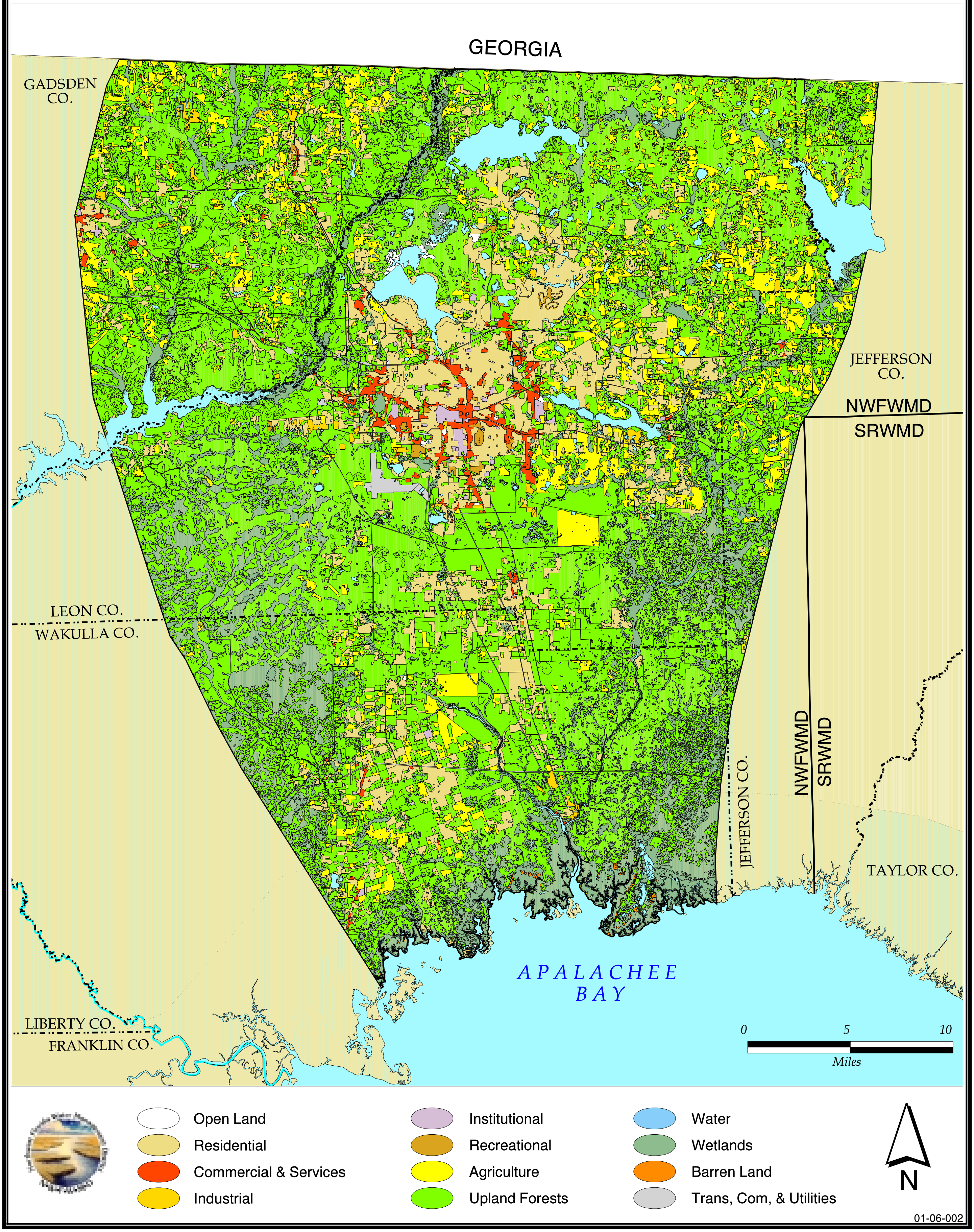


FIGURE 2

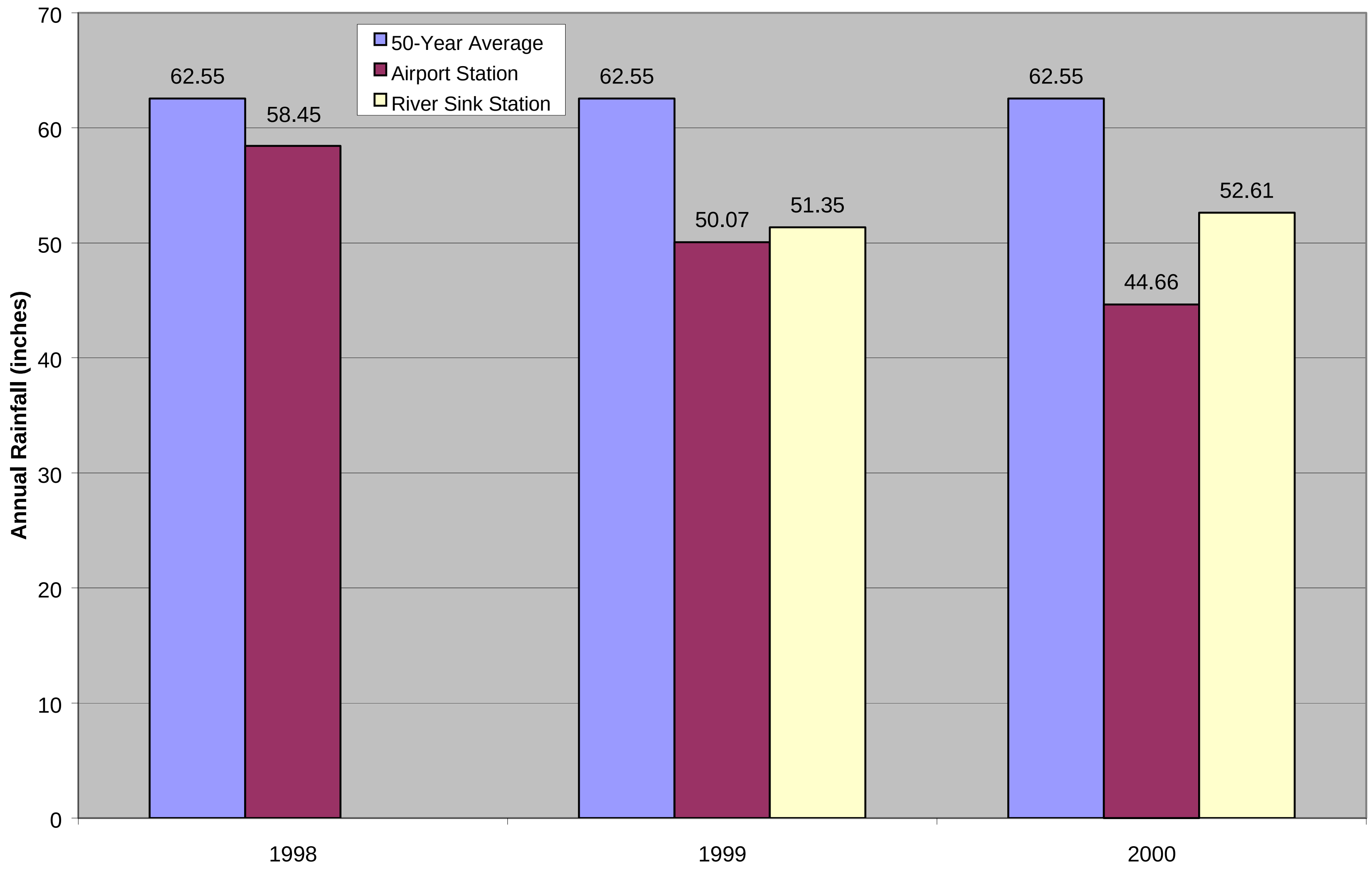


Figure 3. Annual Rainfall Deficit (1998-2000) versus 50-Year Average (1951-2000) at Tallahassee Airport.

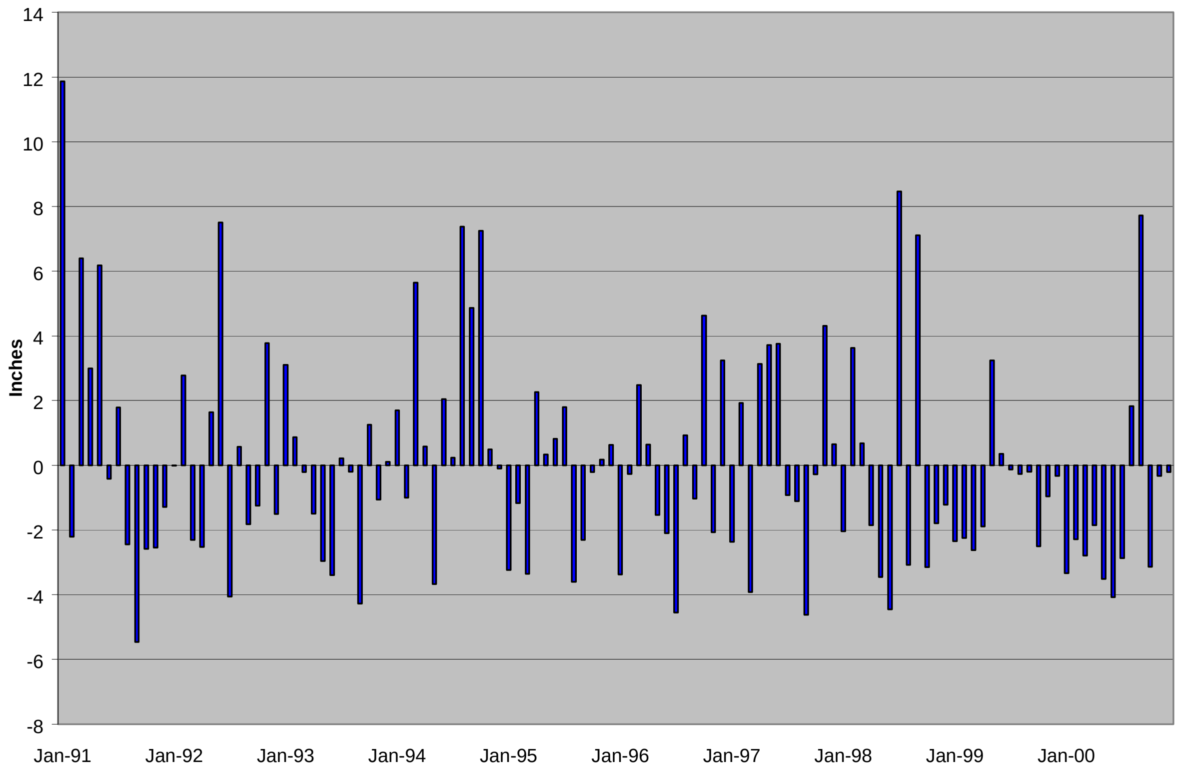


Figure 4. 1991-2000 Monthly Rainfall Deviation from Monthly Mean.

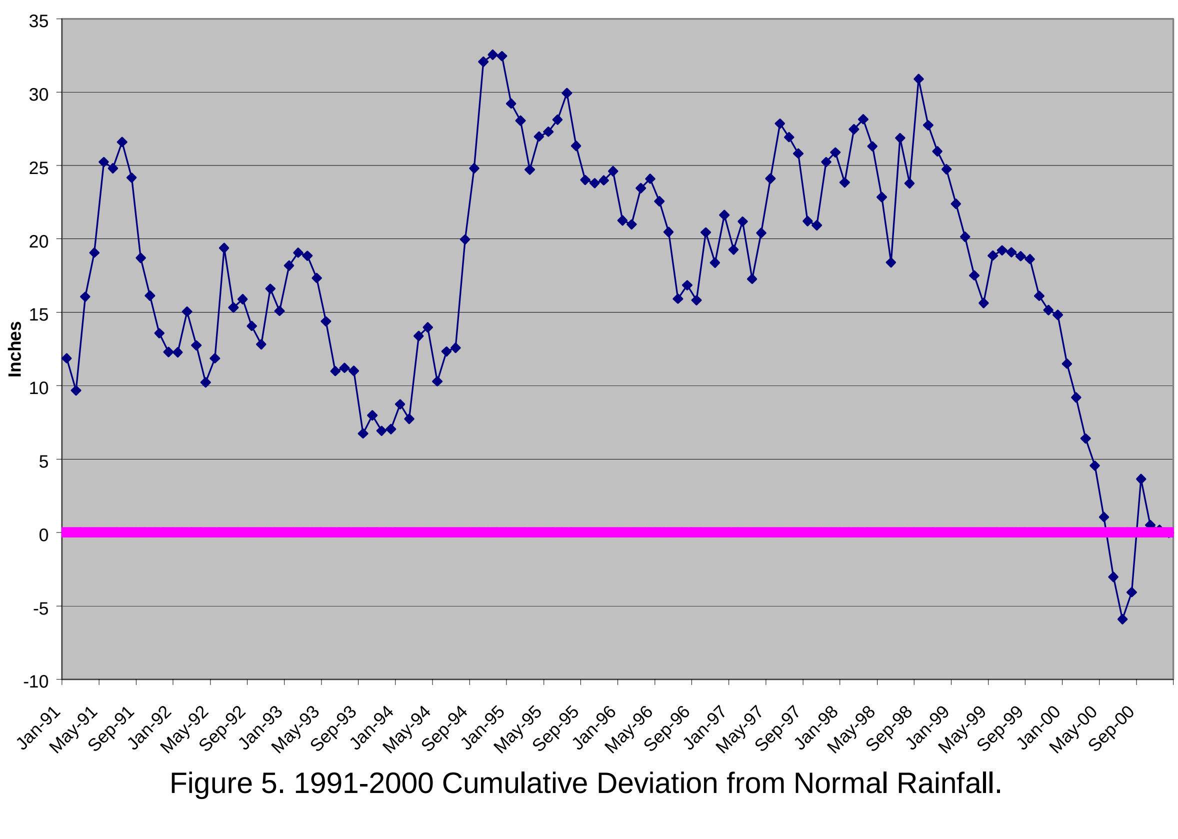


Figure 5. 1991-2000 Cumulative Deviation from Normal Rainfall.

Study period dry conditions had a profound effect on both surface and ground waters, although impacts on surface waters were most evident. Lake Jackson stood at an elevation of 86 ft (MSL) in March 1998. By May 1999, the lake had declined to 81 ft (MSL). On September 9, the lake stood at an elevation of 78.6 ft. On September 16, 1999 Porter Hole Sink drained, leaving the southern half of the lake mostly dry. During the summer of 2000, evaporation and leakage removed much of the remaining water in the northern half of the lake. Lime Sink drained during April and May 2000, leaving the lake effectively dry. The lake remained dry through the remainder of 2000 and the first half of 2001. Heavy rains associated with tropical storm Allison in June 2001 re-flooded much of the lake bottom to a depth of several feet. The lake has not experienced dry conditions for this length of time since the mid- to late 1950s.

Water levels in the Floridan and Intermediate aquifers experienced period-of-record (1966-2001) lows during the study period (Figures 6 and 7). Water levels in both aquifer systems mirror the cumulative departure from normal, rising in relatively wet periods and declining when it is dry. During the extreme dryness of 2000, ground water levels declined to elevations not see for more than 30 years, and likely not since the 1950s.

Ground Water Use in Leon and Wakulla Counties

Effectively, all of the water used for public supply, domestic, agriculture, commercial/industrial, and recreation/landscape uses comes from the Floridan Aquifer. Only in the case of power generation in Wakulla County does a substantial portion of the water use come from surface water. This water is not consumptively used, being almost entirely returned to the St. Marks River after passing through the Purdom Power Generation Station's cooling system. Tables 1 and 2 summarize the most recent water use figures for Leon and Wakulla counties, respectively. The uses are disaggregated by use classification and by source. Table 3 details public water supply use by system in each county.

Table 1. Leon County Estimated Average Ground Water Use, 1995.

Use Classification	Ground Water (Mgal/d)	Surface Water (Mgal/d)	Total (Mgal/d)
Public Supply	27.66	0.0	27.66
Self-supplied Domestic	4.61	0.0	4.61
Agriculture	1.01	0.0	1.01
Recreation/Landscape	0.95	0.0	0.95
Commercial/Industrial	0.23	0.0	0.23
Power Generation	2.64	0.0	2.64
Total	37.10	0.0	37.10

Source: Ryan, P.L., Macmillian, T.L., Pratt, T.R., Chelette, A.R., Richards, C.J., Countryman, R.A., and Marchman, G.L. District Water Supply Assessment. Northwest Florida Water Management District WRA 98-2. 1998.

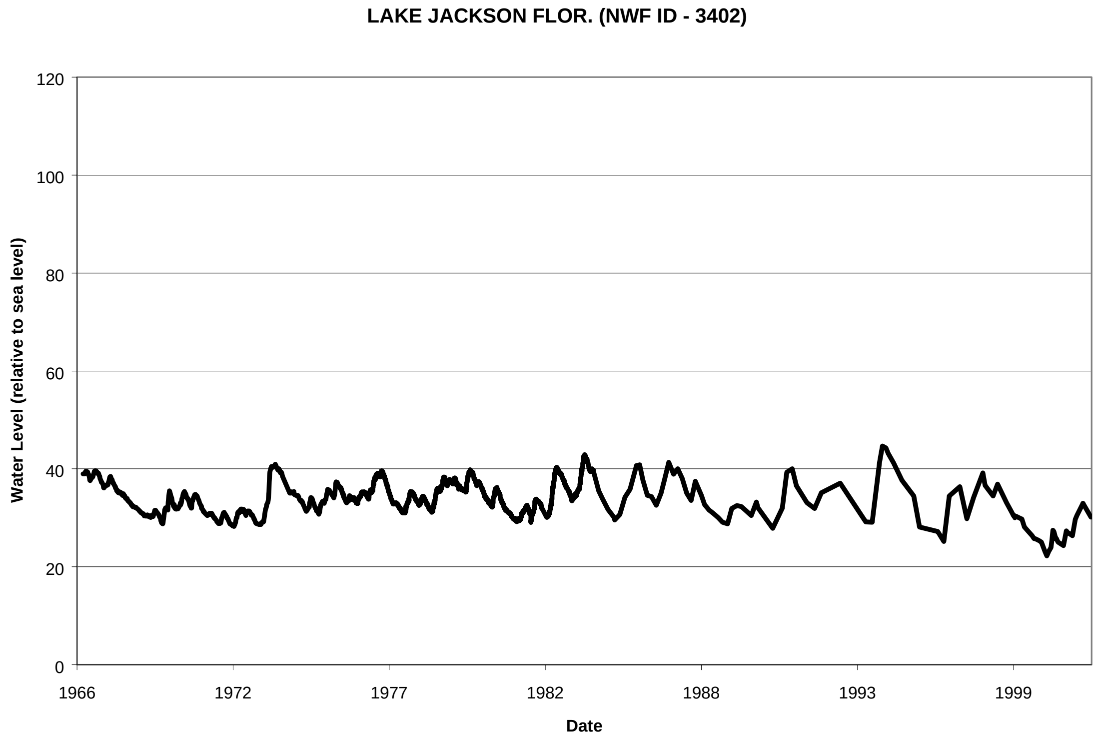


Figure 6. Hydrograph of Lake Jackson Floridan Aquifer Monitor Well, Northern Leon County. (data from USGS and NWFWMD)

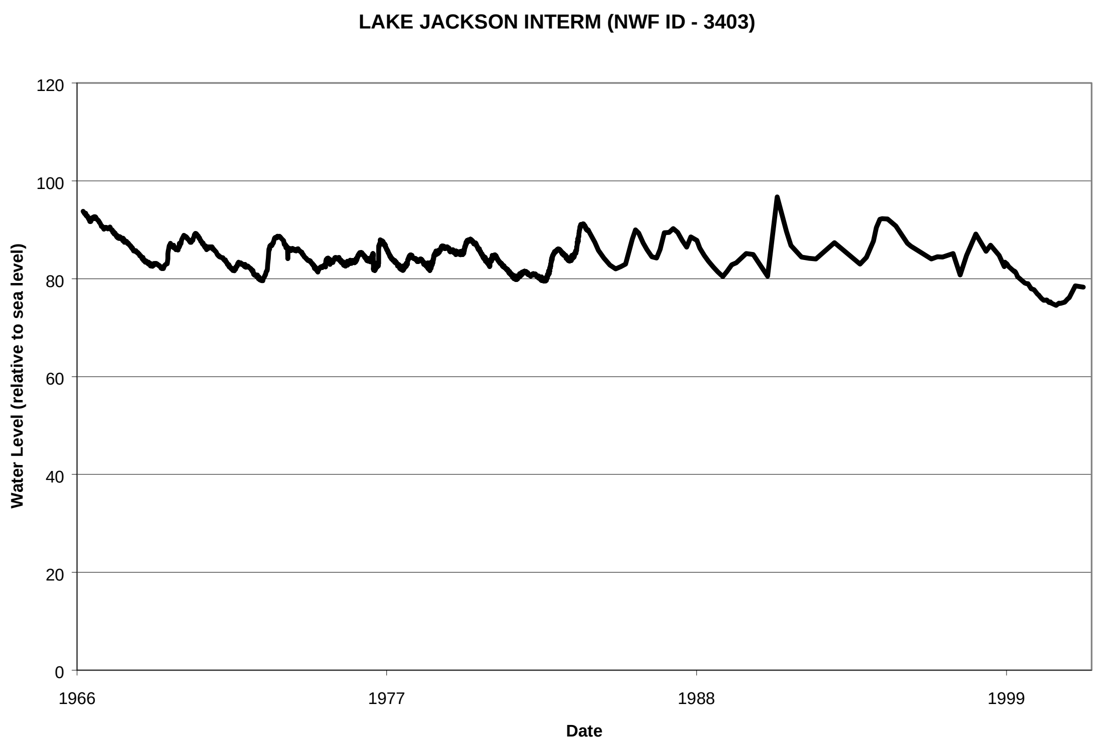


Figure 7. Hydrograph of Lake Jackson Intermediate Aquifer Monitor Well, Northern Leon County. (data from USGS and NWFWMD)

Table 2. Wakulla County Estimated Average Surface and Ground Water Use, 1995.

Use Classification	Ground Water (Mgal/d)	Surface Water (Mgal/d)	Total (Mgal/d)
Public Supply	1.05	0.0	1.05
Self-supplied Domestic	0.93	0.0	0.93
Agriculture	0.0	0.0	0.0
Recreation/Landscape	0.10	0.0	0.10
Commercial/Industrial	0.63	0.0	0.63
Power Generation	0.29	68.84*	69.13
Total	3.00	68.84*	71.84

Sources:
Ryan, P.L., Macmillan, T.L., Pratt, T.R., Chelette, A.R., Richards, C.J., Countryman, R.A., and Marchman, G.L. District Water Supply Assessment. Northwest Florida Water Management District WRA 98-2. 1998.

Marella, R.L., M.F. Mokray and M.J. Hallock-Solomon, 1998. Water Use Trends and Projections in the Northwest Florida Water Management District. U.S. Geological Survey. Open File Report 98-269, 35 pp.

*Almost all of this water is returned to the St. Marks River.

Table 3. Estimated Average Public Water Supply Use by System, 1995.

Public Supply System	Ground Water Use (Mgal/d)	Percent of Leon/Wakulla Public Supply Total
Leon County		
City of Tallahassee	25.32	88.2
TEC/Bradfordville Regional	0.79	2.8
TEC/Meadows at Woodrun	0.32	1.1
TEC/Lake Jackson	1.17	4.1
Pine Ridge Estates	0.06	0.2
Wakulla County		
TEC/Gulf Coast Water System	0.28	1.0
Panacea Area Water System	0.23	0.8
St. Marks	0.10	0.3
Sopchoppy	0.44	1.5
Total	28.71	100

Source: Ryan, P.L., Macmillan, T.L., Pratt, T.R., Chelette, A.R., Richards, C.J., Countryman, R.A., and Marchman, G.L. District Water Supply Assessment. Northwest Florida Water Management District WRA 98-2. 1998.

METHODS

Floridan Aquifer Potentiometric Surface Mapping

The focus of potentiometric surface mapping was that portion of the study area south of the Cody Scarp (in southern Leon County and eastern Wakulla County). In order to determine general flow directions within the Floridan Aquifer in this area, a network of water level monitoring wells was established. 54 wells were identified as being suitable for water level data collection (Appendix A, Table A1 and Figure 8). Wells were selected from records maintained at the District and were chosen to provide as dense a network as was reasonably practicable to monitor. Only Floridan Aquifer wells were included in the water level monitoring effort. Given the flatness of the potentiometric surface, wellhead and land surface elevations were established by survey (NGVD) for all wells included on the potentiometric surface maps. All wells that had not previously been surveyed were instrument leveled to an accuracy of $\pm$0.1 ft. Previous potentiometric surface mapping efforts in this area have been based (predominantly) on elevations estimated from topographic maps. Horizontal locations were determined using differential GPS location techniques.

Drilling

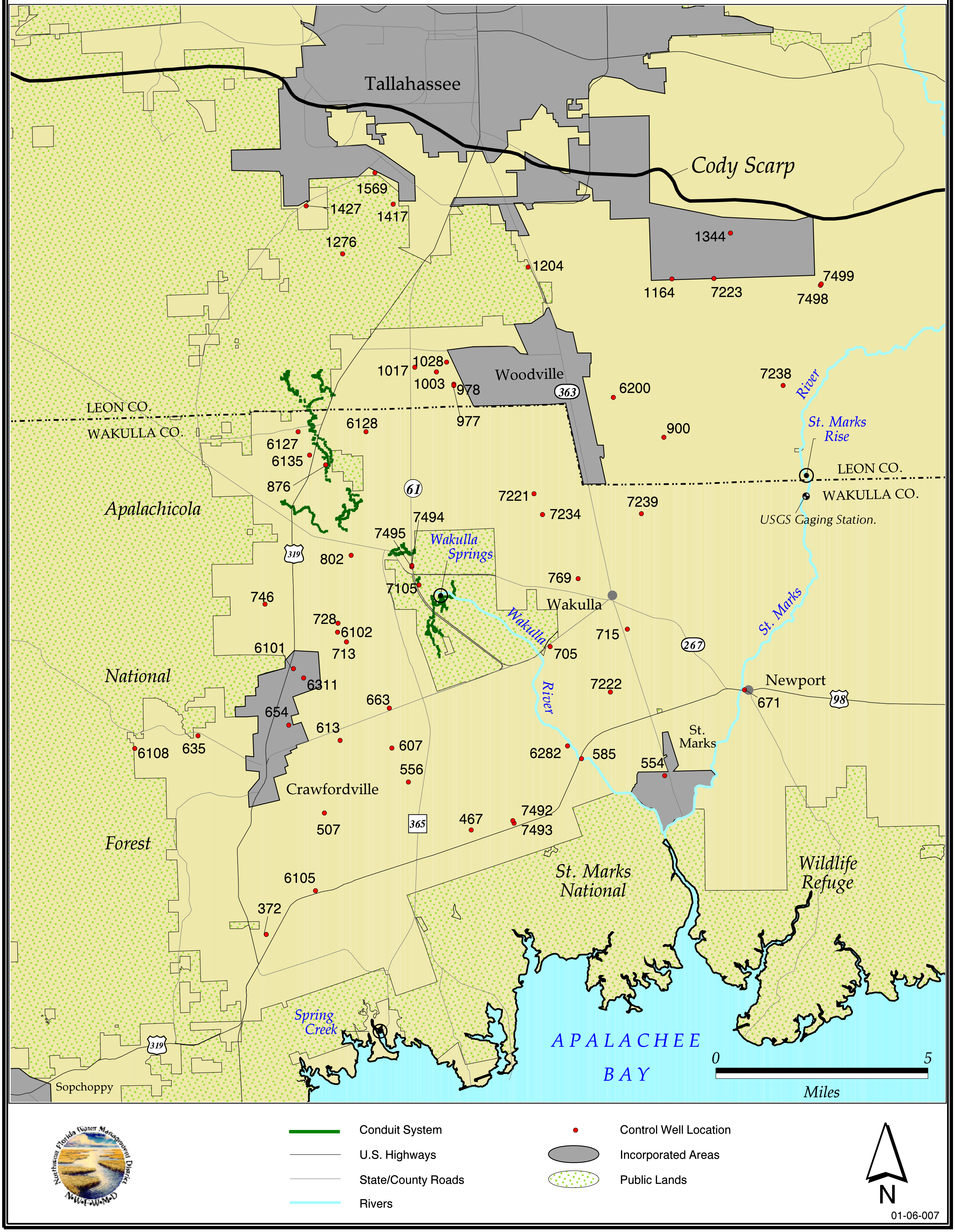
Six Floridan Aquifer monitor wells were constructed as a part of this project. Wells were constructed in three pairs. At each site a deep well and a shallow well were constructed. All wells were constructed using flush-threaded PVC well casing and were grouted with neat cement grout. All were constructed using conventional hydraulic rotary drilling techniques. Well locations and other construction details are found in Appendix A, Table A1.

Ground and Surface Water Sampling

A second network of 41 Floridan Aquifer wells was established for the purpose of ground water sampling (Appendix A, Table A2 and Figure 9). 35 were pre-existing domestic supply, public supply and irrigation wells. The remaining six were constructed specifically for the project. In addition, surface water samples were collected at seven sites (Lost Creek, Fisher Creek, Ames Sink, Middle River Sink, Sally Ward Spring, Wakulla Springs and McBride Slough). Samples were collected by USGS and NWFWMD personnel and were analyzed for major ions, nutrients, silica, DOC and isotopes. Sample collection protocols and analytical methods are discussed in greater detail in Katz et al. (in preparation). The USGS Water Quality and Research Laboratory in Ocala, FL analyzed major ions. The USGS Isotope Fractionation Laboratory in Reston, VA, analyzed O, H and N isotopes. Carbon isotope analyses were performed at the University of Waterloo. Tritium and ^{3}He analyses were performed at the Noble Gas Laboratory of the Lamont-Dougherty Earth Observatory in Palisades, NY.

Ground and surface water sampling was conducted in several mobilizations. Results from the initial ground water sampling were used to guide location selection for the six monitor wells constructed for the project. Once these wells were completed, isotopic sampling was conducted in them and at Middle River Sink and Wakulla Springs. Analyses for this event include ^{15}N/^{14}N; ^{18}O/^{16}O; D/H; ^{13}C/^{12}C; and ^{3}H/^{3}He. A key project objective was to conduct isotopic sampling under low-flow and high-flow conditions. The first isotopic sampling occurred in February 2000 and is considered to represent the low-flow condition. Due to drought conditions that persisted

LOCATION OF WELLS USED FOR WATER LEVEL MONITORING



REVISED - JUNE '03

FIGURE 8

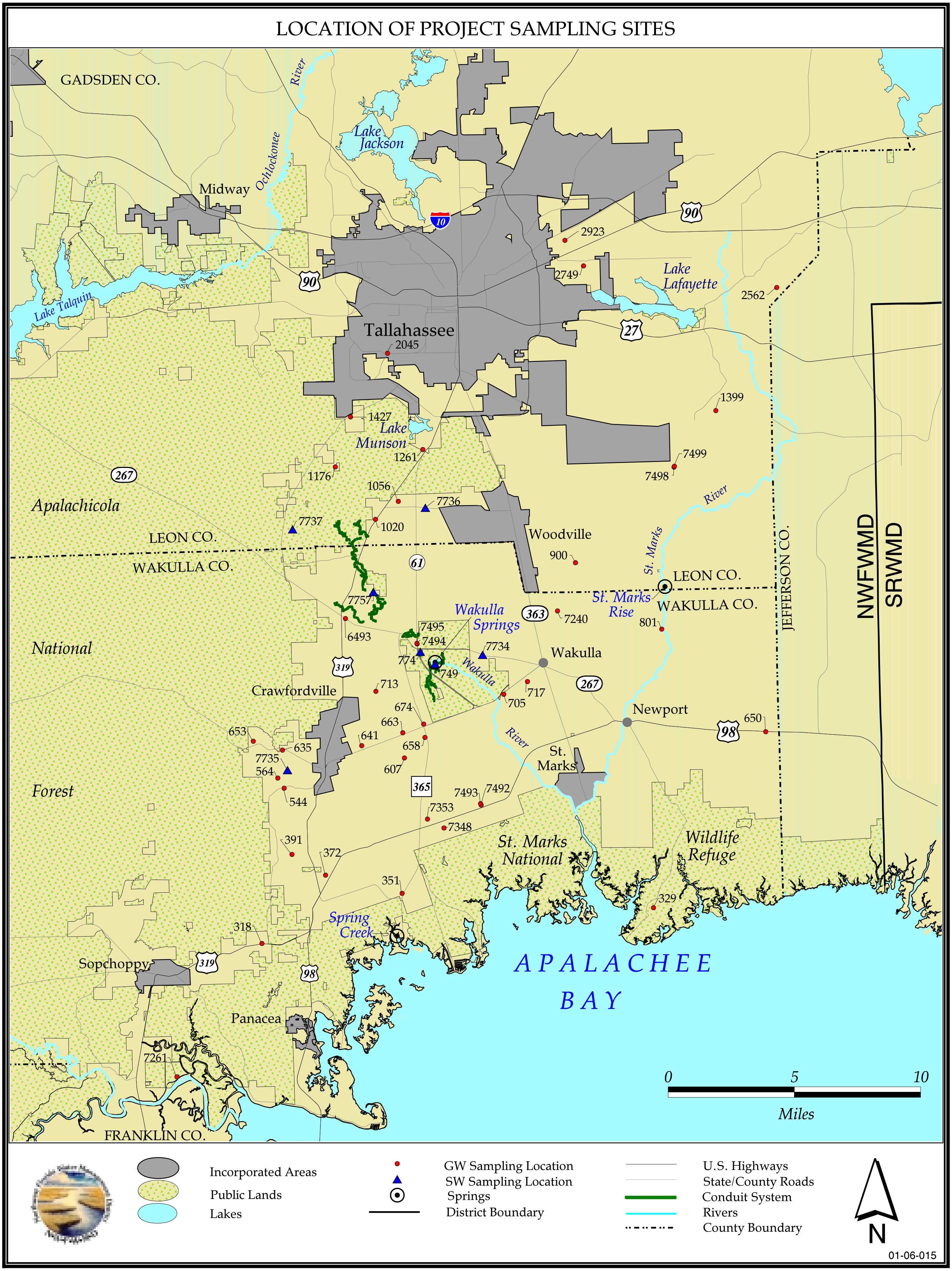

LOCATION OF PROJECT SAMPLING SITES
GADSDEN CO.
Lake Jackson
Ochlockonee River
Midway
Lake Talquin
Tallahassee
Lake Lafayette
Lake Munson
Apalachicola
National
Forest
LEON CO.
WAKULLA CO.
Woodville
St. Marks River
St. Marks Rise
Wakulla Springs
Wakulla River
Wakulla
Crawfordville
Newport
St. Marks
JEFFERSON CO.
NWFWMD
SRWMD
St. Marks National Wildlife Refuge
Spring Creek
Sopchoppy
Panacea
FRANKLIN CO.
APALACHEE BAY
2923
2749
2562
2045
1399
1427
1261
7499
7498
1176
1056
7736
7737
1020
900
7757
7240
801
6493
7495
7494
7734
774
749
713
717
705
674
663
650
653
641
635
658
7735
564
607
544
7493
7492
7353
7348
391
372
351
329
318
7261
0 5 10
Miles
Incorporated Areas
Public Lands
Lakes
GW Sampling Location
SW Sampling Location
Springs
District Boundary
U.S. Highways
State/County Roads
Conduit System
Rivers
County Boundary
N
01-06-015

FIGURE 9

through 2000, it was only following Tropical Storm Helene in September 2000 that conditions were appropriate for high-flow sampling. The project wells, Middle River Sink and Wakulla Springs were sampled again in October 2000 for that purpose.

Nitrogen isotope data gathered to establish the ratio of organic to inorganic nitrogen in the samples were inconclusive for four wells. This was due to nitrate concentrations being below detection limits. Due to this, four alternate wells with elevated nitrate concentrations were selected for additional sampling. These wells were sampled on April 25, 2001.

Surface Water Monitoring

The study plan included collection of continuous hydrologic data to help characterize the dynamics of the hydrologic cycle and the interaction between surface water and ground water resources in the study area. The automated monitoring equipment utilized on the project included an automated rainfall station, a current meter (water velocity) and in-situ water-quality data-sonde meters (water temperature and conductivity). Continuous streamflow monitoring was beyond the scope of the project. Site locations are shown in Figure 10.

Rainfall

An automated rainfall station was established at a central location in Wakulla County (at the River Sink Water Tower located on Highway 319 near the intersection with SR 267 (30°16‘38”/ 84°21’22” NAD27). The station consisted of a rainfall tipping bucket sensor and a data logger, which recorded rainfall data on a ten-minute time interval. The tipping bucket rain gage includes a funnel and a tipping mechanism. Rainfall passes through the funnel onto the tipping mechanism which causes a switch contact closure for each 0.01 inches of accumulated rainfall. The data logger stores the number of tips and records the accumulated rainfall depth. The tipping bucket has an accuracy of ± 2 percent for rainfall rates of less than 1 inch per hour and ± 3 percent for rates above 1 inch per hour. The station was visited each month to retrieve data, perform routine maintenance and insure proper functioning. Annual field calibrations were performed to insure sensor accuracy. The station was installed in May 15, 1999.

Rainfall data was also utilized from two long-term rainfall stations located in Leon County. These included a station operated by NWFWMD located near Lake Munson in southern Leon County and data collected by the National Weather Service at the Tallahassee Regional Airport.

Current Meter

The NWFWMD operates and maintains a self-contained electro-magnetic current meter in the main spring vent of Wakulla Springs. InterOcean Systems, Inc manufactured the meter (S4 model). It has the capability to continuously measure and record velocity and direction components of water movement, water temperature and conductivity. The meter is installed in the main discharge tunnel (A-tunnel) at a depth of approximately 190 ft below the surface of the spring. The meter was installed in May 1997. The geometry of the vent opening has been measured (Figure 11) and the opening area used, with the velocity data and a calibration factor, to calculate continuous discharge data.

The current meter is a ten-inch diameter sphere with four electro-magnetic sensors located symmetrically around the central axis of the sensor. The meter has an internal compass to provide directional information with the velocity data. Conductivity and temperature sensors are also located along the center axis of the meter. The current meter collects data on a three-hour

PRINCIPAL KARST FEATURES

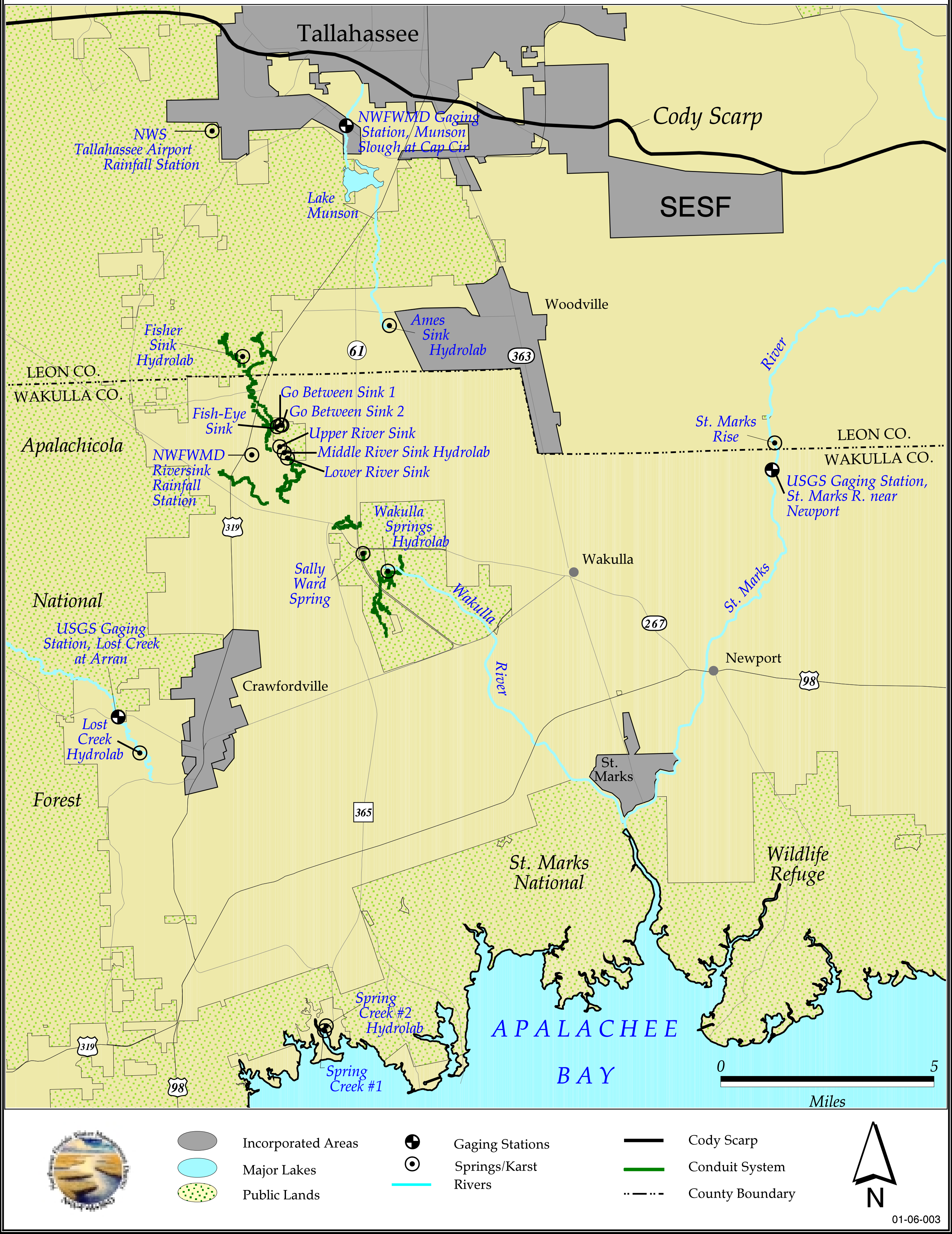


FIGURE 10

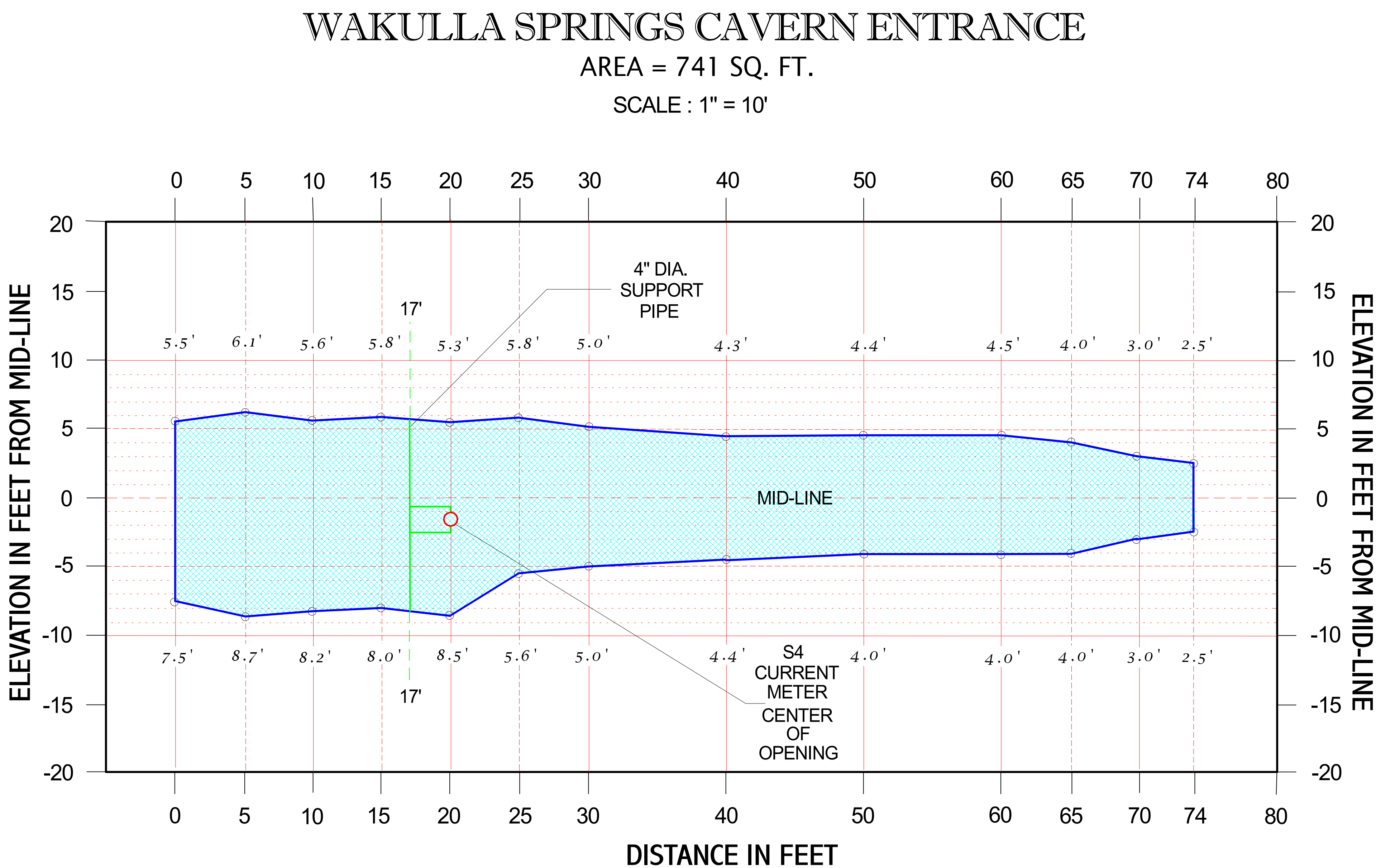


FIGURE 11
CROSS-SECTION OF WAKULLA SPRINGS PRINCIPLE CONDUIT SHOWING S4 EMPLACEMENT

recording cycle and stores it internally. The meter is brought to the surface every eight to twelve months to retrieve data and service the meter.

The meter is installed in the center of a limestone constriction at the mouth of the main spring vent (Figure 11). The mooring system consists of telescoping aluminum pipes that extend between the roof and floor of the spring vent. Two arms extend from the side of the aluminum pipes to support the meter. The mooring system was designed to minimize disturbance of the spring flow, prevent damage to the limestone surfaces of the spring vent opening and facilitate easy removal and installation of the current meter. The cross-sectional area of the conduit at the point where the meter is installed is 741 ft^2.

Main vent discharge has been estimated as the product of observed point velocity in A-tunnel and A-tunnel cross-sectional area at the point of velocity measurement. These estimates have been verified with five conventional channel discharge measurements at the CR 365 bridge and the other three major inflows (Sally Ward Spring and two McBrides Slough inflows) that discharge to the river above the CR 365 bridge. The conventional channel discharge measurements were completed during one-day measuring events. A variable time lag was assumed between the main vent and the CR 365 bridge based on a distance of 2.75 miles and an average channel velocity for the measuring period. Discharges from Sally Ward Spring and the McBrides Slough inflow were subtracted from the Wakulla River discharge at CR 365 to approximate discharge from the main vent. Discharge from small springs and seeps along the river was estimated to contribute little to the total river flow and were excluded. Observed main vent discharge versus calculated discharge is given in Figure 12.

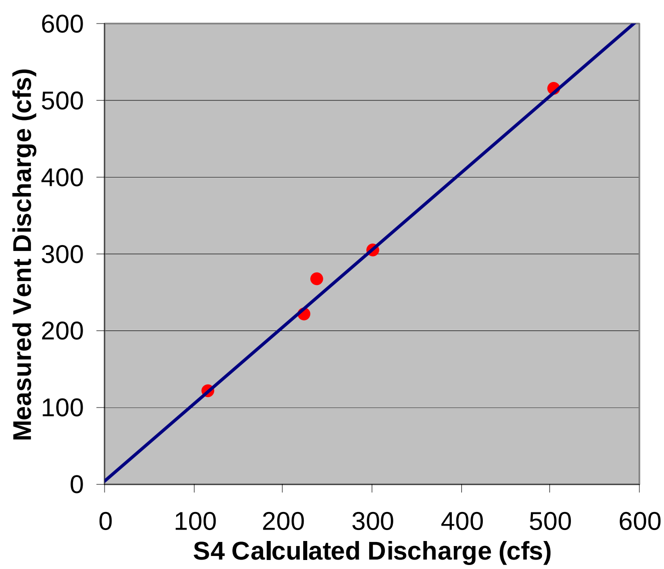


Figure 12. Wakulla Springs Main Vent Measured Discharge versus Calculated Discharge.

In-situ Water Quality Meters

Self-contained water quality data loggers were installed at six locations (stations 1—6 below, Figure 10) to continuously measure surface water conductivity and temperature. The water quality data loggers were programmed to collect data on an hourly time interval at the six stations. The station locations are described below. Three stations, Middle River Sink Spring, Wakulla Springs and Spring Creek #2 had moving water for the entirety of their respective data collection periods. Due to drought conditions, Fisher Creek, Lost Creek and Ames Sink intermittently had conditions of very low to zero flow. However, there was continuous standing water at each of these sites. Time series data for these stations should be evaluated with this in mind. Continuous mean daily flow data for Lost Creek during 1999 and 2000 were obtained from the USGS and are presented later in this report. Collection of continuous stream flow data at Fisher Creek Sink and Ames Sink was beyond the scope of this investigation.

1. Fisher Creek Sink at Leon Sink Geological Area—Fisher Creek is a black-water stream that originates in the Apalachicola National Forest. Fisher Creek disappears underground and re-emerges at several locations along its length below the Springhill Road Bridge. The meter was installed on a walkway in a six-inch diameter PVC support pipe at the point where Fisher Creek disappears underground for the last time (30°18'35.115"/84°21'22.783" NAD83).

2. Ames Sink—Ames Sink is located about eight miles south of Tallahassee and funnels water from Munson Slough underground as it flows south. The meter was installed in a six-inch diameter PVC pipe mounted on the SW bank of the sink near the inflow channel into the sink (30°19'08.859"/84°17'54.916" NAD83).

3. Lost Creek below FR 13—Lost Creek is a black-water stream originating in the Apalachicola National Forest. The creek meanders through the forest before disappearing underground south of Crawfordville. The meter was installed in a six-inch PVC pipe extending into the creek about 0.5 miles upstream from the point where it flows underground (30°10'33.014"/ 84°24'00.696" NAD83).

4. Wakulla River at Boat Dock—The Wakulla River begins at a basin created by the main Wakulla Spring vent located at the Wakulla Springs State Park. The meter was installed on a concrete slab, with a vertical support pipe, below the tour boat dock located about 500 feet downstream of the main spring vent (30°14'08.381"/84°18'05.199" NAD83).

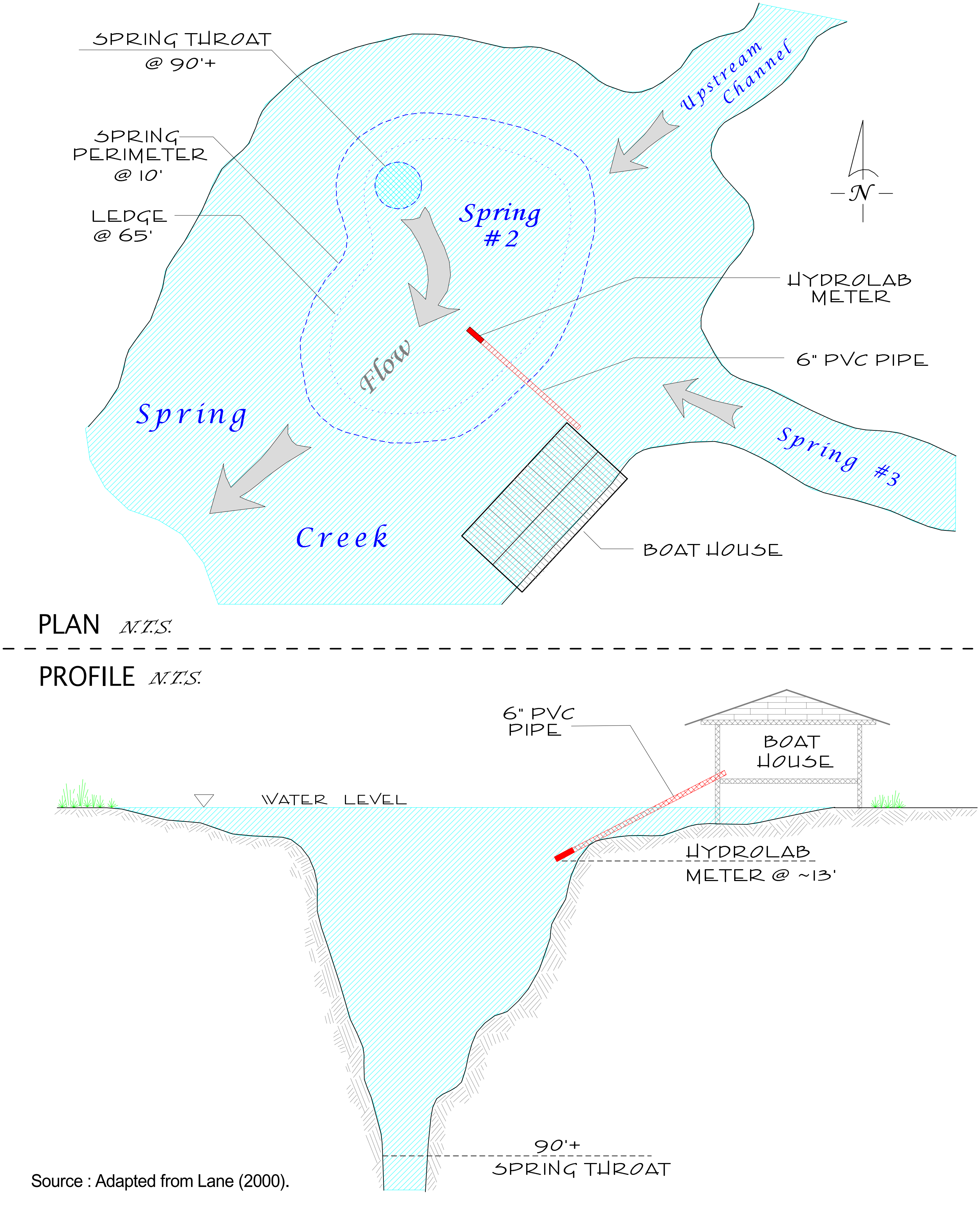
5. Spring Creek Vent #2—Spring Creek Vent #2 is one of several springs that discharge into the estuary near the Spring Creek community. The meter was installed in a six-inch diameter pipe on the upper edge of the sink in the path of the spring flow (Figure 13). The meter was installed in about 13 feet of water (30°04'53.687"/84°19'47.141" NAD83). A schematic representation of the geometry of Spring Creek Vent #2 sink and pool is also given in Figure 13. This figure is adapted from Lane (2001). Lane also gives a map depicting the location of the 13 mapped vents in the Spring Creek group.

Specific conductivity versus time data for this station is given in Figure 14. These data show that, for most of the data collection period, the conductivity at the measurement point was rarely less than 2,000 μmhos/cm. Specific conductivity values daily ranged between about 2,000 μmhos/cm to well in excess of 9,000 μmhos/cm, apparently reflecting the mixing of saline surface water with fresher ground water discharge within the spring pool itself. Only once were waters in the spring pool consistent with what should be expected for Floridan Aquifer water uncontaminated by saline surface water. This occurred for about a week in early November 1999 following heavy rains associated with Hurricane Floyd.

6. River Sink Group—The River Sink area is a series of sinks and karst features in northern Wakulla County. The meter was installed on a concrete slab, with a vertical support pipe, in

SPRING CREEK SPRING #2

NOT TO SCALE



Source : Adapted from Lane (2000).

FIGURE 13

CROSS-SECTION OF SPRING CREEK VENT #2 SHOWING HYDROLAB EMPLACEMENT

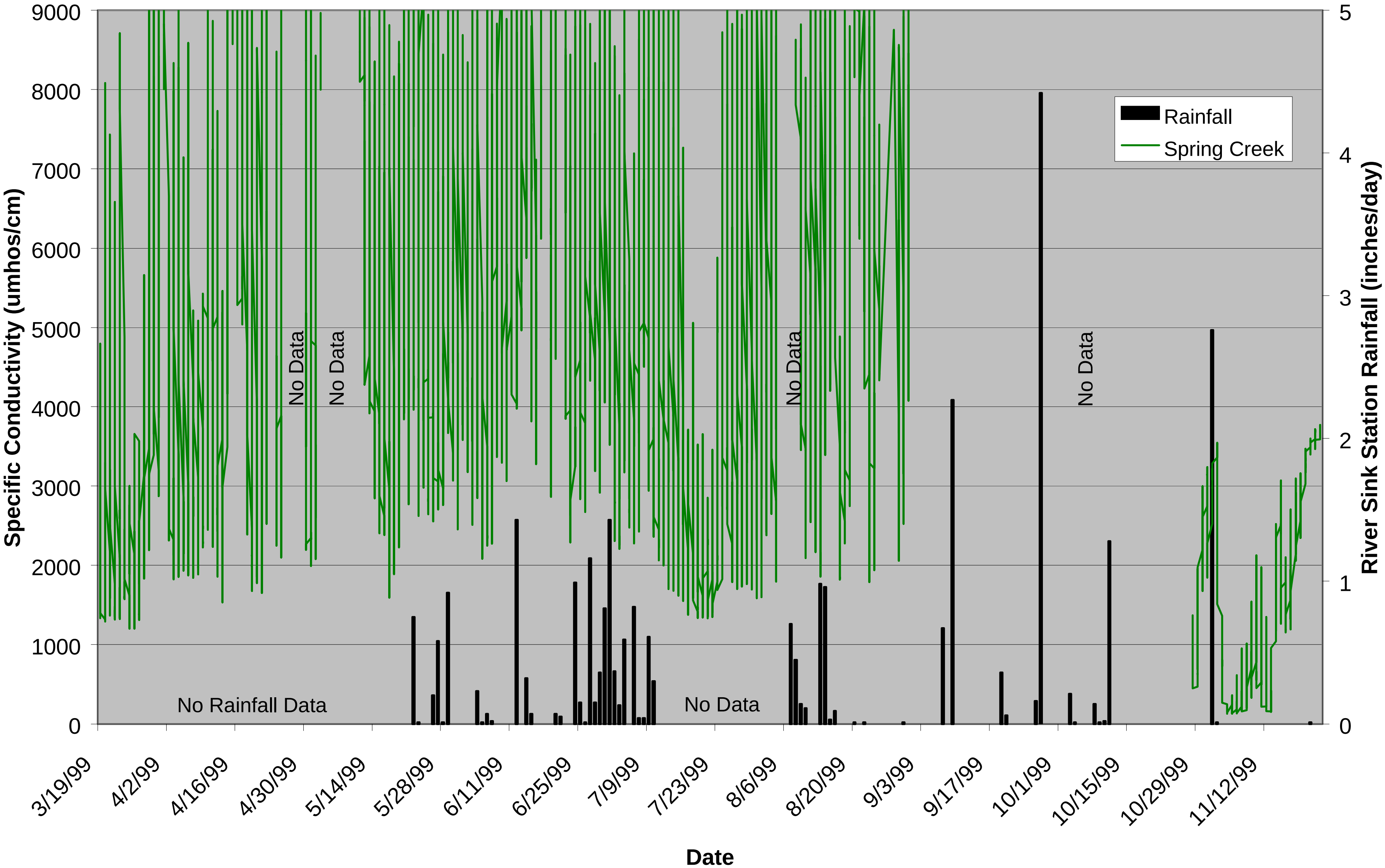


Figure 14. Specific Conductivity and Rainfall versus Time for Spring Creek Vent #2, 1999.

7. the center of a section of collapsed conduit where ground water emerges to create a stream that flows about 200 feet before disappearing underground into a sink (30°16’36.24” 84°20’27.396” NAD83).

Data from three additional stations (Figure 10) were also used in this investigation.

8. USGS Lost Creek Gaging Station—The USGS maintains a continuous stream flow gaging station on Lost Creek. The station is located on the downstream side of the Highway 368 bridge, 0.5 miles east of Arran (30°11‘17”/84°24’30” NAD27). This station is located about 1.8 miles north (linearly) of the point where Lost Creek goes underground and about one mile (linearly) above the NWFWMD water quality data logger site (station #3 above).

Continuous daily mean flow versus conductivity data from the NWFWMD Lost Creek station are given in Figure 15, for the period 3/99 to 11/00. For most of this period, conductivities range between 40 to 70 µmhos/cm. During three low-flow periods (04/99 to 06/99, 12/99, and 04/00 to 08/00) surface water conductivities rose to as high as 200 µmhos/cm. Conductivities this high appear to reflect base flow discharge from the Floridan Aquifer into Lost Creek. Along the lower reach of Lost Creek, Floridan Aquifer heads are above stream channel elevations. Accordingly, it is quite plausible that Floridan Aquifer waters are discharging to the channel above the point where Lost Creek goes underground.

9. USGS St. Marks River Gaging Station—The USGS maintains a continuous streamflow gaging station on the St. Marks River about 0.65 miles below the St. Marks River rise. The station is located on the east bank of the river, about 0.4 miles south of the Leon/Wakulla county line (30°16‘00”/84°09’00” NAD27).

10. Munson Slough north of Lake Munson (S3)—The NWFWMD maintains a continuous stream flow station on Munson Slough. The station is located at the point where Munson Slough crosses under Highway 319 (30°23‘14”/84°18’49” NAD27). This station is located about 0.95 mile north of Lake Munson and about 5.24 miles north of the continuous recording water quality logger in Ames Sink (station #2).

Continuous daily mean flow (station #9) versus conductivity data from the Ames Sink hydrolab station (station #2) are given in Figure 16, for the period 3/99 to 9/00. For most of this period, conductivities range between 57 and 261 µmhos/cm. During relatively dry periods surface water conductivities rose. High conductivities within Ames Sink may reflect re-circulation of Floridan Aquifer water into the sink or discharge of Floridan Aquifer water into lower Munson Slough during periods of minimal surface water inflow.

Four sites had meters installed within six-inch diameter PVC support pipes. For these stations PVC support pipes were installed to protect the meters. Each pipe had vent holes drilled around the perimeter of the pipe to ensure good water flow around the sensors. Two stations were installed on concrete anchor slabs having two-inch diameter PVC support pipes vertically mounted in the center. The two-inch diameter support pipe extended about three feet above the channel bottom. Water quality meters were installed on the two-inch vertical support pipe within the water column.

The water quality meter stations were visited monthly to retrieve data and re-calibrate the meters. The sensor arrays were cleaned monthly and the meters were monthly re-calibrated using appropriate conductivity calibration standards. The temperature probes were monthly

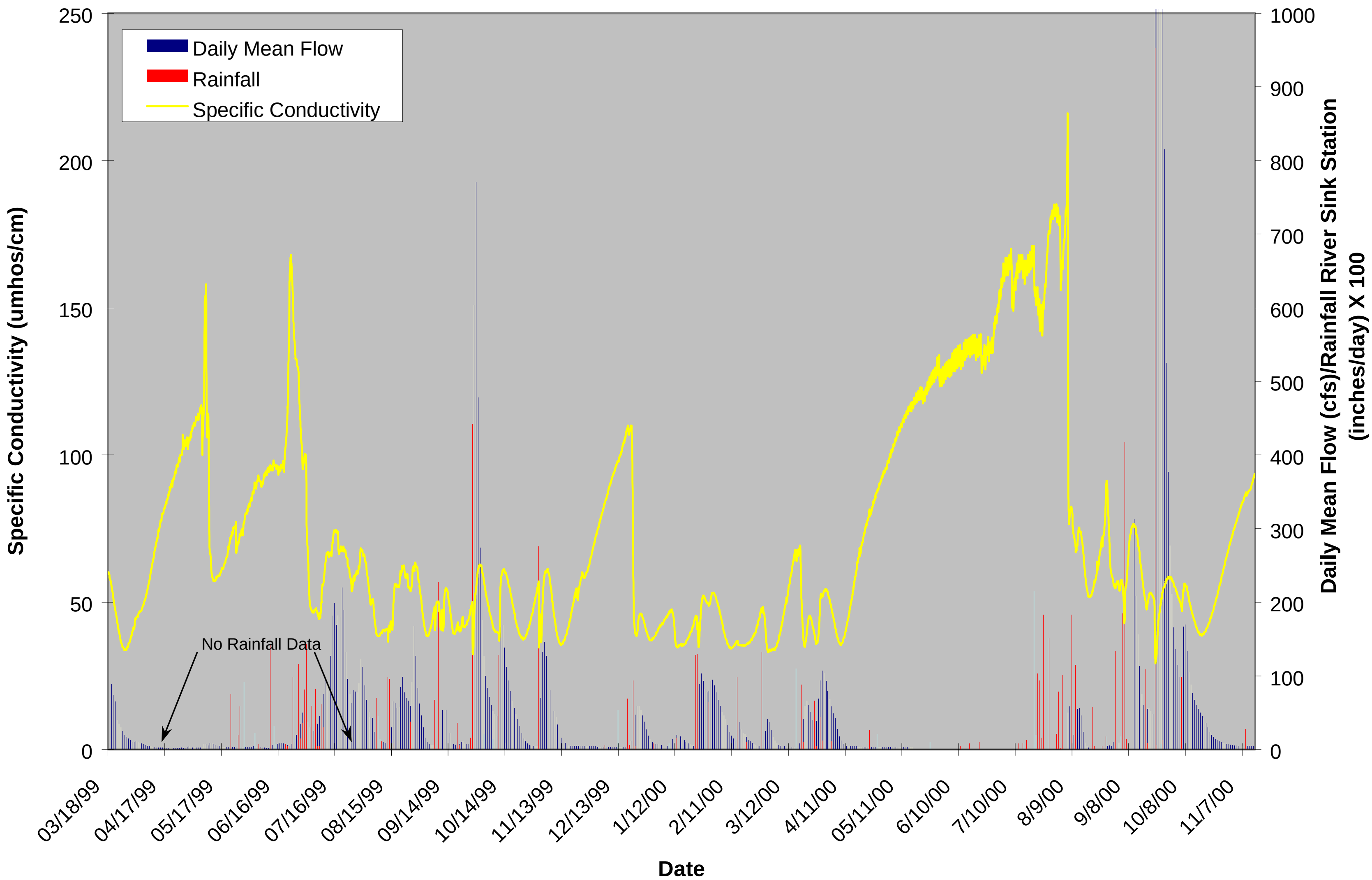


Figure 15. Lost Creek Specific Conductivity, Rainfall and Daily Mean Flow versus Time (flow data from USGS).

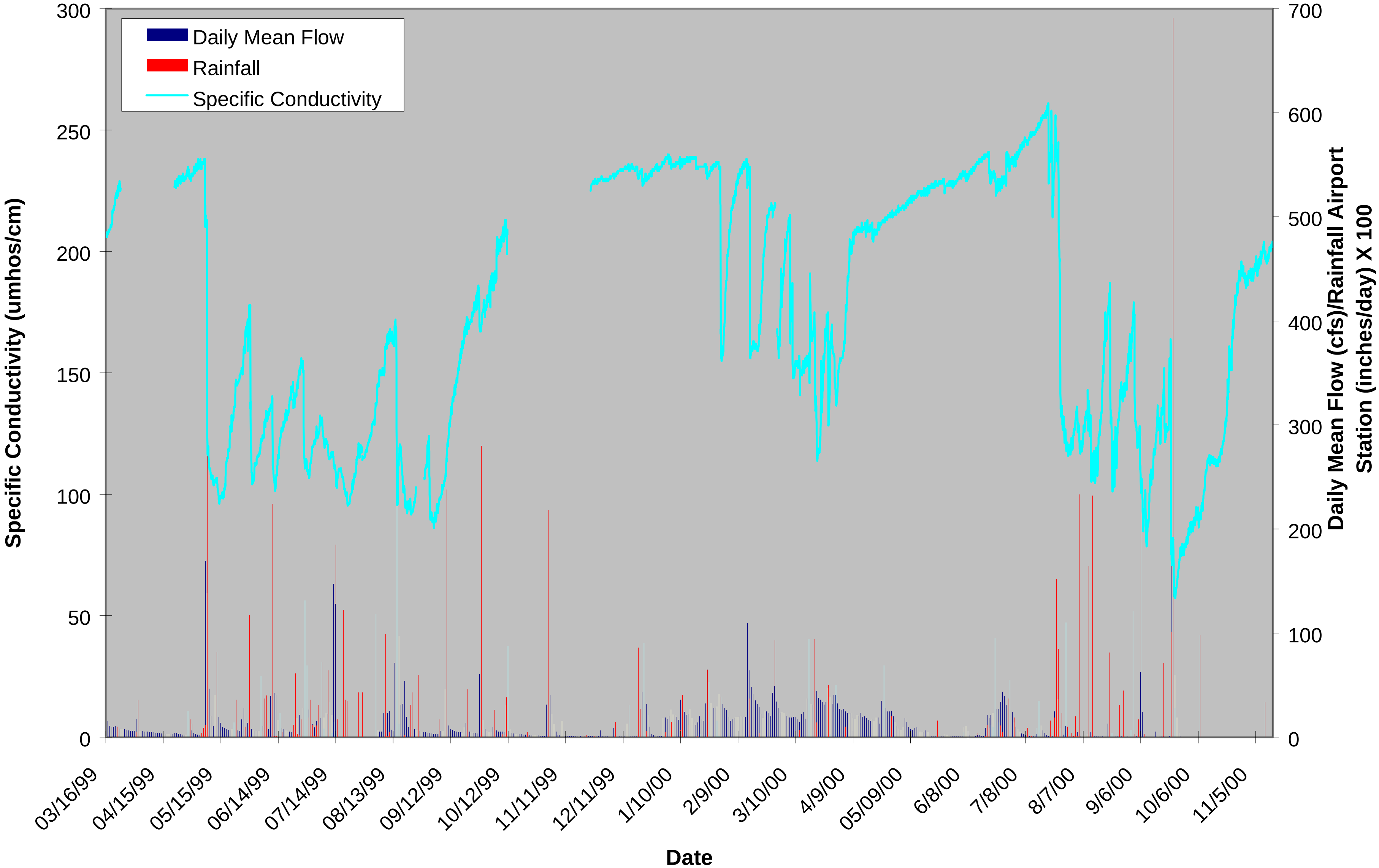


Figure 16. Ames Sink Specific Conductivity, Rainfall and Munson Slough @ Highway 319 Daily Mean Flow versus Time.

calibrated to an external thermometer reading. The meters experienced minimal sensor fouling at all six locations throughout the data collection period. They also experienced minimal drift with respect to both temperature and conductivity. Calibration adjustments for temperature ranged from 0.01 to 4.86 degree Celsius with an average adjustment of 0.35 degrees. The adjustments required for conductivity ranged from zero to 29 µmhos/cm with an average of 6.1 µmhos/cm.

Temperature readings from the hydrolabs under identical conditions were compared once to assure data consistency. Results are as follows:

Fisher Creek @ Leon Sink	Serial #15588	19.6°C
Ames Sink	#15591	19.8°C
Lost Creek below FR13	#18253	19.4°C
Middle River Sink Spring	#15589	19.8°C
External thermometer reading		19.7°C

HYDROLOGY OF THE ST. MARKS-WAKULLA RIVERS WATERSHED

Physiography and Geology

The study area principally lies within the Tallahassee Hills and the Gulf Coastal Lowlands physiographic divisions (Figure 17). The northern two-thirds of Leon County lie within the Tallahassee Hills. The southern third of Leon County and all of Wakulla County lie within the Gulf Coastal Lowlands. The northern portion of Jefferson County lies in the Tallahassee Hills, the southern portion in the coastal lowlands. Elevations in the Tallahassee Hills are quite variable, being as high as 250 ft above sea level and as low as 50 ft above sea level. Elevations on the Gulf Coastal Lowlands are much more uniform and lower, being generally less than 50 ft above sea level.

The Cody Scarp divides these two physiographic divisions and is defined by a fairly abrupt decrease in elevation from the Tallahassee Hills onto the coastal lowlands (Figure 17). It is most evident in eastern Leon County. In the western part of the county, the break in topography is more gentle and the scarp more difficult to map. It represents the landward edge of a transgressional marine erosion event.

South of the Tallahassee Hills, the Woodville Karst Plain forms a subdivision of the Gulf Coastal Lowlands. The Woodville Karst Plain lies in southeast Leon County and eastern Wakulla County. It is an erosional surface bounded on the north by the Cody Scarp and on the west by a second, lower scarp (Figure 17). Land surface elevations on the Woodville Karst Plain are low, rarely more than 50 ft above sea level. The overlying confining units have been stripped away by sea level fluctuations, leaving only a thin veneer of unconsolidated sediments covering the St. Marks Formation. Sinkholes, shallow closed depressions, cenotes, springs, other karst landforms, and an almost complete lack of surface streams dominate the landscape.

Most of the Tallahassee Hills in Leon County lie within one of four large closed lake basins (Figure 18). These are the Lake Iamonia, Lake Jackson, Lake Lafayette and Lake Miccosukee basins. The basins within which Lakes Jackson and Iamonia lie were originally tributary to the Ochlockonee River. Erosion improved the hydraulic connection to the underlying Floridan Aquifer to the point where the drainage became internal and the basins closed. Lake Jackson is effectively completely closed. Lake Iamonia is still hydraulically connected to the Ochlockonee River floodplain under high flow conditions. Under low flow conditions, it is a closed basin. Both lakes have active sinkholes in their beds.

Similarly, Lakes Lafayette and Miccosukee were originally tributary to the St. Marks River. Erosion and internal drainage have more or less closed both of these basins. An intermittent overland hydraulic connect exists between the Lake Lafayette basin and the St. Marks River floodplain. The Lake Miccosukee basin is effectively completely closed by a system of sinks that capture any outflow along the relic stream channel. These include Lake Drain sink and Creek sink. Both lakes have active sinks in their beds as well.

Smaller closed basins lying in the Tallahassee Hills include the Fred George basin draining to Fred George sink, the Patty Sink basin, and the Black Creek basin draining to Bird and Copeland sinks. The Lake Munson basin lies on both the Tallahassee Hills and on the Gulf Coastal Lowlands. Surface waters originating in the Lake Munson basin flow south onto the coastal lowlands, through Lake Munson and eventually drain underground at Ames Sink.

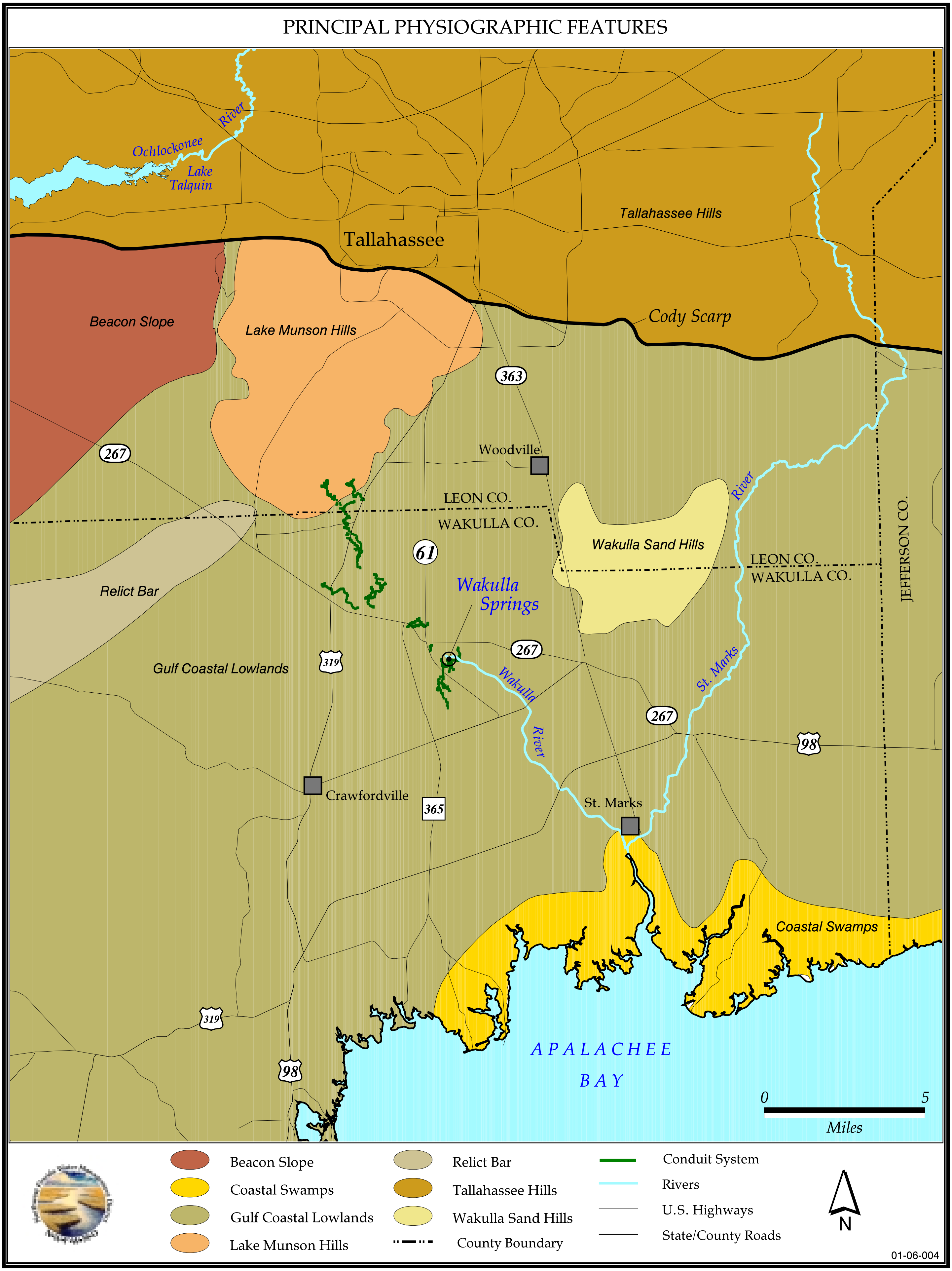

PRINCIPAL PHYSIOGRAPHIC FEATURES
Ochlockonee River
Lake Talquin
Tallahassee
Tallahassee Hills
Cody Scarp
Beacon Slope
Lake Munson Hills
363
267
Woodville
LEON CO.
WAKULLA CO.
61
Wakulla Sand Hills
River
LEON CO.
WAKULLA CO.
JEFFERSON CO.
Relict Bar
Wakulla Springs
267
319
Gulf Coastal Lowlands
Wakulla River
St. Marks
267
98
Crawfordville
365
St. Marks
Coastal Swamps
319
98
APALACHEE BAY
0 5
Miles
Beacon Slope
Coastal Swamps
Gulf Coastal Lowlands
Lake Munson Hills
Relict Bar
Tallahassee Hills
Wakulla Sand Hills
County Boundary
Conduit System
Rivers
U.S. Highways
State/County Roads
N
01-06-004

FIGURE 17

SURFACE WATER BASINS AND PRINCIPAL SURFACE WATER FEATURES

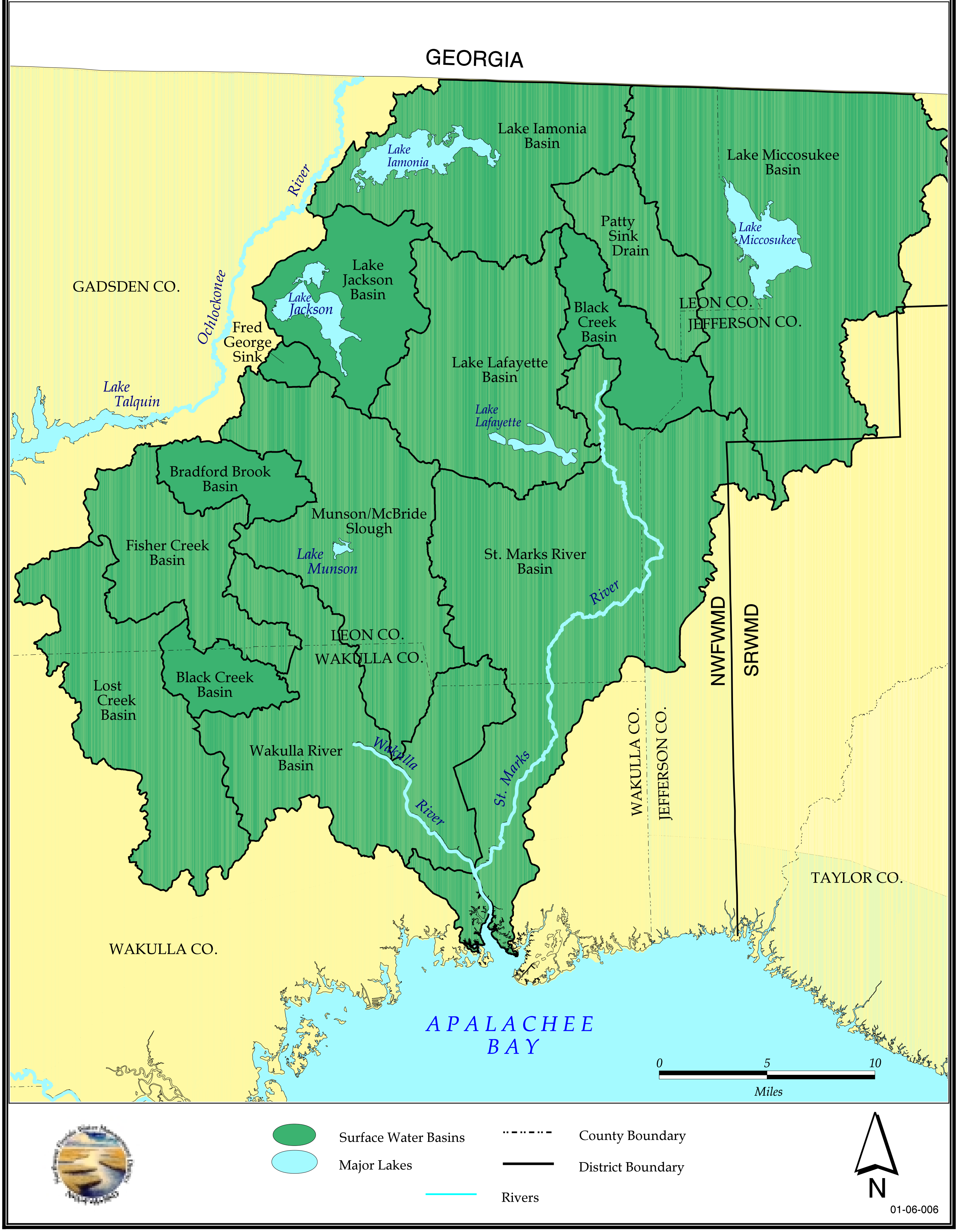


FIGURE 18

The Tallahassee Hills are underlain by (in descending order) the Miccosukee Formation, the Torreya Formation of the Hawthorn Group, the St. Marks Formation, the Suwannee Limestone and older, more deeply lying units. Hendry and Sproul (1966) first described the geology of Leon County. Scott (1988) describes the lithostratigraphy of the Hawthorn Group in Florida, including Leon County. The Hawthorn Group is absent in southeast Leon County and eastern Wakulla County, having been removed by the marine transgression that formed the Cody Scarp. Within the Tallahassee Hills the Miccosukee Formation is limited to the higher elevations found on inter-stream divides (Figures 19 and 20). Elsewhere, it has been removed by erosion. The Torreya Formation is near the surface along lower elevations within the Tallahassee Hills. These include the many stream channels that dissect the hills and in the bottoms of the large lakes that dot the landscape. Torreya Formation is frequently seen in scoured stream channels and drainage ditches found throughout Tallahassee and the surrounding urbanized area. Lying immediately south of the Tallahassee Hills, fairly thick deposits of undifferentiated sand mantle the northern edge of the Gulf Coastal Lowlands. These consist of relict beach and dune deposits. One portion of this sequence is known as the Lake Munson Hills.

Undifferentiated sands, Jackson Bluff Formation, Intracoastal Formation, Torreya Formation, St. Marks Formation, Suwannee Limestone and older, more deeply lying units underlie the Gulf Coastal Lowlands south of the Tallahassee Hills. Rupert and Spencer (1988) describe the geology of Wakulla County. The area of occurrence of the Intracoastal and Torreya Formations is limited to approximately the western half of the county (Figure 21). The relatively low hydraulic conductivity of the Intracoastal and Torreya formations hydraulically isolates the surficial sands from the underlying Floridan Aquifer. Given the flatness of the terrain, the thinness of the surficial sands and the low permeability of the underlying sediments, broad expanses of wet pine flatwoods dominate the landscape. The Ochlockonee River and Fisher, Black and Lost creeks drain these flatwoods. Fisher, Black and Lost creeks flow from west to east. Once they encounter the western edge of the Woodville Karst Plain, they disappear underground. Their waters drain either to Wakulla Springs or to the Gulf of Mexico. On the karst plain itself, the stratigraphy consists of the thin veneer of sands lying directly on top of the St. Marks and older formations (Figures 20 and 21).

Hydrology of the Floridan Aquifer

The work of Davis (1996) provides a comprehensive overview of the Floridan Aquifer flow system beneath Leon and Wakulla counties. Davis calibrated and applied a Floridan Aquifer flow model to a large study area in southwest Georgia and north Florida (including Leon and Wakulla counties). Based on potentiometric surface mapping, Davis defined an approximate recharge area for the coastal Wakulla County discharge features (Wakulla Springs, Spring Creek, lower St. Marks River and other submerged lands beneath the Gulf of Mexico). That area includes all or portions of Leon, Gadsden and Jefferson counties in Florida and Thomas, Grady, Colquitt, Mitchell and Decatur counties in Georgia. The Florida portion of this area is delineated in Figure 1. In both Georgia and Florida the total recharge area for these features is about 2,200 mi^2.

As a part of his conceptual model development, Davis divided Leon County into three areas: unconfined where the Floridan Aquifer is near land surface; unconfined where the Floridan Aquifer is overlain but not confined by low-permeability sediments; and confined. The first two of these areas generally correspond to areas identified as unconfined and semi-confined, respectively, in Figure 1. In Wakulla County, Davis conceptualized the Floridan Aquifer as being either unconfined and near land surface, or confined. Davis' unconfined area generally

SURFACE GEOLOGY

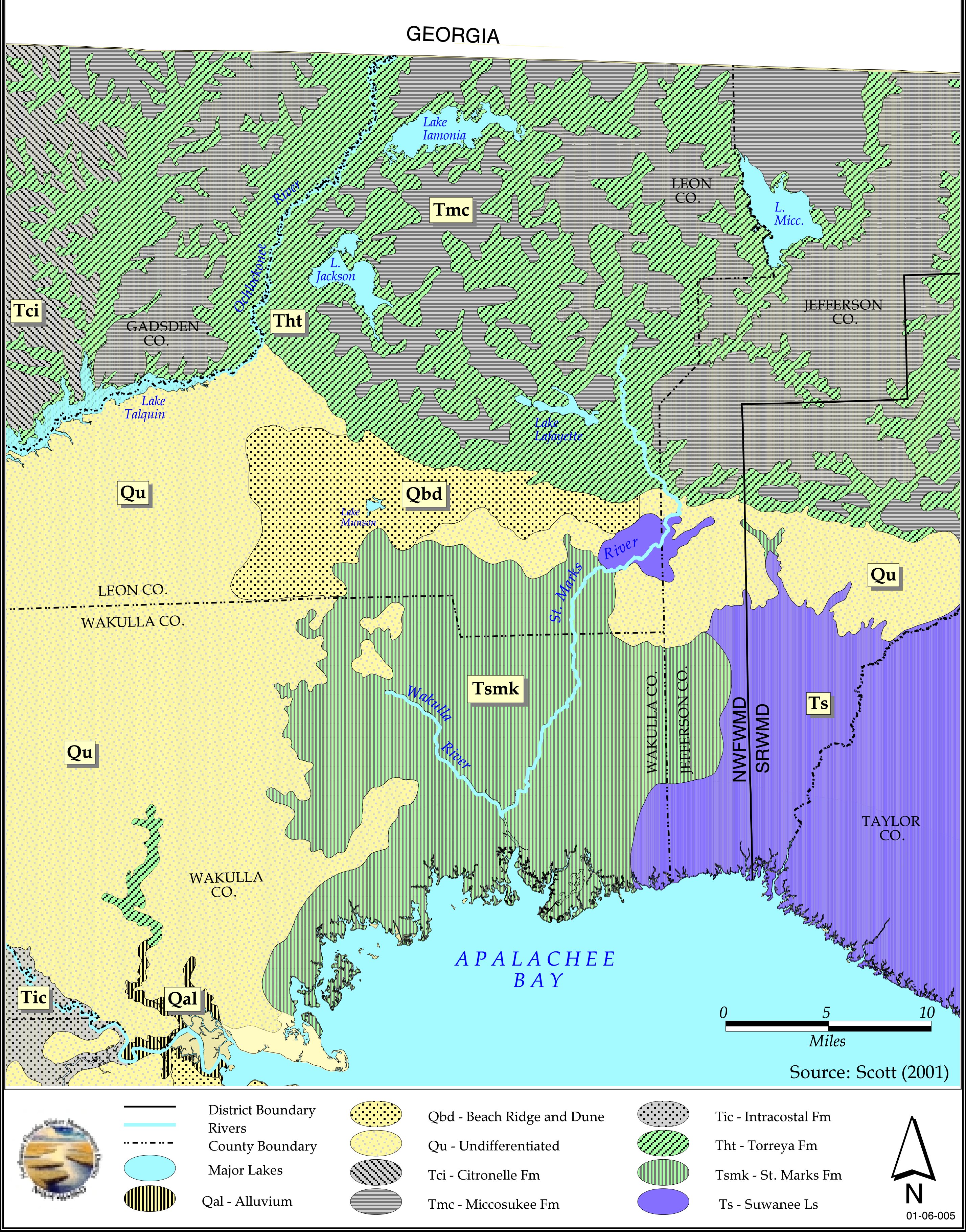
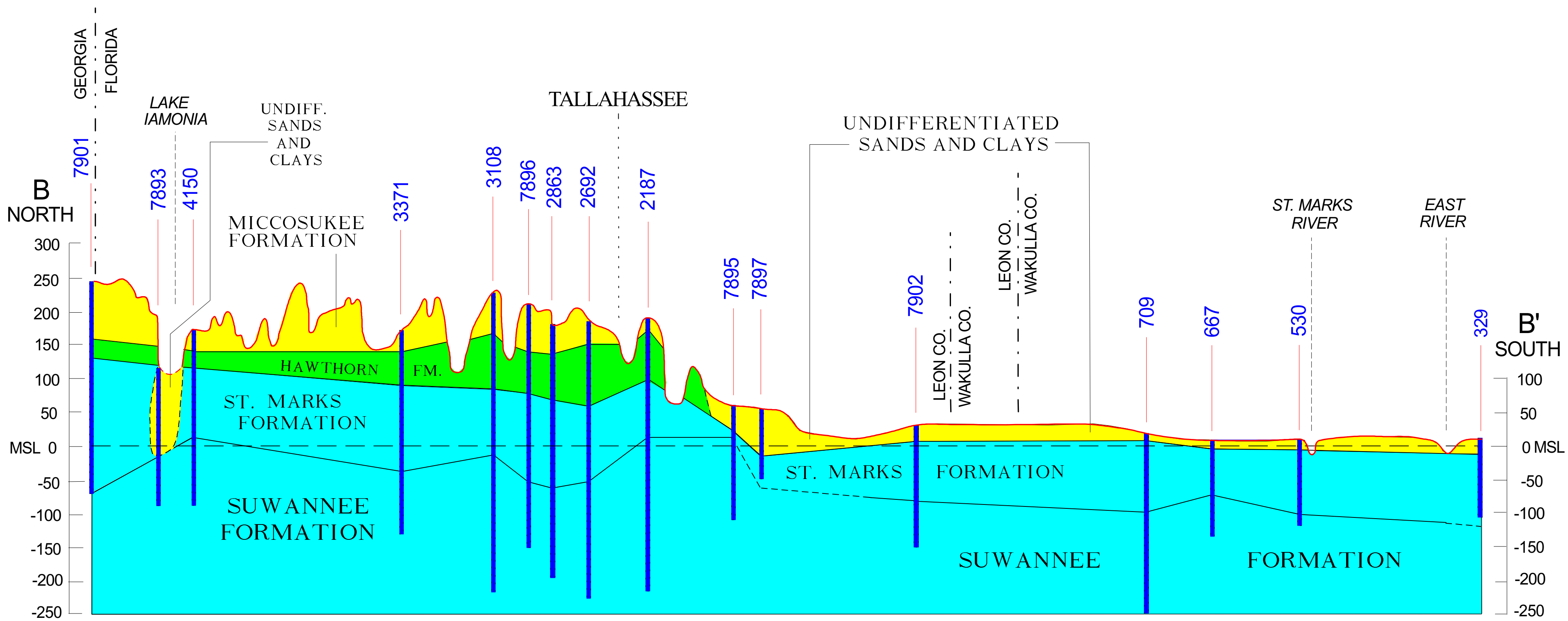
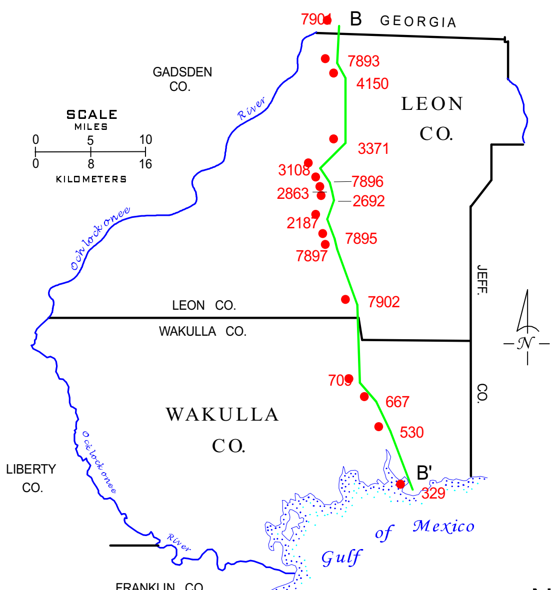


FIGURE 19

GEOLOGIC CROSS-SECTION B-B' IN LEON AND WAKULLA COUNTIES





Source : Wakulla County - After Rupert and Spencer, Bulletin 60, Florida Geological Survey, 1988.
Leon County - After Hendry and Sproul, Bulletin 47, Florida Geological Survey, 1966.

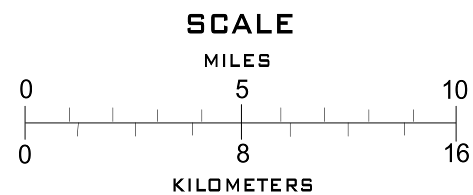


FIGURE 20
NORTH-SOUTH HYDROGEOLOGIC CROSS-SECTION

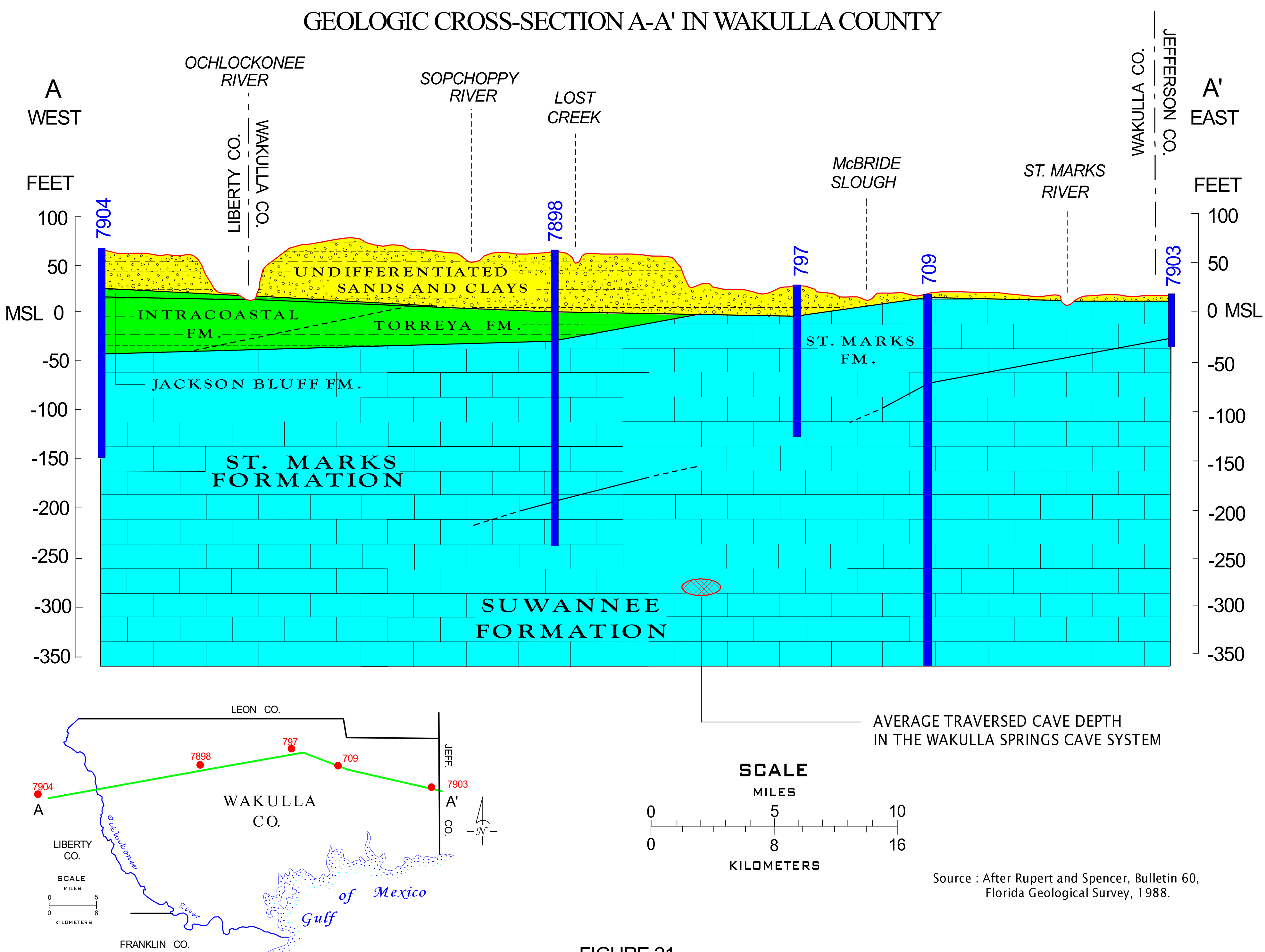


FIGURE 21
EAST-WEST HYDROGEOLOGIC CROSS-SECTION

corresponds to what is mapped as unconfined on Figure 1. This also corresponds to what was mapped as the Woodville Karst Plain by Hendry and Sproul (1966), Lane (1986), Rupert and Spencer (1988) and Rupert (1988).

Davis calibrated his model to conditions in October and November 1991. Based on the calibration results, Davis developed Floridan Aquifer recharge rates for each of these three areas. For that portion of Leon County overlain by low-permeability sediments but not confined, he calibrated a recharge rate of 7.9 in/yr. For that portion of Leon and Wakulla counties under unconfined conditions, he calibrated a recharge rate of 18 in/yr. For the two sprayfields operated by the City of Tallahassee he applied recharge rates of 62 in/yr (reflecting the volume of effluent applied to the sprayfield). For confined portions of both counties, he calibrated fluxes into the Floridan Aquifer (recharge across the confining unit) as high as 10 in/yr and out of the aquifer (discharge) as high as 10 in/yr. Discharge across the confining unit was simulated to occur in the immediate vicinity of the Ochlockonee River. The highest recharge rates occurred immediately adjacent to the unconfined parts of the model.

Davis measured discharge from the Floridan Aquifer at several sites in Wakulla County. On November 1, 1991 the following flows were measured: Spring Creek sub-aqueous spring group—307 cfs, Wakulla Springs—350 cfs, St. Marks River south of Leon/Wakulla county line—602 cfs. The total discharge from these three features is 1,259 cfs, virtually all of which comes from the Floridan Aquifer. Davis' calibrated model simulated a discharge from these features of 1,246 cfs. Diffuse discharge to the Gulf of Mexico (the only other discharge sink for the coastal Wakulla County recharge area) was simulated as being minimal.

Ground water flowing beneath Leon County in the Floridan Aquifer flows in a generally north to south direction. Because of extremely high transmissivities, pumping by the City of Tallahassee has relatively little effect on the potentiometric surface and no significant cone of depression has formed. The potentiometric surface at the State line stands at an elevation of about 70 ft above sea level. This declines to about 10 ft above sea level at the Leon-Wakulla county line. Water that flows across the state line is augmented by water that leaks into the Floridan Aquifer within the county.

In spite of fact that the Floridan Aquifer rarely outcrops within Leon County, it is well connected to the overlying land surface. Downward leakage occurs in the base of closed depressions, through lakebeds and sinkholes, and through the confining unit. Sediments of the St. Marks Formation are rarely observed in Leon County, but they are not far beneath the surface. Sediments that comprise the Torreya Formation are relatively thin. In the eastern two-thirds of the county, they are typically 100-ft thick or less. In many low-lying areas they have been significantly thinned by erosion. In the northern part of the county the top of the St. Marks Formation stands at elevations as high as 100 to 120 ft above sea level, resulting in a significant thickness of unsaturated carbonate rock north of the Cody Scarp. Unsaturated thicknesses of St. Marks sediments in this area are as great as 80 ft.

Katz et al. (1997a) conducted an investigation into ground water/surface water interactions at two sites in Leon County, near Fred George Sink within the Tallahassee Hills and near Lake Bradford, on the Gulf Coastal Lowlands. They also collected samples from 11 City of Tallahassee public supply wells open to significant portions of the highly permeable uppermost Floridan Aquifer. Katz et al. observed that ground waters from five City wells are, in part, composed of surface waters enriched with ^{18}O and D. In the case of two wells (CW-19 and CW-26), and based on mixing model studies, up to 32 percent lake water (subjected to evaporation prior to recharging the Floridan Aquifer) is required to provide the chemical and isotopic composition observed in ground water from these wells. They postulate Fred George Sink and Lake Jackson as plausible sources for this evaporated surface water.

Floridan Aquifer water that flows into Wakulla County flows in a southerly direction toward points of discharge. These include Wakulla Springs, Spring Creek springs group, the lower St. Marks River and the Gulf of Mexico. Water that flows into the county subterraneanly is augmented by downward leakage of local rainfall and sinking streams. These include Lost, Black and Fisher creeks and Munson Slough. Lost, Black and Fisher creeks drain pine flatwoods lying west of the Woodville Karst Plain. Munson Slough drains the Lake Munson basin, which lies on both the Tallahassee Hills and the Woodville Karst Plain. Beginning with an elevation of 10 ft at the Leon-Wakulla county line, water levels in the Floridan Aquifer decline to near zero at the coastline.

Potentiometric Surface of the Floridan Aquifer on the Woodville Karst Plain

Based on water-level data collected during the term of the project, three Floridan Aquifer potentiometric surface maps of the Woodville Karst Plain were prepared. Maps (Figures 22 through 24) are representative of conditions in January 1999, August 1999, and March 2000. Numbers of control points included on the maps ranged from 42 to 48. All wellhead elevations were leveled to NGVD. Water level values given on these maps are reliable to $\pm$ 0.1 ft, NGVD.

All three maps show basically the same potentiometric surface contour pattern. Contours are closest together immediately south of the Cody Scarp. Within about four miles of the scarp, the potentiometric surface begins to flatten. From the point where the flattening becomes apparent (just north of the Leon/Wakulla County line), water levels decline very gently toward the south. Over eastern Wakulla County they decline as little as a foot over distances of as much as 10 miles (0.0001). Wakulla Springs is situated more or less at the center of this flattening, although it imparts no visible (from these data) perturbation to the potentiometric surface. Rather, the potentiometric surface continues to slope away from the spring to the southwest. The Big Dismal—Turner Sink conduit system is imbedded in the zone of low hydraulic gradient. The extremely high Floridan Aquifer transmissivities associated with this feature undoubtedly facilitate potentiometric surface flattening. However, flatness is not limited to the axis of the conduit system, as it also extends to the north and to the northeast, in the direction of Woodville.

These data imply that an eight to 10-mile wide highly transmissive band of the Floridan Aquifer is situated in central Wakulla County. This zone of high conductivity locally perturbs the general north to south flow regime and funnels water to Wakulla Springs from the northwest, north and northeast. It includes the mapped conduit system, a paleo surface drainage channel connecting Munson Slough and McBride Slough, and presumes the existence of other, unmapped conduits north and northeast of Wakulla Springs. Using other lines of evidence, Werner (2000) postulates the existence of a second, significant conduit system due north of Wakulla Springs. The calibrated transmissivity distribution of Davis (1996) is consistent with this interpretation, as it shows a band of very high transmissivity (as high as 10M ft^2d) aligned north/south through the center of Wakulla County.

The potentiometric surface data also imply that Wakulla Springs incompletely captures ground water flow moving from north to south to the west of the spring. The prevailing wisdom is that the Big Dismal—Turner Sink conduit system is connected to Wakulla Springs. However, this hypothesis has yet to be proved by direct exploration. While there is, likely, some connection, the completeness with which the conduit system captures and conveys ground water flow to Wakulla Springs is unknown. These head data imply some significant quantity of bypass flow.

POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER,
SOUTHERN LEON AND WAKULLA COUNTIES, JANUARY 1999

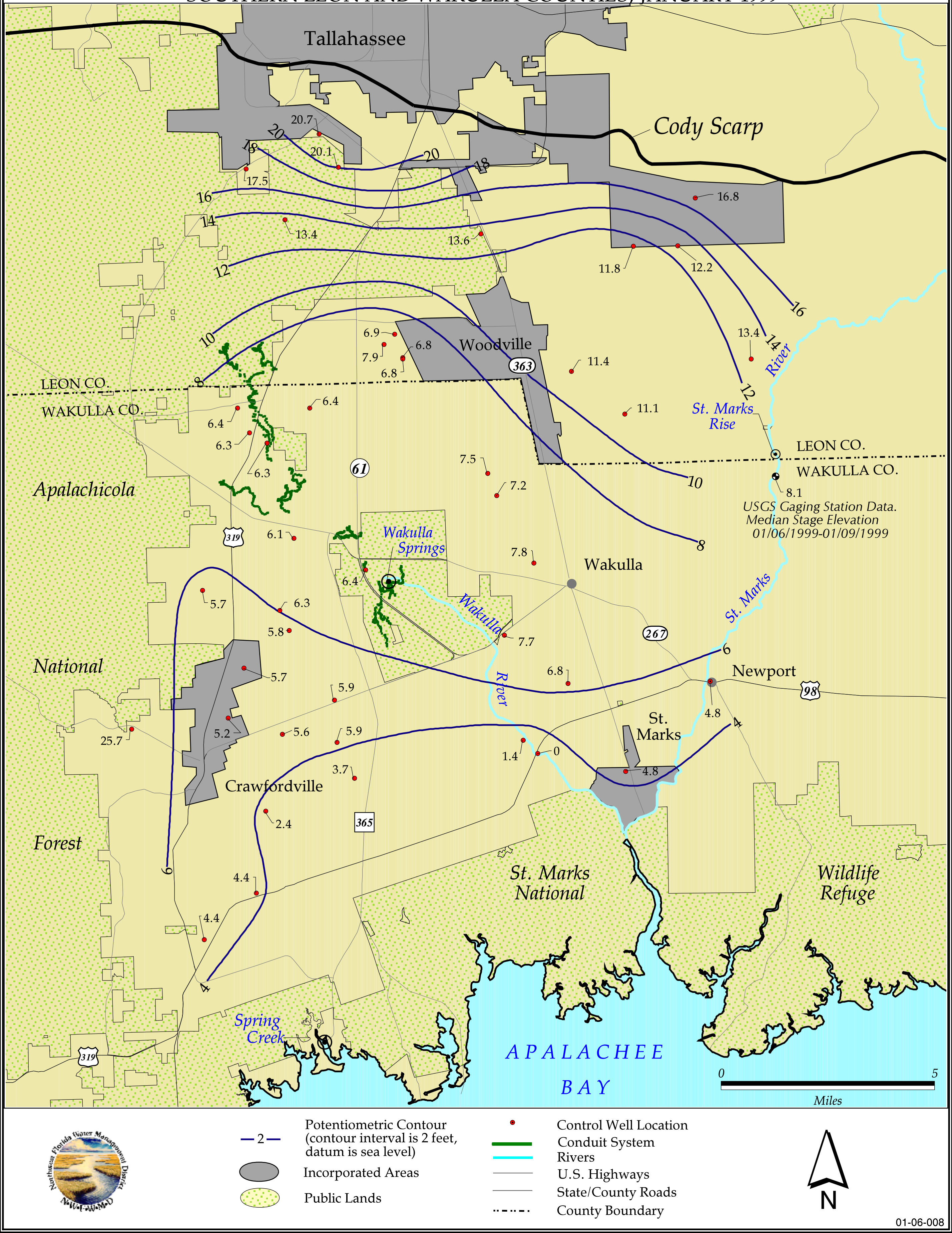


FIGURE 22

REVISED - JUNE '03

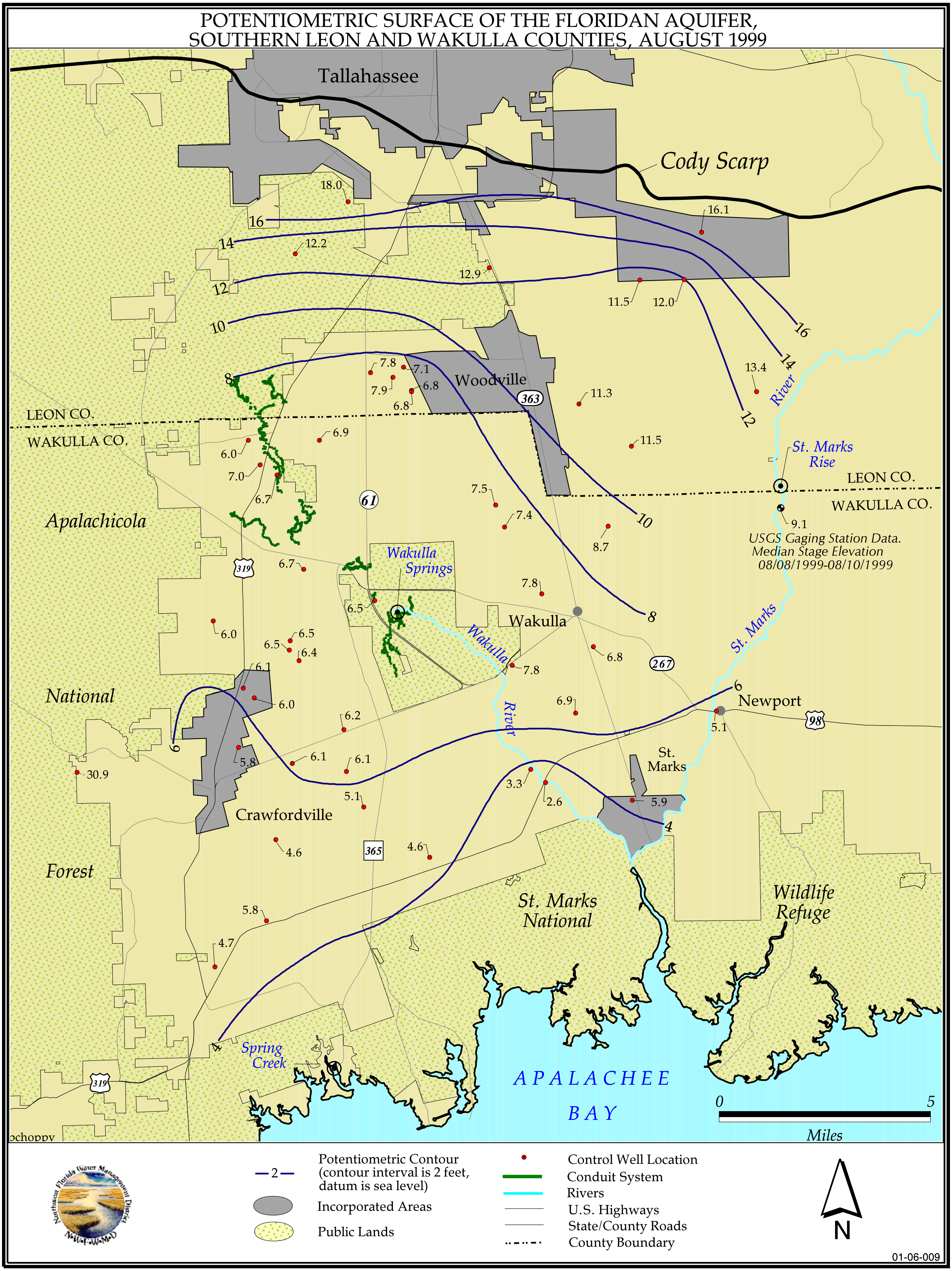

POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER,
SOUTHERN LEON AND WAKULLA COUNTIES, AUGUST 1999
Tallahassee
Cody Scarp
Woodville
Wakulla
Newport
St. Marks
Crawfordville
Apalachicola
National
Forest
St. Marks
National
Wildlife
Refuge
APALACHEE
BAY
Wakulla Springs
Wakulla River
St. Marks River
St. Marks Rise
Spring Creek
LEON CO.
WAKULLA CO.
USGS Gaging Station Data.
Median Stage Elevation
08/08/1999-08/10/1999
0
5
Miles
Potentiometric Contour
(contour interval is 2 feet,
datum is sea level)
Incorporated Areas
Public Lands
Control Well Location
Conduit System
Rivers
U.S. Highways
State/County Roads
County Boundary
N
01-06-009
REVISED - JUNE '03

FIGURE 23

POTENTIOMETRIC SURFACE OF THE FLORIDAN AQUIFER, SOUTHERN LEON AND WAKULLA COUNTIES, MARCH 2000

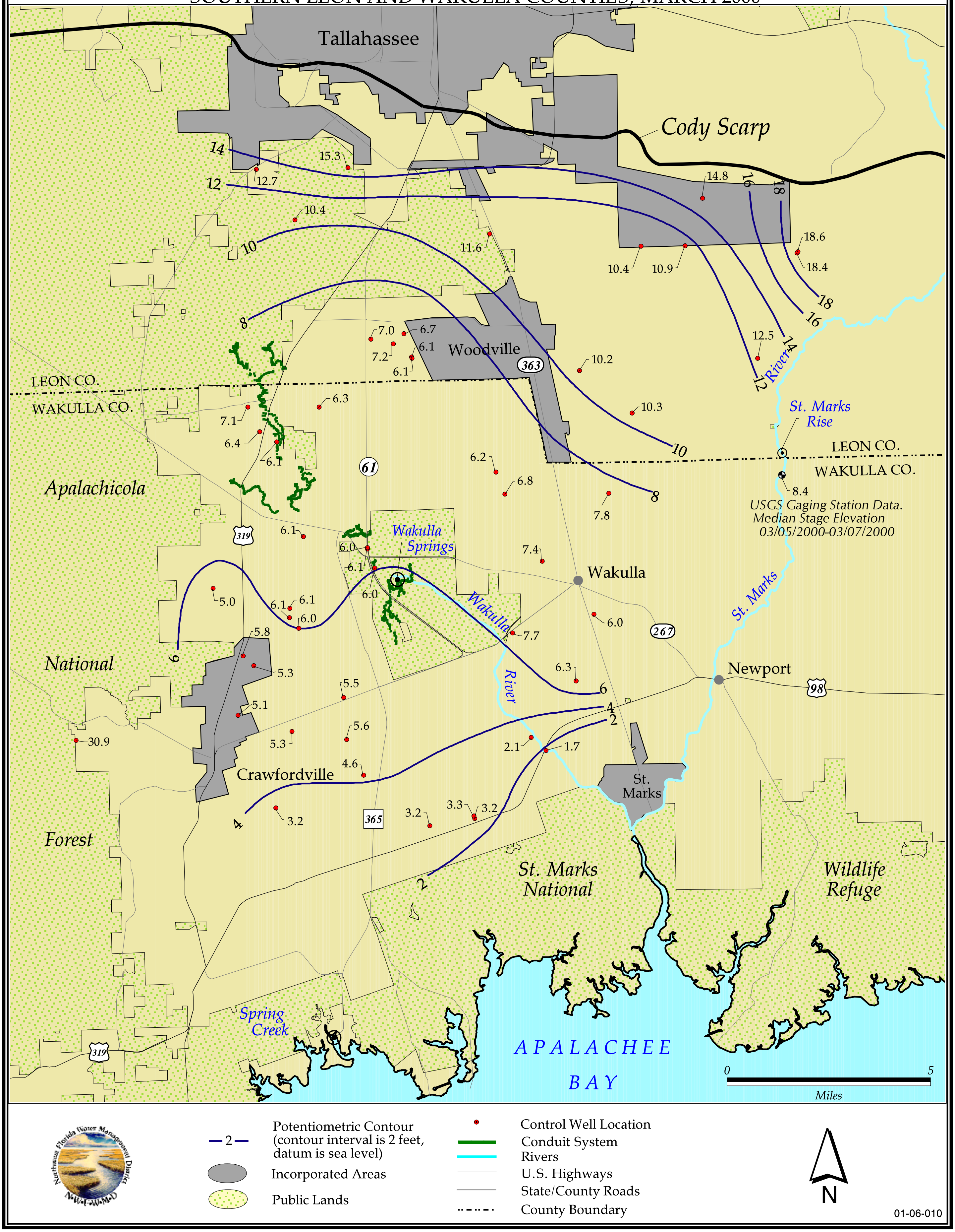


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FIGURE 24

Based on the potentiometric surface mapping conducted for this investigation, general flow directions on the karst plain are identified (Figure 25). Werner (2000) gives information on the position of a stagnation point within the Wakulla Springs conduit system. He notes that a separation between north-flowing and south-flowing waters is observable in the main conduit system and that it occurs at distances ranging between 2,100 ft and 7,500 ft south of the spring, depending on flow conditions.

Data collected on and near the City of Tallahassee southeast sprayfield (SESF) indicate a southwesterly flow direction into the zone of high conductivity. Such an interpretation is counterintuitive, given the proximity of the sprayfield to the St. Marks River. St. Marks Rise (located near the Leon/Wakulla county line and about half the distance between the SESF and Wakulla Springs) is a significant source of ground water outflow from the Floridan Aquifer. Presumably, the drain effect of the St. Marks Rise should perturb Floridan Aquifer flow directions in southeast Leon County to the southeast. This does not seem to be the case, although the reason for this is not clear. A southwesterly flow direction near the sprayfield, while based in this instance on a limited number of wells is substantiated by previous potentiometric surface mapping at the sprayfield itself (Pruitt et al., 1988 and Berndt, 1990). Additional water level data along the lower St. Marks River would be of value in refining localized flow directions.

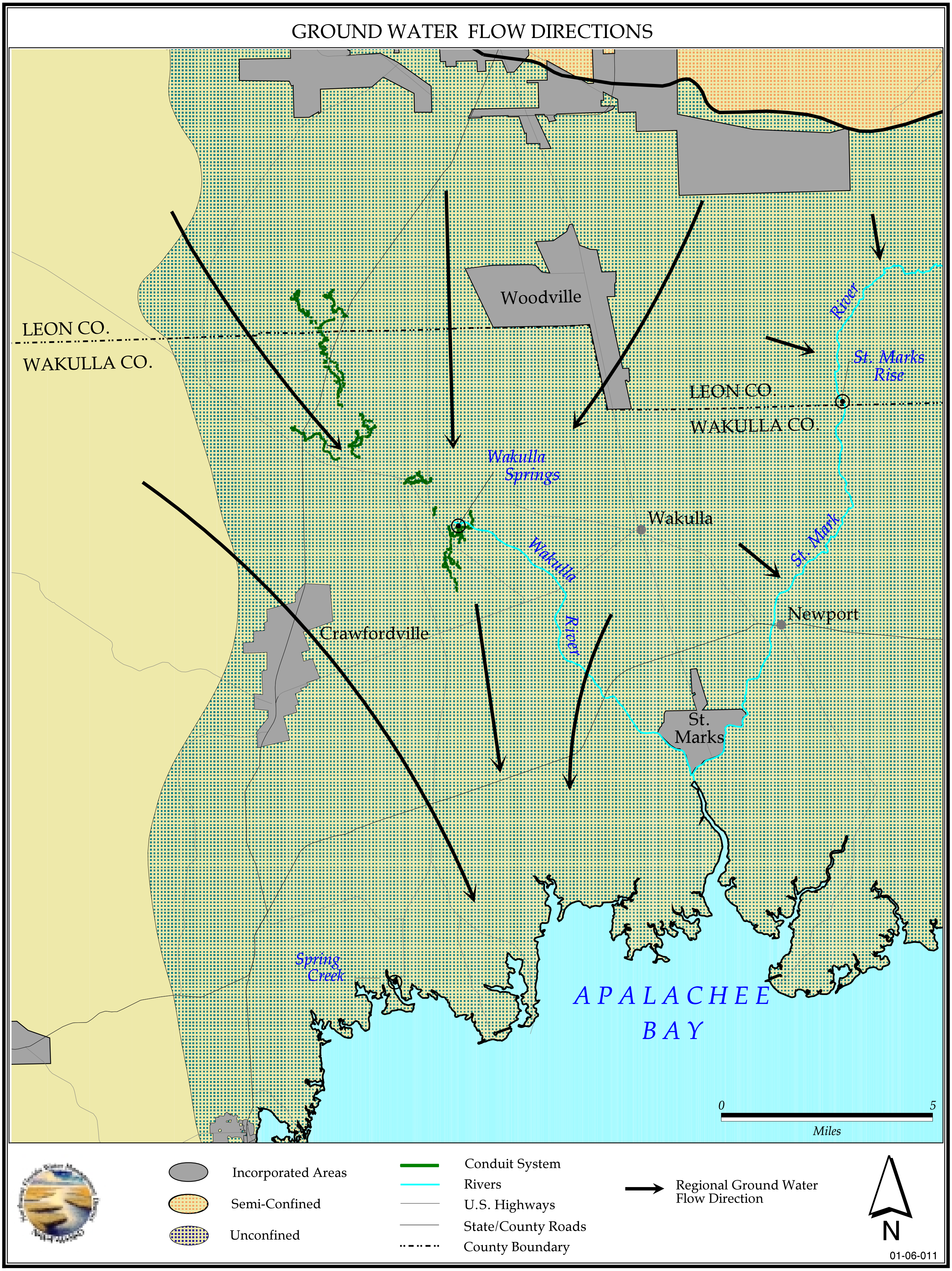
GROUND WATER FLOW DIRECTIONS
LEON CO.
WAKULLA CO.
Woodville
River
St. Marks
Rise
LEON CO.
WAKULLA CO.
Wakulla
Springs
Wakulla
Wakulla
St. Mark
Newport
Crawfordville
River
St.
Marks
Spring
Creek
APALACHEE
BAY
0
5
Miles
Incorporated Areas
Semi-Confined
Unconfined
Conduit System
Rivers
U.S. Highways
State/County Roads
County Boundary
Regional Ground Water
Flow Direction
N
01-06-011

FIGURE 25

Surface Waters

Wakulla Springs and River

Wakulla Springs is a major Floridan Aquifer ground water discharge point within the St. Marks and Wakulla rivers basin. The output from the spring is sufficient to form the Wakulla River, which flows southeast about nine miles and discharges into the Gulf of Mexico. Based on USGS data, the period of record median flow from Wakulla Springs is 340 cfs (n=297, mean=397, stdev=266, Figure 26). The lowest observed flow was 25.2 cfs, on June 18, 1931. The largest observed flow, 1,910 cfs, occurred on April 11, 1973. Beneath the spring pool of Wakulla Springs lies an extensive network of large-diameter conduits. The main trunk of the conduit system lies more or less horizontally at depths ranging between 230 ft and 280 ft below sea level. This conduit system runs northeast and south away from the spring, consists of multiple branches, and has been extensively traversed and mapped by divers.

Another large conduit system has been mapped by divers starting in the Leon Sinks Geologic Area. This system connects Big Dismal Sink on the north end, with Cheryl Sink, River Sink Group and Turner Sink on the south end (Werner, 2000). It also receives surface water inflow from Fisher Creek. River Sink Group is a collection of three tunnel collapse features that have a significant perennial flow. In each case, water emerges from the ground on the upstream end of the sink, flows along the length of the sink and disappears into the ground on the downstream end. Middle River Sink, which has been measured seven times, has a median discharge of 160 cfs, or about 47 percent of the median discharge of Wakulla Springs. Cave divers have explored several smaller conduit systems on the karst plain including Chip's Hole, Indian Springs, Sally Ward Spring, McBride's Slough (Werner, 2000). Though the Big Dismal-Turner Sink and Wakulla Springs systems have not been shown to connect through direct exploration, it is reasonable to presume some degree of interconnection.

In the last 25 years, Wakulla Springs has experienced a significant increase in NO_3 concentrations (Figure 27). These data were gleaned from USGS and EPA STORET databases and represent a compilation of analyses for (1) NO_3, total (as N); (2) NO_3, dissolved (as N); (3) NO_2+NO_3, total (as N); (4) and NO_2+NO_3, dissolved (as N). These analyses were considered to yield relatively equivalent results for the purpose of illustrating the increase in NO_3 experienced at Wakulla Springs. Historically, there has been no measurable NO_2 in the ground waters of the study area and, presumably, all detectable NO_3 in ground water is dissolved.

Based on data from 1971 through 1977, the median NO_3 concentration was 0.26 mg-N/L (n=22). Based on data from 1989 through 2000, the median concentration had increased to 0.89 mg-N/L (n=26). Concentrations appear to have peaked in the early 1990s and have declined slightly since. Over similar periods, the NO_3 concentration in Middle River Sink increased from a median of 0.06 mg-N/L (n=14) to 0.19 mg-N/L (n=3). The postulated increases are considered accurate, as the data from the 1970s are reported as NO_3-N, total and the data from the 1980s and 1990s are reported as NO_3-N, dissolved. Based on a median flow of 340 cfs (3.04×10^{11} L/yr), and a median NO_3 concentration of 0.89 mg-N/L, the NO_3 load discharged from Wakulla Springs is 270,000 kg-N/yr.

The difference in the NO_3 concentration histories of Wakulla Springs and Middle River Sink is of note. Both show increases with time. River Sink had what are generally considered background concentrations during the 1970s. Currently, River Sink nitrate concentrations are similar to what Wakulla Springs experienced 25 years previously. River Sink lies northwest of Wakulla Springs and, presumably, passes water to the spring from the western edge of the area contributing water to the spring. This water has a much lower nitrate concentration than

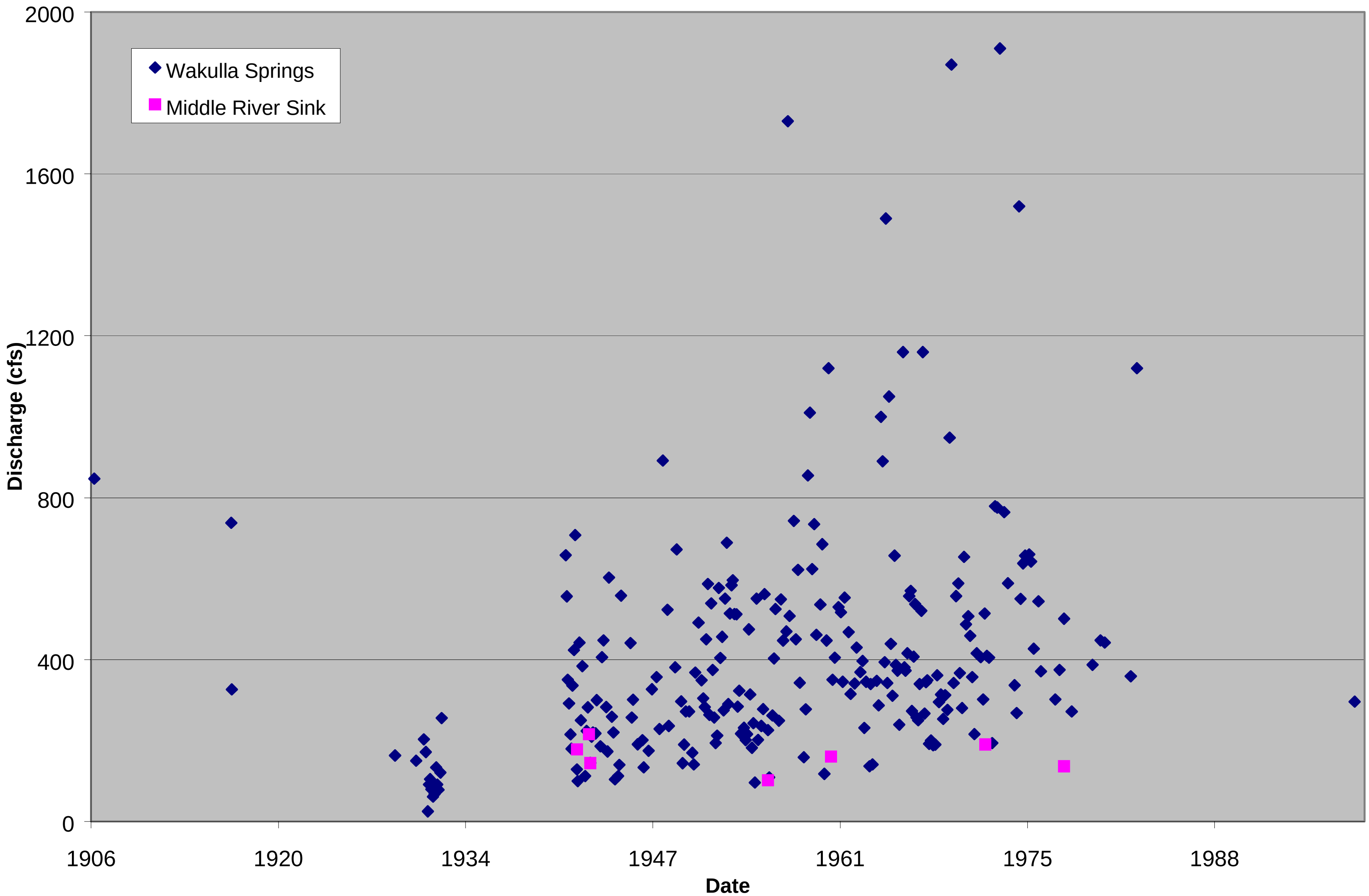

Figure 26. Wakulla Springs and Middle River Sink Spring Historic Discharge (data from USGS).

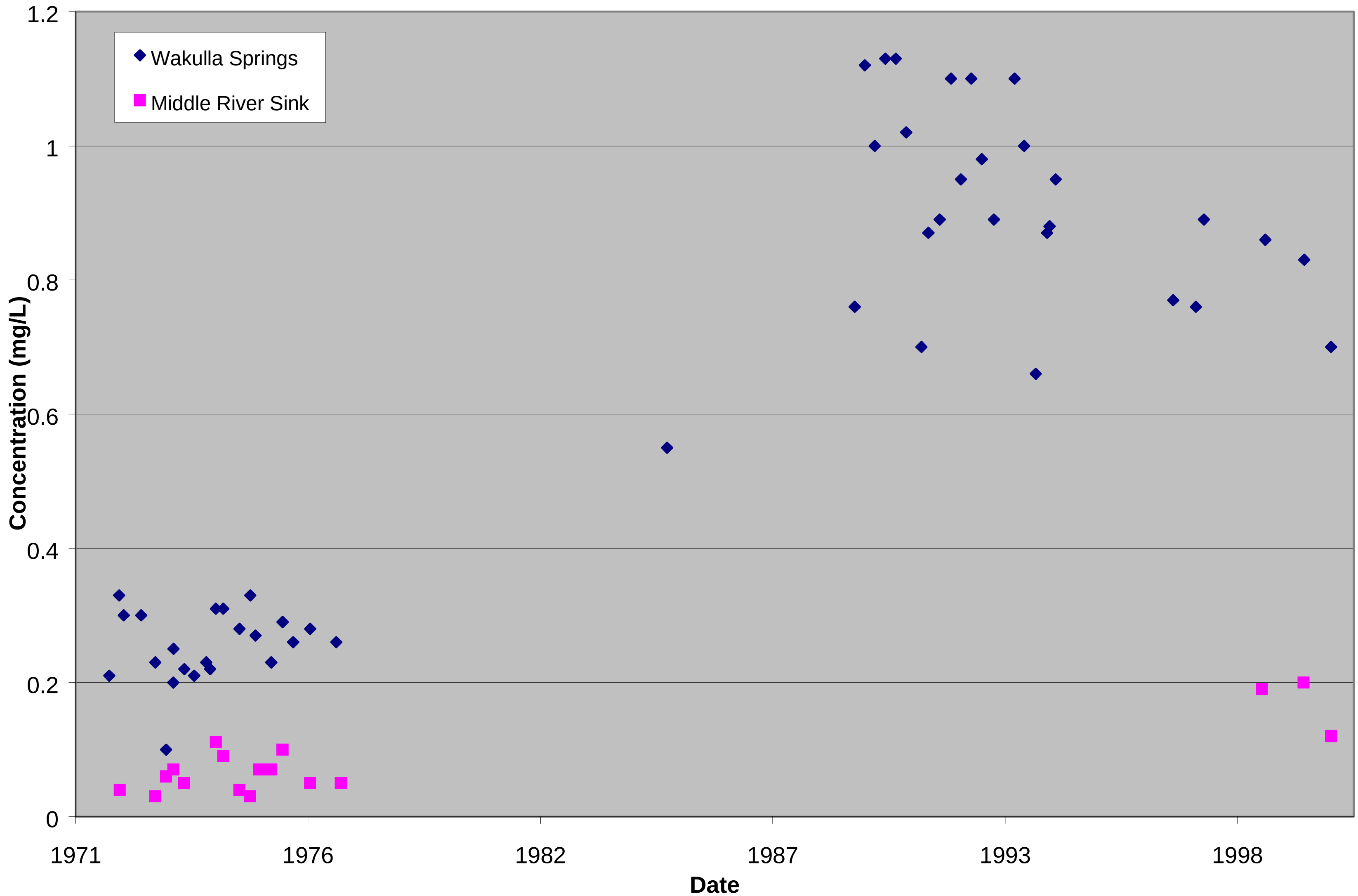

Figure 27. Compilation of NO_3-N and NO_2+NO_3-N Concentration Data for Wakulla Springs and Middle River Sink Spring.

Wakulla Springs itself. If it is true that River Sink discharges to Wakulla Springs, and if the three recent River Sink nitrate concentration measurements are representative of current conditions, the source of elevated nitrates in Wakulla Springs must lie north and east of the Big Dismal—Turner Sink conduit system. If the flow through River Sink bypasses Wakulla Springs, the same conclusion is true.

NO_3 concentrations in waters currently discharging from the spring are promoting the growth of undesirable vegetation. *Hydrilla* and filamentous algae are particularly problematic. According to the FDEP EcoSummary (FDEP, 2000) for Wakulla Springs, "nitrate-nitrite concentrations (ranging from 0.77-0.84 mg/L) at the sampling site were consistently higher than the values found in 90% of Florida streams." Based on four determinations made during 2000, "the stream condition index (SCI) ranked the site 'very poor' once, 'poor' twice, and at the lowest end of 'good' category once" during 2000. The report further observes that the periphyton community is dominated by taxa that are tolerant of nutrient enriched conditions. Further, they conclude that "the poor macroinvertebrate health was related to the habitat and dissolved oxygen problems caused by *Hydrilla*, which in turn was due to high nitrate levels" (FDEP, 2000).

Katz (2001) performed sampling and isotopic analysis of ground and surface waters from the Woodville Karst Plain, including Wakulla Springs, Fisher Creek, Lost Creek and Munson Slough. Water from most sampled wells and from Wakulla Springs had δ^{15} N-NO_3 values ranging between 6.8 and 8.9 per mil, indicating that their NO_3 originates from a blend of organic and inorganic sources. Using $^3H/^3He$ age-dating techniques, Katz (2001) determined that the average residence time of ground water discharging from Wakulla Springs was 38.7 +/-1.07 years. He also concluded that surface water inflows from sinking streams contributed little NO_3-N to ground waters on the karst plain.

St. Marks River

The St. Marks River is a second major source of Floridan Aquifer discharge on the Woodville Karst Plain. The St. Marks River originates in the Tallahassee Hills physiographic subdivision. The river headwaters were originally what are now the Lakes Miccosukee and Lafayette drainage basins. Erosion modified the headwater basins to the point where drainage became predominantly internal and the basins closed. Between these basins and the St. Marks River Rise, overland surface flows are intermittent, depending on the amounts of rainfall and overland runoff.

In periods of low flow, the St. Marks Rise is the head of the perennial St. Marks River (Rosenau et al., 1977). Based on 42 years of record, the USGS St. Marks River gage (0.65 miles south of the rise) has the following statistics; Q_{10}—1090 cfs; Q_{50}—635 cfs; Q_{90}—408 cfs. Median stage at this station is 8.9 ft, NGVD (Marvin Franklin, personal communication, 2001).

Interaction between Wakulla Springs and Up-gradient Surface Water Features

<u>Ames Sink</u>

Ames Sink lies about 5.5 miles due north of Wakulla Springs and is within the capture zone of the spring. Accordingly, waters that enter Ames Sink eventually discharge from the spring. Ames Sink is on the downstream end of Munson Slough, which conveys surface waters from the lake to the sink. In turn, Lake Munson receives water from the urban drainage system that drains much of the southern part of the City of Tallahassee.

Conductivity data collected at Ames Sink and flow data collected on Munson Slough above Lake Munson are given in Figure 16. Collection of flow data at Ames Sink was beyond the scope of this investigation. Conductivity and flow data are given for the period 03/99 to 11/00, which includes the very dry summer of 2000. For much of this period, inflows at the sink were minimal to nonexistent. However, the water quality meter used to collect these data was continually submerged. Measured conductivity values ranged from 60 and 250 µmhos/cm. Typically, conductivities dipped after rainfall events and rose during dry periods. It is possible that the elevated conductivities observed during dry periods reflect re-circulation of Floridan Aquifer waters into the sink in the absence of surface water inflows. Otherwise, conductivity decreases during rainy periods seem to reflect the inflow of stormwater derived from low conductivity rainfall.

1999 Surface Water Conductivity Data

During 1999, specific conductivities of water from Wakulla Springs ranged between 275 and 340 µmhos/cm (Figure 28). These data are typical of Floridan Aquifer conductivities found up-gradient of Wakulla Springs. 238 conductance samples collected in Leon County between 1986 and 1999 had a median conductance of 247 µmhos/cm (mean=241, stdev=62). Elevated conductivity is primarily due to dissolved carbonate from the limestone aquifer. As a function of time, the 1999 Wakulla Springs conductivity data exhibit relatively little variability.

1999 conductivities in the three other surface water features were lower (Figure 28). Fisher Creek is a black-water sinking stream whose watershed lies within the Apalachicola National Forest. During 1999, it had the lowest range of conductivity values, between 30 and 75 µmhos/cm and exhibited little variability during the year. Fisher Creek conductivities were lowest during dry periods and (curiously) rose following rain events. Lowest observed values for Lost Creek (another black-water sinking stream draining the national forest) were similar to Fisher Creek, in the vicinity of 30 µmhos/cm. However, during dry periods, conductivities in Lost Creek rose well above those of Fisher Creek, to about 170 µmhos/cm. This increase is likely attributable to the discharge of Floridan Aquifer water into Lost Creek during low-flow periods. Conductivities in Ames Sink were typically higher than in either Fisher or Lost creeks.

2000 Surface Water Conductivity Data

During much of 2000, conductivities in Wakulla Springs were similar (>300 µmhos/cm) to the previous year (Figure 29). However, September rains were sufficient to perturb the prevailing pattern. During September a total of 19.29 inches of rain fell at the River Sink Station. Of this, 8.31 inches fell during the first week, 1.09 inches fell on September 17 and an additional 9.53 inches were associated with the passage of Tropical Storm Helene on September 22. During September, conductivities in Wakulla Springs declined rather sharply from 310 µmhos/cm to 250 µmhos/cm, or by about 20 percent. Within about three weeks of Tropical Storm Helene's passage through the area, conductivities in the spring rebounded to 320 µmhos/cm.

Middle River Sink had a 2000 conductivity history similar to that of Wakulla Springs. During much of the year values varied through a small range (between 220 to 240 µmhos/cm). These high values reflect the high proportion of Middle River Sink water originating in the Floridan Aquifer. Rains occurring around the first of September were sufficient to reduce the conductivity by about 20 percent. A precipitous decline followed Tropical Storm Helene (Figure 30). During a six-day period, conductivities fell from 220 µmhos/cm to 60 µmhos/cm. For a short period of time, flow through Middle River Sink consisted entirely of surface water, much of it undoubtedly originating from Fisher Creek. The high surface water inflow following rains associated with

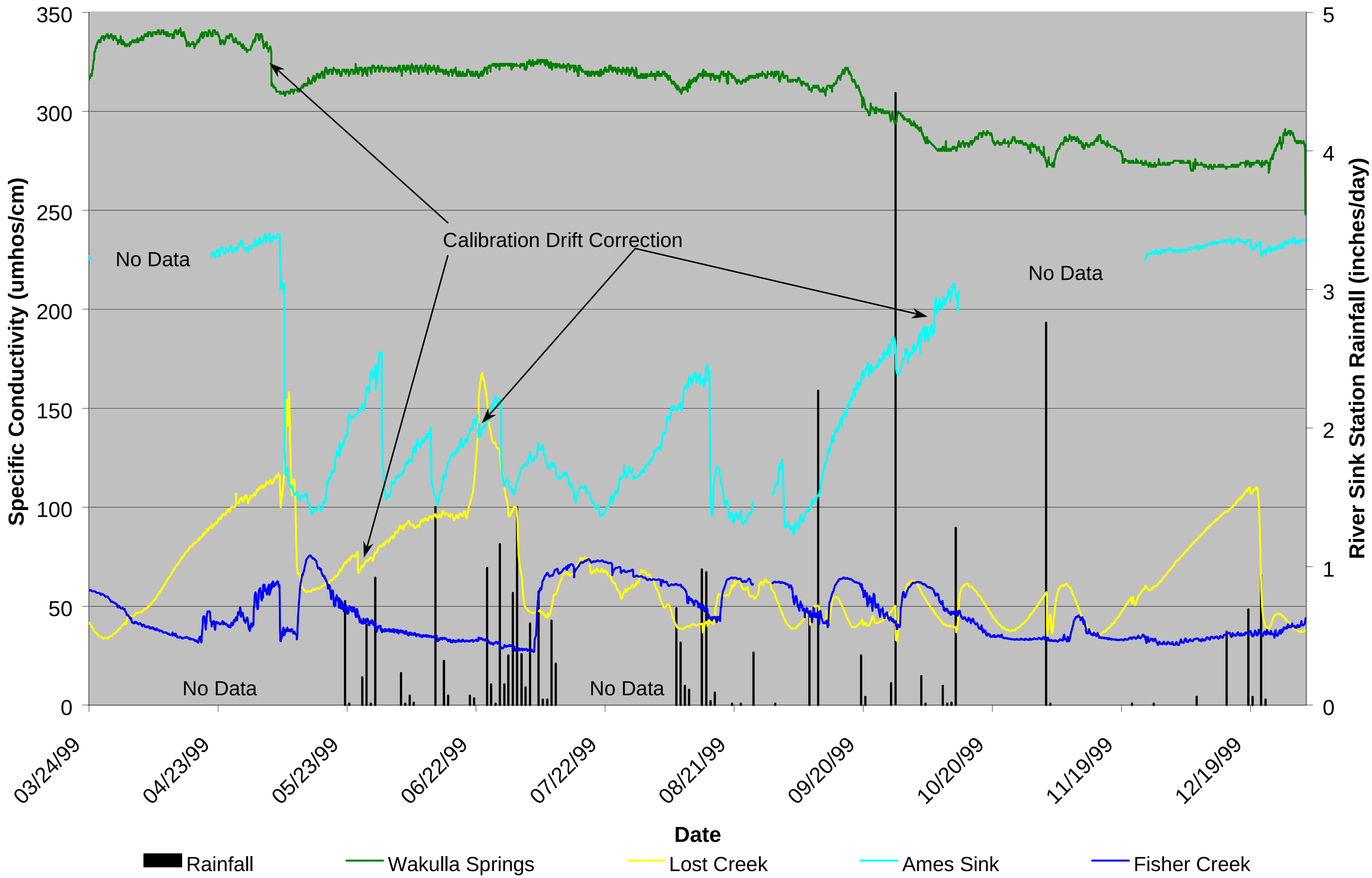

Figure 28. 1999 Specific Conductivity and Rainfall versus Time for Fisher Creek, Ames Sink, Lost Creek and Wakulla Springs.

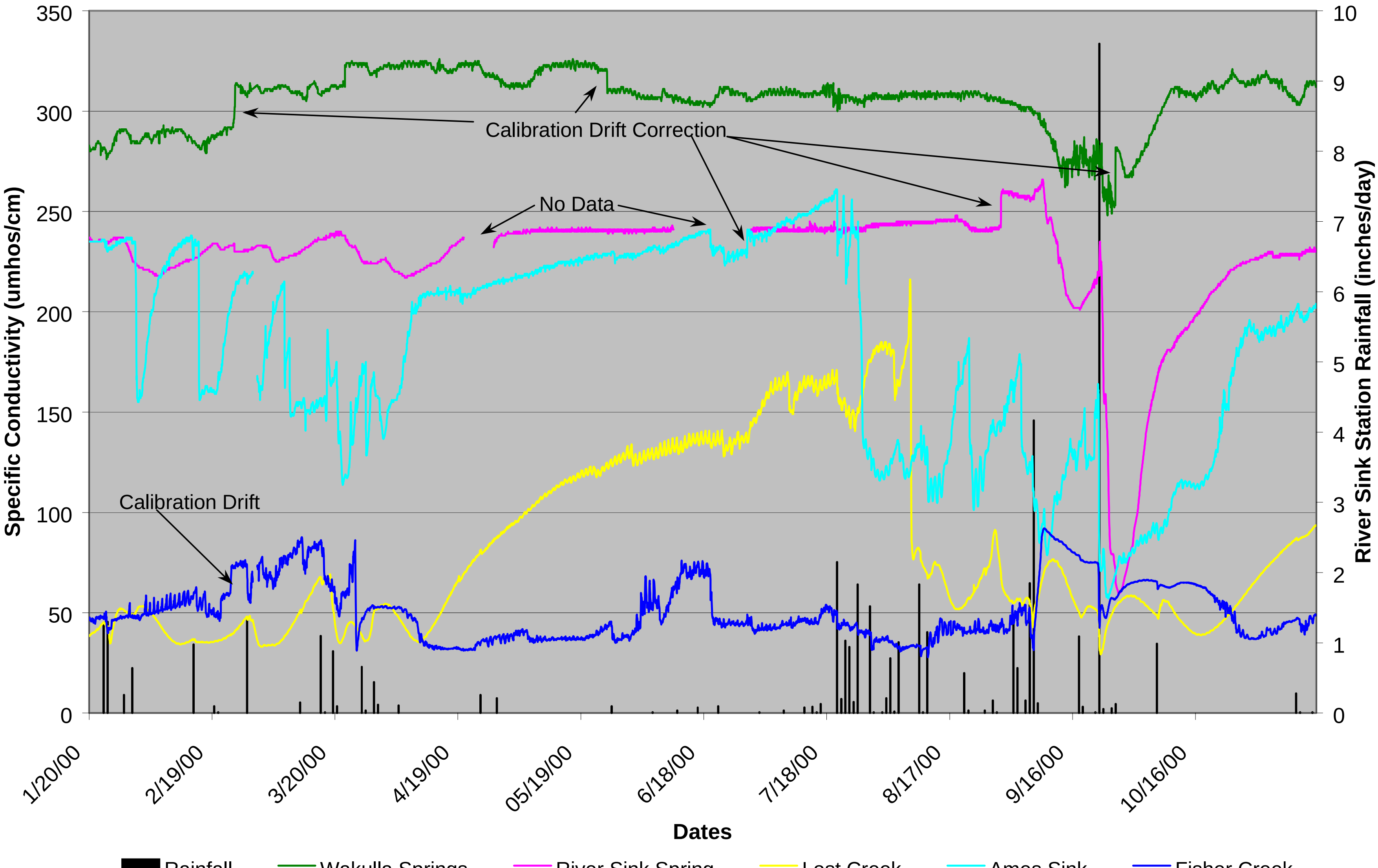

Figure 29. 2000 Specific Conductivity and Rainfall versus Time for Fisher Creek, Ames Sink, Lost Creek, Middle River Sink and Wakulla Springs.

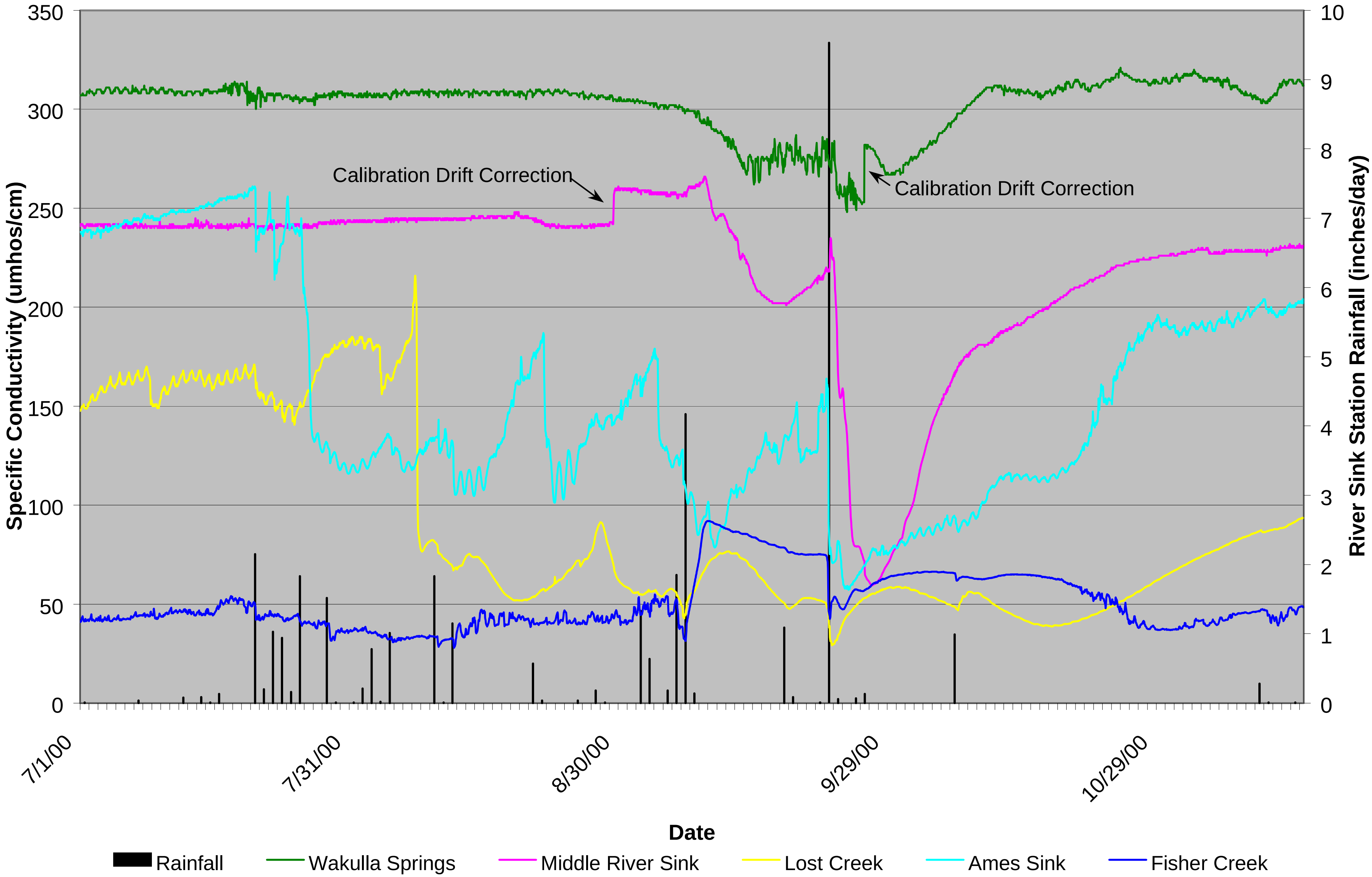

Figure 30. Specific Conductivity and Rainfall versus Time Prior to and Following Tropical Storm Helene, July-November, 2000.

Tropical Storm Helene completely overwhelmed the ground water component of Middle River Sink Spring. During this period, waters in Ames Sink, Fisher Creek, Middle River Sink and Lost Creek all had similar conductivities, on the order of 60 µmhos/cm. By late October, Middle River Sink returned to its typical, Floridan Aquifer dominated flow regime. Wakulla Springs recovered to its typical conductivities over the same period.

In Ames sink, Fisher Creek and Lost Creek, conditions during 2000 were similar to 1999. During the prolonged dry period that began around the first of April and ended around mid-July, conductivities in Lost Creek and Ames sink rose well above typical wet period values. For the year Fisher Creek had a fairly narrow range of values, between 30 and 90 µmhos/cm.

Surface Water Temperature Data

Figures 31 and 32 give temperature versus time data for Fisher Creek, Ames Sink, Lost Creek, Middle River Sink, Spring Creek and Wakulla Springs for 1999 and 2000. The Wakulla Springs temperature data given in these figures were collected with the S4 meter inside A-tunnel. Mean-daily air temperature data from the Tallahassee Airport are also given. For both years, the temperature profile of Wakulla Springs is virtually invariant. During the entire period the only perturbation followed Tropical Storm Helene and that disturbance was slight. Middle River Sink (for which only 2000 data was collected) is only slightly less invariant. The two most significant disturbances occurred in mid-January 2000, during a period of very cold air temperatures, and in September 2000, during periods of high rainfall. In contrast, temperature data for the surface water features closely follow the average daily air temperature, being cooler than Wakulla Springs in winter and warmer in summer.

The invariant nature of the temperature data from Wakulla Springs partially substantiates the observation that the spring is deeply imbedded in the regional flow system. Likely, much of the seasonal temperature signal is removed from recharge water by the time it reaches the Floridan Aquifer. There are observations of seasonal temperature fluctuations in individual Floridan Aquifer wells on the order of 2 °C. Wakulla Springs undoubtedly integrates waters over a wide range of temporal scales. In the process, any remaining seasonal (or other) temperature signals are almost completely removed.

Wakulla Springs Velocity and Conductivity Data

Specific conductivity and velocity data from Wakulla Springs are given in Figures 33 and 34 for 1999 and 2000. Specific conductivity data were collected from the data logger installed beneath the boat dock (Station #4, above). These data show a generally inverse relationship between conductivity and velocity. Inflows of relatively low conductivity rainfall via sinking streams will undoubtedly mix with and dilute Floridan Aquifer waters discharging from the spring, reducing conductivity in the process.

Hurricane Floyd and Tropical Storm Helene passed through the area in September 1999, contributing to a monthly total rainfall of 13.31 inches at the Tallahassee Airport and 19.29 inches at the River Sink Station. In August, A-tunnel velocities were on the order of 8 cm/s and specific conductivities were on the order of 325 µmhos/cm. In mid-September, tunnel velocities increased to ~17 cm/s. Concurrently, the conductivity declined to ~300 µmhos/cm. The observed increase in velocity from 8 cm/s to 17 cm/s should represent roughly a doubling of the spring discharge. Assuming that 325 µmhos/cm represents 100 percent Floridan Aquifer water and assuming a surface water conductivity of about 40 µmhos/cm, a blending ratio of 93 percent Floridan Aquifer water to 7 percent surface water is required to reduce the conductivity from 325 to 300 µmhos/cm. This mixing ratio is independent of spring flow.

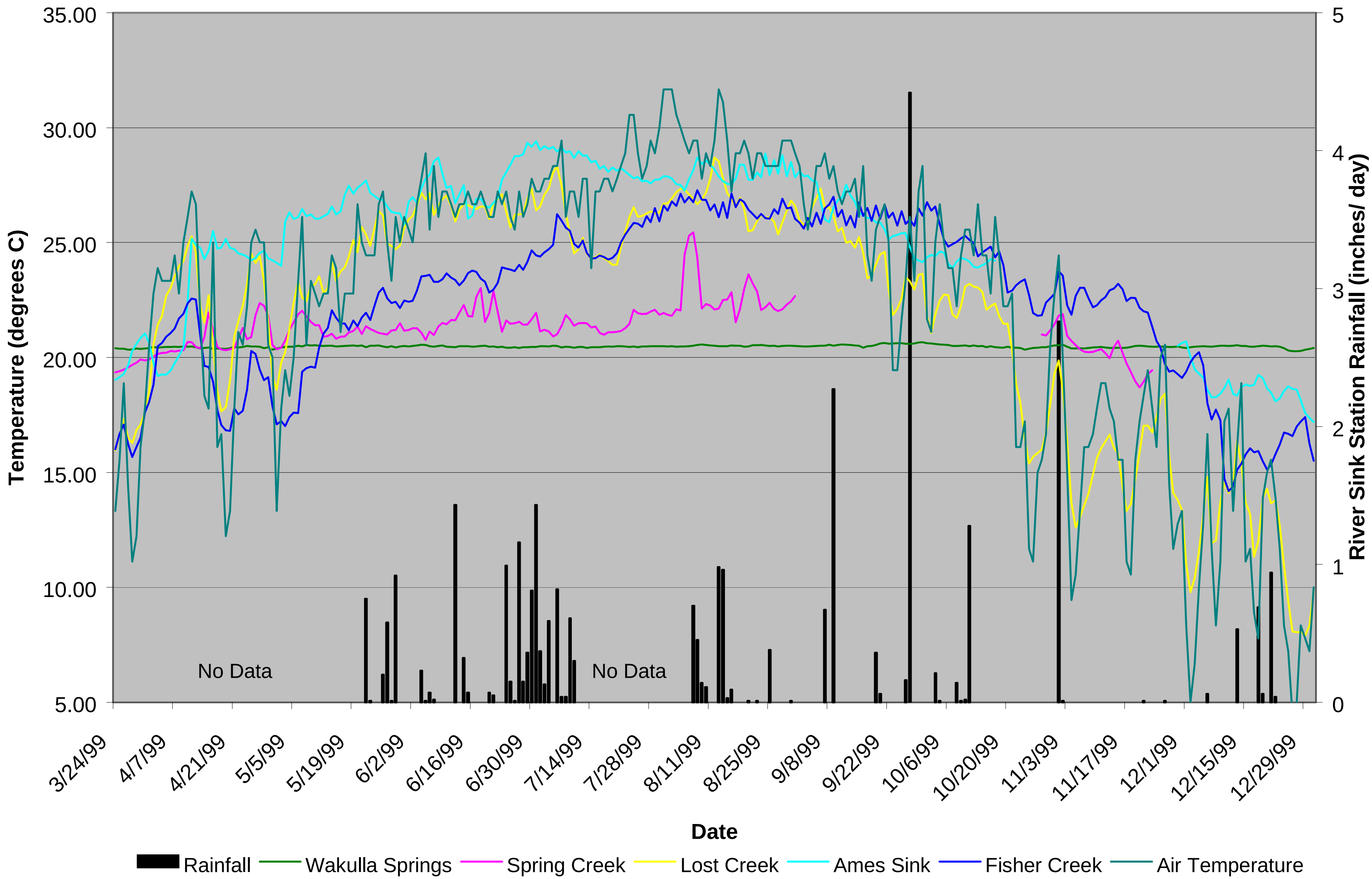

Figure 31. 1999 Temperature and Rainfall versus Time for Fisher Creek, Ames Sink, Lost Creek and Wakulla Springs.

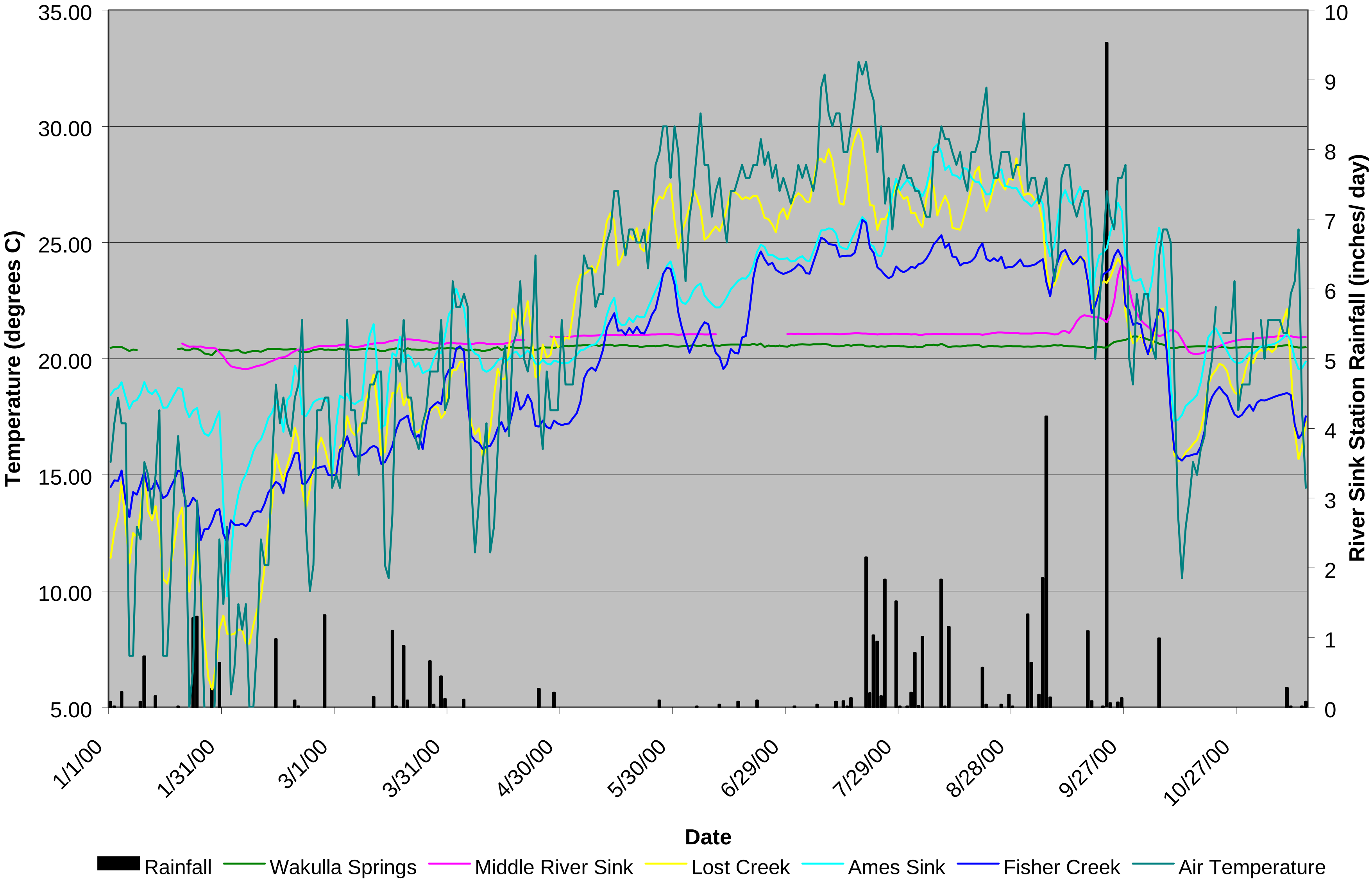

Figure 32. 2000 Temperature and Rainfall versus Time for Fisher Creek, Ames Sink, Lost Creek, Middle River Sink and Wakulla Springs.

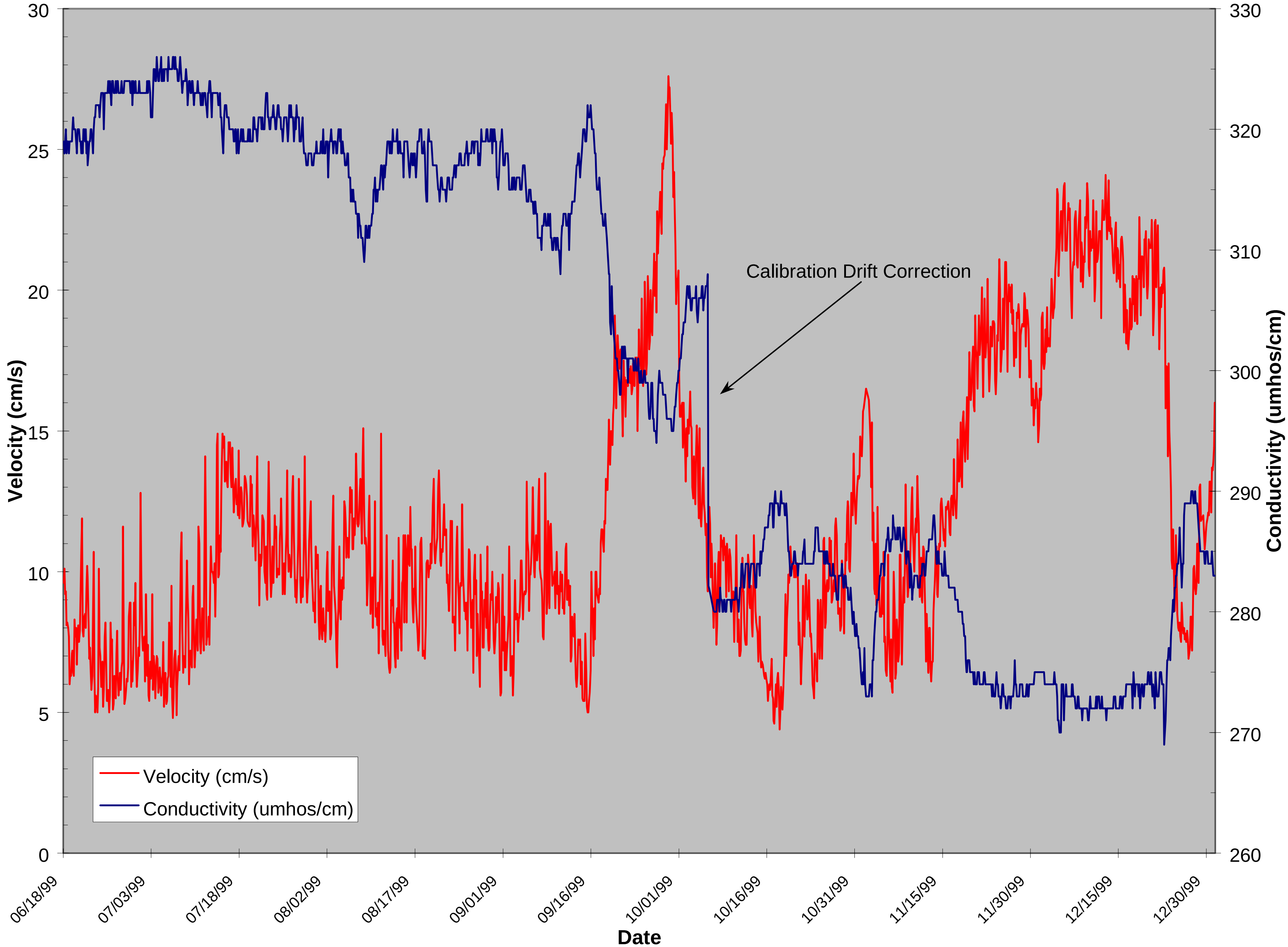

Figure 33. 1999 Wakulla Springs Velocity versus Specific Conductivity.

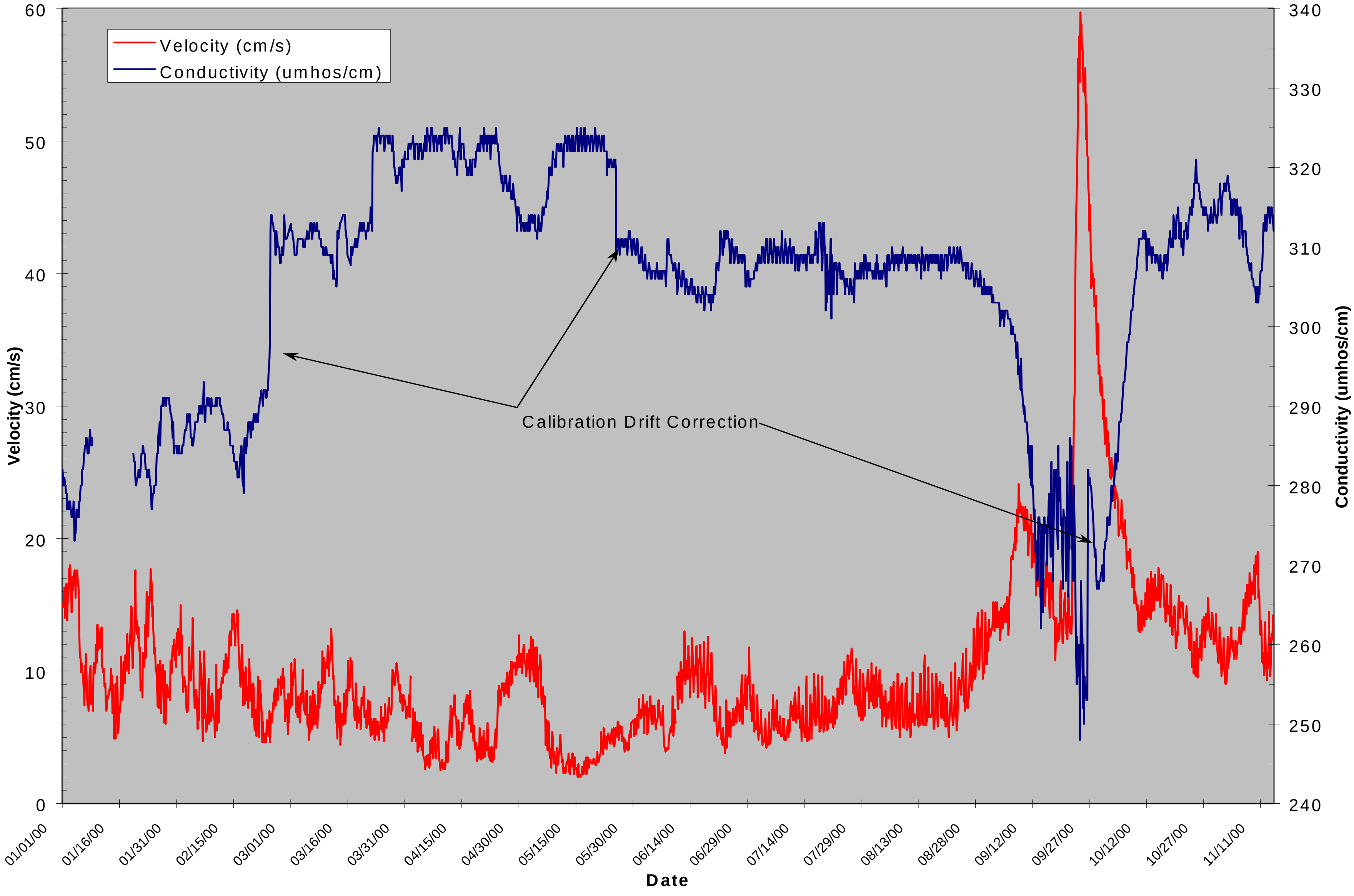

Figure 34. 2000 Wakulla Springs Velocity versus Specific Conductivity.

The addition of surface water inflow from sinking streams is not sufficient to double discharge from the spring. Rather, the increase in flow is mostly accounted for by additional discharge from the Floridan Aquifer. The increase in Floridan Aquifer discharge through the spring results from a slight increase in Floridan Aquifer water levels attributable to short-term, relatively intense rainfall events. Given the extremely high hydraulic conductivity of the Floridan Aquifer, it is not surprising that small increases in hydraulic head result in a significant increase in discharge.