![USGS science for a changing world]

Prepared in cooperation with the City of Tallahassee

Nitrate-N Movement in Groundwater from the Land Application of Treated Municipal Wastewater and Other Sources in the Wakulla Springs Springshed, Leon and Wakulla Counties, Florida, 1966-2018

Scientific Investigations Report 2010-5099

U.S. Department of the Interior
U.S. Geological Survey

Nitrate-N Movement in Groundwater from the Land Application of Treated Municipal Wastewater and Other Sources in the Wakulla Springs Springshed, Leon and Wakulla Counties, Florida, 1966-2018

By J. Hal Davis, Brian G. Katz, and Dale W. Griffin

Prepared in cooperation with the City of Tallahassee

Scientific Investigations Report 2010-5099

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010
Revised: 2011

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

Suggested citation:
Davis, J. H., Katz, B.G., and Griffin, D.W., 2010, Nitrate-N Movement in Groundwater from the Land Application of Treated Municipal Wastewater and Other Sources in the Wakulla Springs Springshed, Leon and Wakulla Counties, Florida, 1966-2018: U.S. Geological Survey Scientific Investigations Report 2010-5099, 90 p.

9781411328570

Contents

Figures

Tables

Conversion Factors, Datum, and Abbreviations

Multiply	By	To Obtain
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)		meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per second (ft^3/s)	0.2832	cubic meters per day
gallons per day	0.003785	cubic meter per day
million gallons per day (Mgal/d)	0.4381	cubic meter per day
acre	0.4047	hectare

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations and Acronyms

bls	below land surface
kg/yr	kilograms per year
kg N/yr	kilograms of nitrogen per year nitrate-N nitrate-nitrogen
µS/cm	microsiemens per centimeter
Mgal	million gallons
Mgal/yr	million gallons per year
mg/L	milligrams per liter
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
MT3D	Modular Three-Dimensional Multi-Species Transport Model
OSDS	onsite sewage disposal system
RASA	Regional Aquifer-System Analysis
SEF	Southeast Farm
SWF	Southwest Farm
the City	the City of Tallahassee
TKN	total Kjeldahl nitrogen
USGS	U.S. Geological Survey
UFA	Upper Floridan aquifer

Nitrate-N Movement in Groundwater from the Land Application of Treated Municipal Wastewater and Other Sources in the Wakulla Springs Springshed, Leon and Wakulla Counties, Florida, 1966-2018

by J. Hal Davis, Brian G. Katz, and Dale W. Griffin

Abstract

The City of Tallahassee began a pilot study in 1966 at the Southwest Farm sprayfield to determine whether disposal of treated municipal wastewater using center pivot irrigation techniques to uptake nitrate-nitrogen (nitrate-N) is feasible. Based on the early success of this project, a new, larger Southeast Farm sprayfield was opened in November 1980. However, a recent 2002 study indicated that nitrate-N from these operations may be moving through the Upper Floridan aquifer to Wakulla Springs, thus causing nitrate-N concentrations to increase in the spring water. The increase in nitrate-N combined with the generally clear spring water and abundant sunshine may be encouraging invasive plant species growth. Determining the link between the nitrate-N application at the sprayfields and increased nitrate-N levels is complicated because there are other sources of nitrate-N in the Wakulla Springs springshed, including atmospheric deposition, onsite sewage disposal systems, disposal of biosolids by land spreading, creeks discharging into sinks, domestic fertilizer application, and livestock wastes.

Groundwater flow and fate and transport modeling were conducted to simulate the effect of all of the nitrate-N sources on Wakulla Springs from January 1, 1966, through December 31, 2018. The total simulated nitrate-N load to Wakulla Springs in 1967 was a relatively modest 72,000 kilograms per year (kg/yr). The major sources of the nitrate-N load in 1967 were determined to be:

1. Inflow to the study area across the lateral model boundaries at 31,000 kg/yr (43 percent),
2. Biosolids disposal by land spreading at 14,000 kg/yr (21 percent),
3. Creeks discharging into sinks at 7,800 kg/yr (11 percent), and
4. The Southwest Farm sprayfield at 4,500 kg/yr (6 percent).

The total simulated nitrate-N load to Wakulla Springs in 1987 had increased dramatically to 306,000 kg/yr. The major sources of nitrate-N load in 1987 were determined to be:

1. The Southeast Farm sprayfield at 186,000 kg/yr (61 percent),
2. Biosolids at 37,000 kg/yr (12 percent), and
3. Inflow to the study area across the lateral model boundaries at 36,000 at kg/yr (12 percent). All of the other sources were 8 percent or less.

The Wakulla Springs discharge can change rapidly, even during periods of little or no rainfall. This rapid change is probably the result of Wakulla Springs intermittently capturing groundwater that has been going to the Spring Creek Springs Group. This spring group is located in a marine estuary and is affected by tidally influenced saltwater intrusion. Two modeling scenarios were simulated and results are presented for 2007 and 2018 in an effort to bracket the range of possible current and future changes in the flow of Wakulla Springs. In scenario 1, it was assumed that Wakulla Springs was not capturing Spring Creek Springs Group flow. In scenario 2, it was assumed that Wakulla Springs was capturing Spring Creek Springs Group flow.

Under the assumptions of scenario 1, the total simulated nitrate-N load to Wakulla Springs in 2007 was 222,000 kg/yr. The major sources of nitrate-N load were determined to be:

1. The Southeast Farm sprayfield at 111,000 kg/yr 50 percent),
2. Inflow to the study area across the lateral model boundaries at 44,000 at kg/yr (20 percent), and
3. Onsite sewage disposal systems at 38,000 kg/yr (17 percent).

All of the other sources contributed 6 percent or less. Under the assumptions of scenario 2, the total simulated nitrate-N load to Wakulla Springs was 320,000 kg/yr. The major sources of nitrate-N load were determined to be:

1. The Southeast Farm sprayfield at 111,000 kg/yr (35 percent),
2. Onsite sewage disposal systems at 83,000 kg/yr (26 percent),
3. Inflow to the study area across the lateral model boundaries at 52,000 at kg/yr (16 percent), and
4. Creeks discharging into sinks at 31,000 kg/yr (10 percent).

All of the other sources contributed 8 percent or less.

The nitrate-N loads to Wakulla Springs from the Southeast Farm sprayfield for scenarios 1 and 2 were both 111,000 kg/yr. These amounts were the same because most of the water from the Southeast Farm sprayfield went into Wakulla Springs in both simulations. In contrast, the nitrate-N loads from onsite sewage disposal systems for scenarios 1 and 2 were 38,000 kg/yr and 83,000 kg/yr, respectively. The additional water captured by Wakulla Springs in scenario 2 came from an area that had a high density of residential and commercial sites using onsite sewage disposal systems.

Under the assumptions of scenario 1, the total simulated nitrate-N load to Wakulla Springs in 2018 will be 175,000 kg/yr. The major sources of nitrate-N load for scenario 1 are anticipated to be:

1. Inflow to the study area across the lateral model boundaries at 48,000 at kg/yr (28 percent),
2. The Southeast Farm sprayfield at 42,000 kg/yr (24 percent),
3. Onsite sewage disposal systems at 51,000 kg/yr (29 percent), and
4. Fertilizer at 18,000 kg/yr (10 percent).

All of the other sources will contribute 5 percent or less. Under the assumptions of scenario 2, the total simulated nitrate-N load to Wakulla Springs in 2018 will be 305,000 kg/yr. The major sources of nitrate-N load for scenario 2 are anticipated to be:

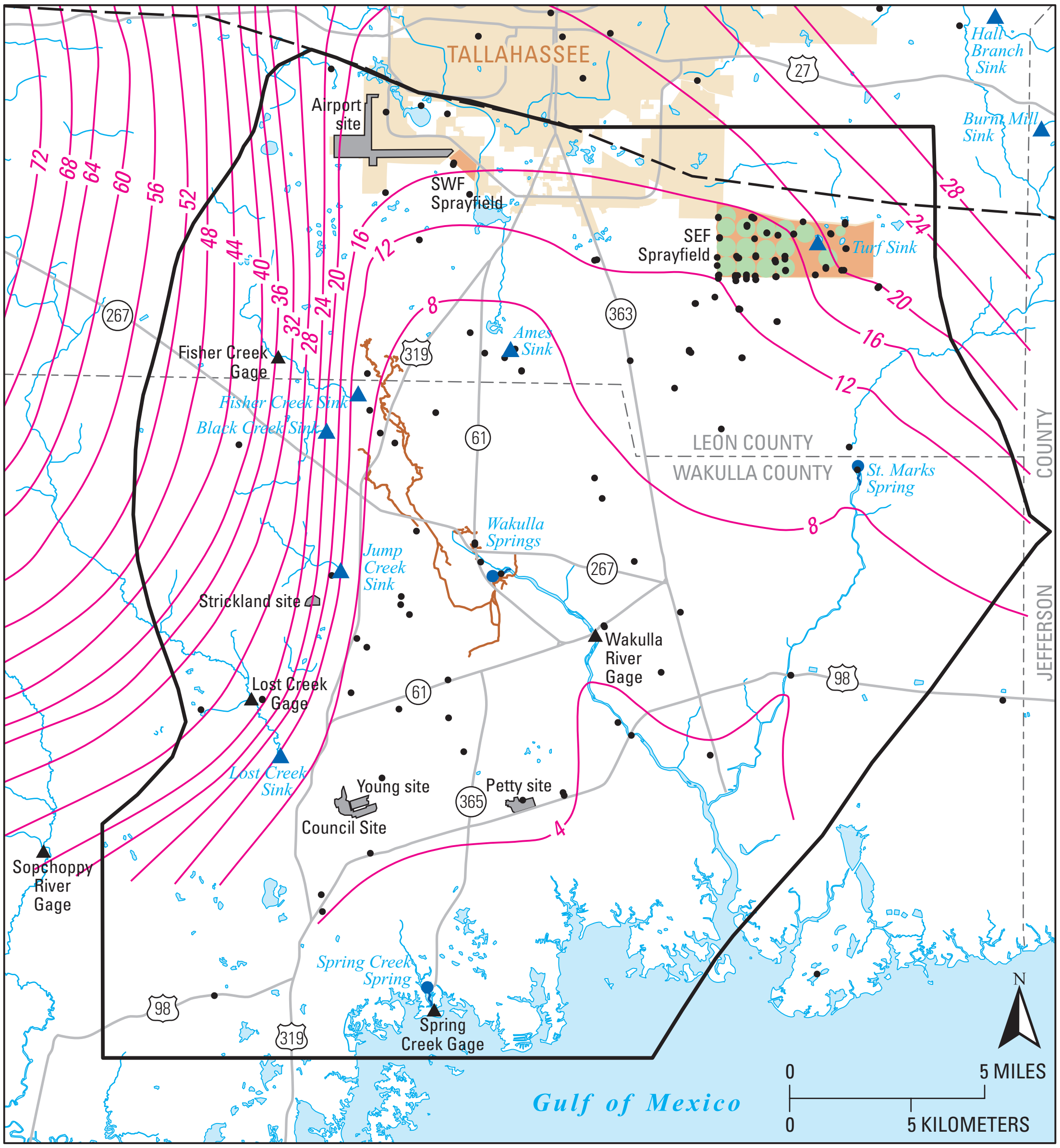
1. Onsite sewage disposal systems at 119,000 kg/yr (39 percent),
2. Inflow to the study area across the lateral model boundaries at 57,000 at kg/yr (19 percent),
3. The Southeast Farm sprayfield at 43,000 kg/yr (16 percent),
4. Creeks discharging into sinks at 31,000 kg/yr (10 percent), and
5. Fertilizer at 32,000 kg/yr (10 percent).

All of the other sources will contribute 6 percent or less.

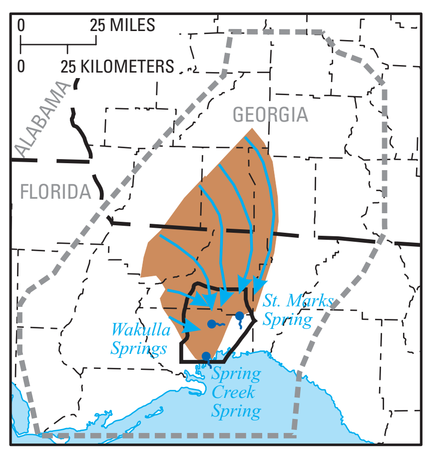
The simulated nitrate-N load from the Southeast Farm sprayfield to Wakulla Springs during 2007 through 2018 decreases from 111,000 kg/yr to 42,000 kg/yr in scenario 1 and decreases from 111,000 kg/yr to 43,000 kg/yr in scenario 2. Both scenarios show these decreases because of the simulated planned reduction in the concentration of nitrate-N in the wastewater used for irrigation from approximately 12 milligrams per liter (mg/L) in 2007 to 3 mg/L in 2018. In contrast, the simulated nitrate-N load from onsite sewage disposal systems to Wakulla Springs from 2007 through 2018 increases from 38,000 kg/yr to 51,000 kg/yr in scenario 1, and increases from 83,000 kg/yr to 119,000 kg/yr in scenario 2. Both scenarios show increases respective to the increases in population and residential and commercial sites using onsite sewage disposal systems. In addition, the simulated nitrate-N load to Wakulla Springs from 2007 through 2018 from inflow to the study area across the lateral model boundaries increases from 44,000 kg/yr to 48,000 kg/yr in scenario 1, and increases from 54,000 kg/yr to 57,000 kg/yr in scenario 2. Both scenarios show increases due to increasing nitrate-N levels upgradient in Leon County.

Introduction

Karstic aquifers and their associated springs are particularly vulnerable to nitrate contamination from various anthropogenic activities at land surface. Public concern about increased nitrate-nitrogen (nitrate-N) levels from land applications in northern Florida is understandable, particularly as Wakulla Springs is a major groundwater discharge point for the Upper Floridan aquifer (UFA), which serves as the source of public water supply for much of Leon and Wakulla Counties (fig. 1; Katz and others, 2009). Increased loading of nitrate-N to receiving waters in many parts of Florida has resulted in detrimental effects to aquatic ecosystems, including a proliferation of nuisance aquatic vegetation and accelerated algal growth (Florida Springs Task Force, 2000). Wakulla Springs is affected as these



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′



EXPLANATION

- RESIDUALS DISPOSAL AREA
- SPRAYFIELD LOCATION—Southeast farm (SEF) and southwest farm (SWF)
- SPRINGSHEDS—For Wakulla, St. Marks, and Spring Creek.
- REGIONAL MODEL BOUNDARY
- SUBREGIONAL MODEL BOUNDARY—and study area boundary
- 4 POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased wells. Contour interval is 4 feet.
- CODY SCARP
- DIRECTION OF GROUNDWATER FLOW
- MAPPED SUBMERGED CAVES
- CENTER PIVOT LOCATION
- GAGING STATION
- MONITORING WELL
- SINK—With creek inflow.
- SPRING LOCATION

Figure 1. Study area and potentiometric surface of the Upper Floridan aquifer during late May through early June 2006. Monitoring well details are included in table 1 of the appendix.

higher levels of nitrate-N, in combination with the generally clear spring water and abundant sunshine, may be encouraging invasive plant species growth. Nitrate-N concentrations in Wakulla Springs have varied during the last several decades. Nitrate-N was about 0.2 milligram per liter (mg/L) in the early 1960s; it had increased to more than 1.0 mg/L by the 1980s; it declined to about 0.8 mg/L (Chelette and others, 2002) in the 1990s; and it further declined to between 0.5 to 0.7 mg/L (fig. 2; Katz and others, 2009) in the 2000s. The increase of nitrate-N at Wakulla Springs was relative to an increase of populations for Leon and Wakulla Counties from 1965 to about 1990; however, nitrate-N decreased from 1990 to 2007 even though population growth continued for both counties.

Nitrate-N sources in the area surrounding Wakulla Springs were inventoried by Chelette and others (2002). The sources and percent loading at land surface during the period 1990 through 1999 were determined to be: the City of Tallahassee (the City) wastewater treatment facilities (40 percent), atmospheric deposition (26 percent), biosolids from wastewater treatment (15 percent), commercial fertilizer application (7 percent), onsite sewage disposal systems (OSDS, 6 percent; OSDS are generally known as septic tanks), creeks discharging into sinks (4 percent), and livestock wastes (2 percent). Biosolids, as used in this report, refer to the solid residue produced as a result of sewage treatment.

The Chelette and others report (2002) indicated that the City wastewater treatment facilities were contributing 40 percent of the nitrate-N load to Wakulla Springs; however their analysis was based on a mass balance approach that did not directly tie the increase in nitrate-N in Wakulla Springs to the wastewater treatment facilities. To reduce the nitrate-N load, the wastewater treatment facilities would require expensive upgrades. Before considering these upgrades, the City wanted to be certain that its facilities were at least partially responsible for the problem. For this reason, the City and the U.S. Geological Survey began this cooperative study to determine if nitrate-N from the City wastewater treatment facilities were affecting Wakulla Springs and to what degree.

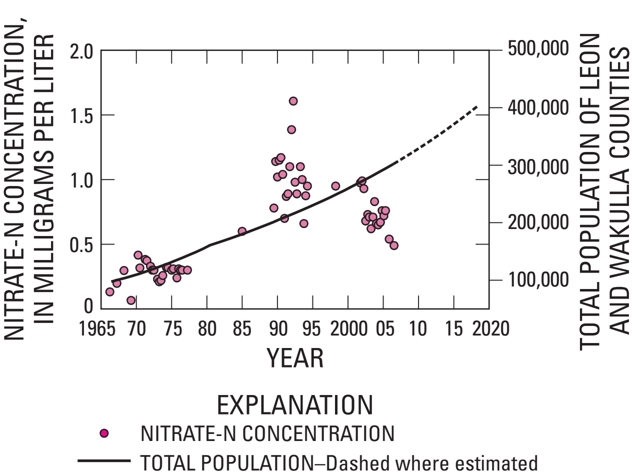


Figure 2. Nitrate-N concentration in Wakulla Springs from 1966 through 2007 compared to Leon and Wakulla County population. (Data sources: Population data is from the U.S. Census Bureau (2005), nitrate-N concentrations are from the U.S. Geological Survey and Jamie Shakar, City of Tallahassee, written commun., 2005).

Purpose and Scope

This report documents the development of a groundwater flow model that simulates the movement of groundwater to Wakulla Springs and other local springs from the period 1966 through 2018. Next, the report describes the development of a fate and transport model that simulates the evolution of nitrate-N concentrations in the UFA and springs during the same period. Finally, the report presents the results of each of these simulations. Also included are details about previous work in the region and the specific study area. The report discusses the compilation of available nitrate-N and other data, and the collection of additional water-quality data to fill in the gaps prior to characterizing the groundwater system. Each of the determined sources of nitrate-N in the study area is reviewed.

Previous Investigations

Hendry and Sproul (1966) investigated the geology and groundwater resources of Leon County. They described the geology and hydrology of the UFA, overlying units, and the general water quality. Miller (1986) described the geology of the Floridan aquifer system that underlies all of Florida and parts of Georgia and South Carolina. In some areas, Miller divided the Floridan aquifer system into the UFA and the Lower Floridan aquifer; however, only the UFA was determined to be present within this study area. Miller mapped the top, bottom, and thickness of the UFA and described the geology of the formations that comprise the aquifer as part of the Regional Aquifer-System Analysis (RASA) of the U.S. Geological Survey (USGS). Bush and Johnston (1988) simulated groundwater flow in the entire Floridan aquifer system using a finite-difference model as part of the RASA. Based on Miller’s determination, they simulated only the presence of the UFA in the study area for this report. During their investigation, model-derived transmissivities were determined for the UFA, as well as rates of recharge and discharge. A relatively coarse grid with spacing of 8 × 8 miles (mi) was used for these simulations. The major springs within the study area of this report were simulated, but the coarse grid spacing restricted the amount of fine detail that could be included in the modeling. Groundwater flow to Wakulla Springs, St. Marks River springs, and the Spring Creek Springs Group was simulated in studies by Davis (1996) and Davis and Katz (2007). These two studies simulated the entire recharge area for these springs using a much finer model grid than Bush and Johnston (1988) and refined the model-derived transmissivities and rates of recharge and discharge. The model documented by Davis and Katz (2007) was used as the regional model in this report, with some minor modification.

Description of the Study Area

The study area (also referred to in this report as the subregional model area) covers about 500 square miles (mi^2) and extends from the Cody Scarp south to the Gulf of Mexico (fig. 1). The study area is located within the Coastal Plain physiographic province (Brooks, 1981), where the topography is characterized by rolling hills and land-surface altitudes that range from 0 to about 200 feet (ft) just north of the Cody Scarp. South of the scarp, the land-surface altitudes are generally less that 50 ft and are characterized by closed basins typical of karst terrains. The climate is humid subtropical with relatively high rainfall. The average annual temperature in Tallahassee is 67 °F and the average annual precipitation is about 66 inches per year (in/yr). The average yearly potential evapotranspiration for the Tallahassee area was estimated to be about 46 in/yr (Smajstrla and others, 1984).

Background and Approach

Disposal of wastewater in a manner that does not cause environmental problems is always a challenge. Prior to 1966, the City disposed of treated wastewater by discharging it to a local lake, but the nitrate-N in the wastewater caused algal blooms. To prevent this, the City began changing its disposal method. In 1966, the City began a pilot project called the Southwest Farm (SWF) sprayfield that used center pivot irrigation techniques (figs.1 and 3). In the first year of operation, the City sprayed 91 million gallons per year (Mgal/yr)

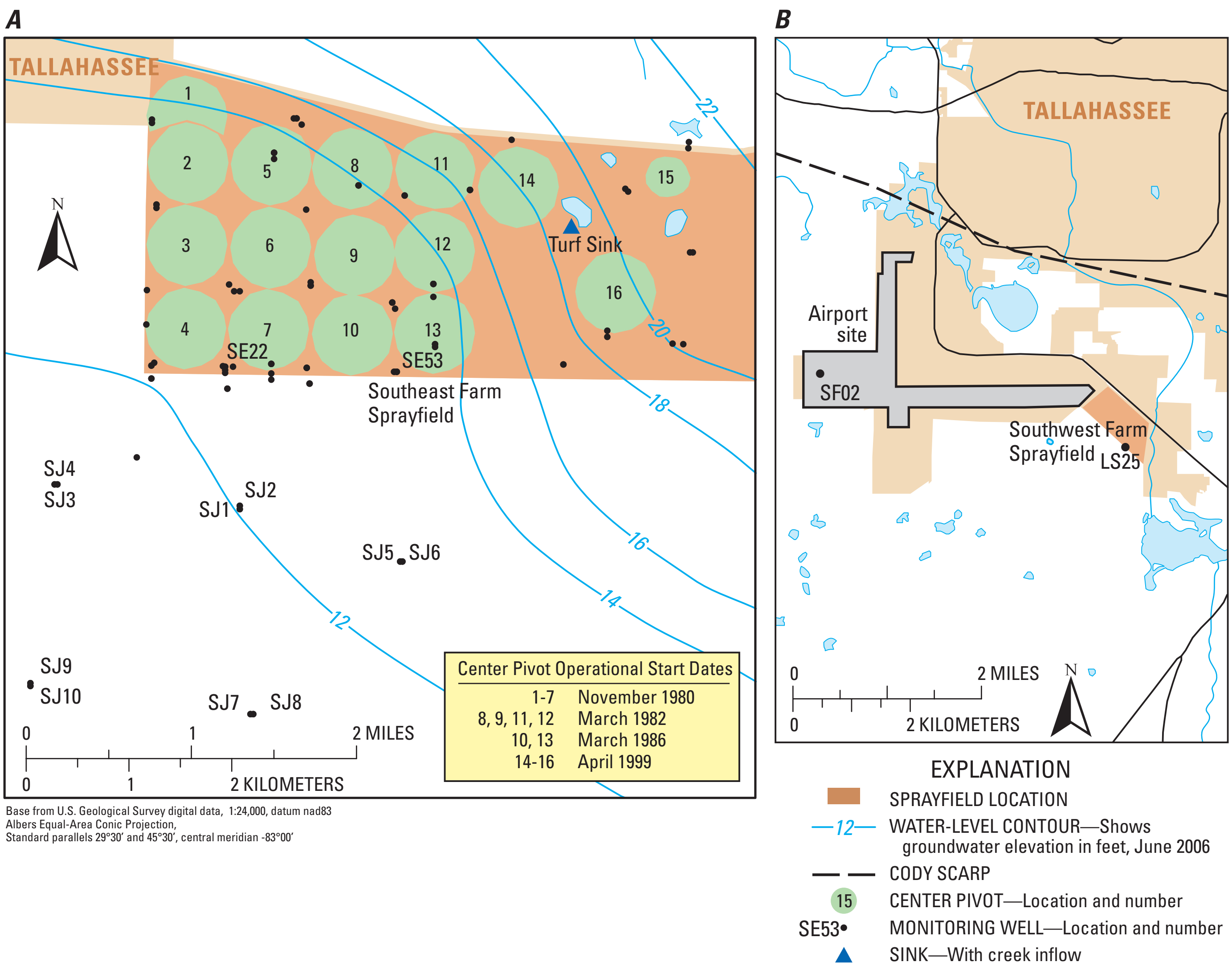


Figure 3. Location of *A*, Southeast Farm sprayfield and *B*, Southwest Farm sprayfield and airport biosolids disposal area.

of wastewater (Chellette and others, 2002) on the 16-acre site. From 1966 through 1980, the flow volume increased to an estimated 2,522 Mgal/yr and the site expanded to cover 118.5 acres (Jamie Shakar, City of Tallahassee, written commun., 2005). After November 1980, the volume of wastewater disposed of by the SWF sprayfield decreased to an estimated 112 Mgal/yr because the new, larger Southeast Farm (SEF) sprayfield became operational (Jamie Shakar, City of Tallahassee, written commun., 2005). The new sprayfield began operation in November 1980 with center pivots 1-7 (fig. 3). In March 1982, center pivots 8, 9, 11, and 12 began operation; in March 1986, center pivots 10 and 13 began operation; and in November 1999, center pivots 14-16 began operation (Jamie Shakar, City of Tallahassee, written commun., 2005). In 1981, the first full year of operation, the City sprayed 2,824 Mgal/yr of wastewater (Jamie Shakar, 2005, City of Tallahassee, written commun.); from 1981 through 2005, the flow volume increased to an estimated 7,154 Mgal/yr.

The investigation into the effects of the land application of treated municipal wastewater on water quality in the UFA and Wakulla Springs is composed of two parts. The first part consists of extensive water-quality sampling at the SEF sprayfield, Wakulla Springs, and other local springs that has been documented by Katz and others (2009). The second part of the investigation described herein presents the results of groundwater flow and solute transport modeling simulations that were conducted to determine the cause of increased nitrate-N concentrations in Wakulla Springs from the years 1966 through 2007, and to estimate future concentrations through 2018. The end date of December 31, 2018, was selected because the planned reductions in nitrate-N concentrations at the SEF and SWF sprayfields will have had sufficient time to travel through the groundwater flow system and to be evident in the nitrate-N concentrations occurring in local springs.

Geohydrologic Setting of the Wakulla Springs Springshed

The study area includes the southern parts of the three major springsheds (fig. 1): Wakulla Springs, the St. Marks River springs, and the Spring Creek Springs Group. These springs are regional groundwater discharge points for the UFA of northern Florida and southern Georgia. Groundwater flow in the study area is shaped by the karstic subsurface conditions and those features resulting from karstification at land surface. Limestone sediments comprising the aquifer underlying the study area have secondary permeability features that strongly influence transport times of contaminants through the system. This section describes the development of long-term water-level trends, recharge, and secondary porosity as they relate to the local geology and hydrology of the Wakulla Springs springshed. These factors provide the framework for the model needed to gain a better understanding of groundwater flow and transport concepts.

Geologic Setting

The study area is underlain by sedimentary rocks of Tertiary through Quaternary age that consist of limestone, dolostone, clay, and sand of varying degrees of lithification (Miller, 1986). These rock units generally dip southward toward the Gulf of Mexico. A list of geologic units and the principal hydrogeologic units (aquifers and confining units) with corresponding model layers are shown in figure 4. For reference, the model layer correlations for the regional model by Davis and Katz (2007) are included. The geologic descriptions given in this section are based on work by Miller (1986) unless otherwise cited.

The Paleocene Clayton Formation underlies the entire study area and consists of massive calcareous marine clay. The Eocene sediments can be subdivided from oldest to youngest into the Oldsmar and Avon Park Formations and the Ocala Limestone, all consisting of permeable limestone. The Oligocene Suwannee Limestone is generally permeable to very permeable. The Miocene sediments can be subdivided into the Chattahoochee Formation, the St. Marks Formation, and the Hawthorn Group. The Chattahoochee Formation is primarily a dolostone containing quartz sand, clay, calcite, limestone, chert, mica, heavy minerals, phosphate, and fossils (Huddlestun, 1988). The St. Marks Formation is a predominantly fine- to medium-grained, silty to sandy limestone that has undergone degrees of secondary dolomitization (Hendry and Sproul, 1966). The permeability of the St. Marks and Chattahoochee Formations can range from highly permeable to relatively impermeable. The Hawthorn Group is predominantly sand and clay; subordinate components include dolomite, dolostone, calcite, limestone, phosphorite, phosphate, silica in the forms of claystone, chert, and siliceous microfossils, feldspar, heavy minerals, carbonaceous material and lignite, zeolites, and fossils (Huddlestun, 1988). The Pliocene sediments are represented by the Miccosukee Formation, which is most commonly sandy and silty clay. Sediments of the Hawthorn Group and the overlying clay, silts, and sandy clays of the Miccosukee Formation form a low-permeability hydrogeologic unit that is present only in the extreme northern part of the study area.

Pleistocene sediments consist of medium- to coarse-grained, tan, white, and brown sand that locally contains trace amounts of carbonaceous material and shell fragments. The Holocene deposits include thin sand and gravel accumulations deposited mostly adjacent to streams, estuaries, and lagoons.

SYSTEM	SERIES	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT	MODEL LAYERS	
				Davis and Katz (2007)	Sub-regional model (This study)
QUATERNARY	HOLOCENE	Undifferentiated deposits	Water-table aquifer	Layer 1	Not simulated (Generally not present)
	PLEISTOCENE	Undifferentiated terrace and shallow marine deposits			
TERTIARY	PLIOCENE	Miccosukee Formation			
	MIOCENE	Hawthorn Group	Hawthorn Clays	Layer 2	Not simulated (Generally not present)
		Chattahoochee and St. Marks Formations	Upper Floridan aquifer	Layers 3 and 4	Layers 1 and 2
	OLIGOCENE	Suwannee Limestone			
	EOCENE	Ocala Limestone			
		Avon Park Formation			
		Oldsmar Formation			
	PALEOCENE	Clayton Formation	Low-permeability sediments	No-flow boundary	No-flow boundary

Figure 4. Geologic units, hydrogeologic units, and model layers in north-central Florida.

Hydrologic Setting

The UFA is part of the Floridan aquifer system that is present in Florida and parts of Georgia, South Carolina, and Alabama; it is utilized for municipal, industrial, agricultural, and domestic water supply. Where transmissivities are high, the UFA generally yields large quantities of potable water; where transmissivities are low, the water quality is generally also low because of high levels of dissolved solids. Bush and Johnston (1988) concluded that carbonate rocks of the UFA are nearly always characterized by an uneven distribution of permeability. The water-bearing openings consist of one or more of the following:

1. Openings in loosely cemented fossil hashes that are similar to the interstices of sands,
2. Mosaics of many fractures and solution-widened joints, and
3. Solution cavities ranging in size from less than 1 ft to tens of feet or greater.

Large solution cavities generally are present near large springs and sinkholes, where dissolution of the limestone is greatest. In areas away from the large solution openings, the first two conditions dominate. The permeability of the UFA is directly related to the thickness and lithology of the overlying low-permeability sediments. Thinner and more permeable overlying sediments allow greater rates of infiltration and increased dissolution of the limestone. The removal of these low-permeability sediments from some areas during Pleistocene time is largely responsible for the current distribution of karst, and thus, the current distribution of transmissivity. Values of transmissivity determined by aquifer tests for the UFA vary greatly in the study area, ranging from 1.3×10^3 to 1.3×10^6 feet squared per day (ft^2/d) (Davis, 1996).

The structure of the UFA was described by Miller (1986) and the remainder of this section is based on his work unless otherwise cited. The altitude of the top of the UFA is about 50 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29) in the northeast corner of the study area and dips to about -100 ft below NGVD 29 in the southwest corner (fig. 5). The altitude of the base of the UFA (fig. 6) was modified from Miller (1986) based on new information collected during the well drilling part of this study (this is discussed in the Data Collection and Field Methods section). In brief, the boring associated with well SJ-7 indicated that the base of the freshwater flow system was about 400 ft NGVD 29, so Miller's (1986) map was recontoured in this area. The base of the UFA dips to -1,800 ft NGVD 29 on the western side of the study area because of a paleochannel that existed during the early Tertiary and was described by Huddlestun (1988). The thickness of the UFA was determined by subtracting the altitude of the base of the UFA from that of the top (fig. 7).

Groundwater Flow

On the western side of the study area, the potentiometric surface is steepest due to low-permeability limestone deposited within a deepwater paleochannel (Huddlestun, 1988). In the central and eastern parts of the study area, the potentiometric surface slopes gently to the south and southeast; the gentle slope is caused by very high permeabilities due to dissolution of the limestone. The UFA within the study area is in a state of dynamic equilibrium in which there have been no known long-term changes in the potentiometric surface; but water levels do fluctuate seasonally and yearly in response to variations in rainfall (Davis and Katz, 2007). Bush and Johnston (1988) found no evidence for a net decline between the estimated predevelopment potentiometric surface and the observed potentiometric surface in May 1980.

Groundwater flows to Wakulla Springs by one of the most extensive submerged cave systems in the United States, with approximately 37 mi of mapped cave passage (Loper and others, 2005; fig. 8). Cave divers have entered the submerged cave system through Wakulla Springs and numerous sinkholes in the Wakulla Springs springshed. Identifying individual cave passages as tunnels with alphabetic letter designations is a standard naming convention established by cave explorers. This cave system, for orientation and description purposes in this report as shown in figure 8, is assumed to start at the spring vent and initially heads southward where it branches into the A- and K-tunnels. The A- and K-tunnels eventually merge to form the O-tunnel, which eventually connects to the Q-tunnel. The Q-tunnel continues heading toward the Spring Creek Springs Group, at least to the point where a diving exploration team had to turn around. The B-tunnel initially trends eastward then turns northward in the general direction of the SEF sprayfield; the C-tunnel is located close to the B-tunnel and trends toward south. The relatively short D-tunnel heads northward. The extensive R-tunnel connects near the A-K-O tunnel junction; the R-tunnel connects with other tunnels that extend several miles north westward passing through several sinkholes.

Tracer tests have been conducted using dye injection techniques at several sites to determine the direction and velocity of groundwater flow (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006; fig. 8). Dye injected into Fisher Creek Sink was detected in Emerald, Upper River, and Turner Sinks and Wakulla Springs (fig. 8); the measured traveltime from Fisher Sink to Wakulla Springs was about 10 days (the straight line distance is 5.7 mi); dye injected into Ames Sink traveled to Wakulla Springs in about 20 days (the straight line distance is 5.6 mi) (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006). The traveltime, as used in this report, refers to the length of time that it takes for a dye (or other tracer) to travel from the injection point to a point where it is detected. Dye injected into Turf Sink, located at the SEF (fig. 1), arrived at Wakulla Springs in about 40 days (11.7 mi straight line distance) indicating a direct connection between the SEF sprayfield and Wakulla Springs (Todd Kincaid,

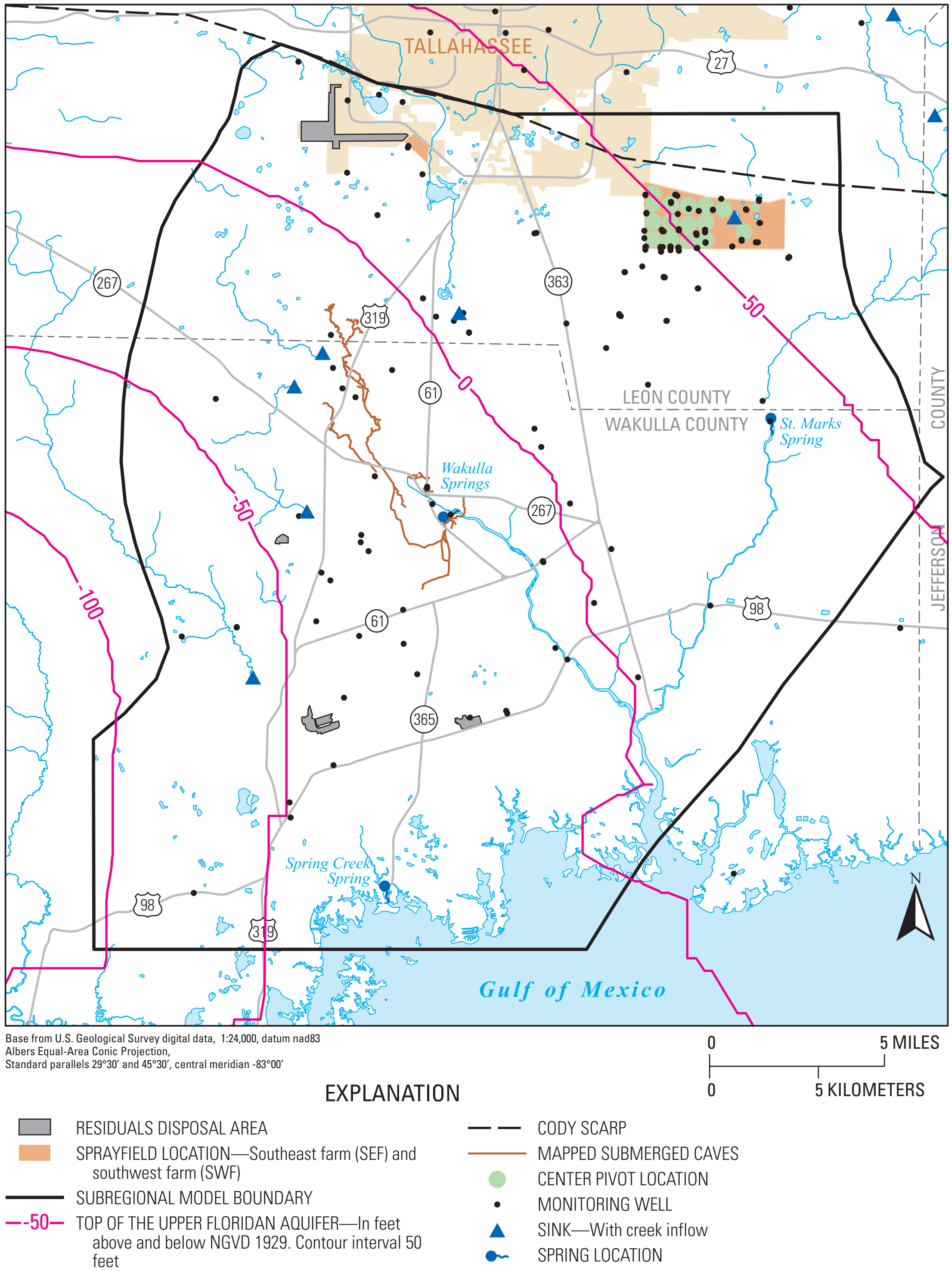


Figure 5. Top of the Upper Floridan aquifer used to set the top of model layer 1. (Contours modified from Miller 1986.)

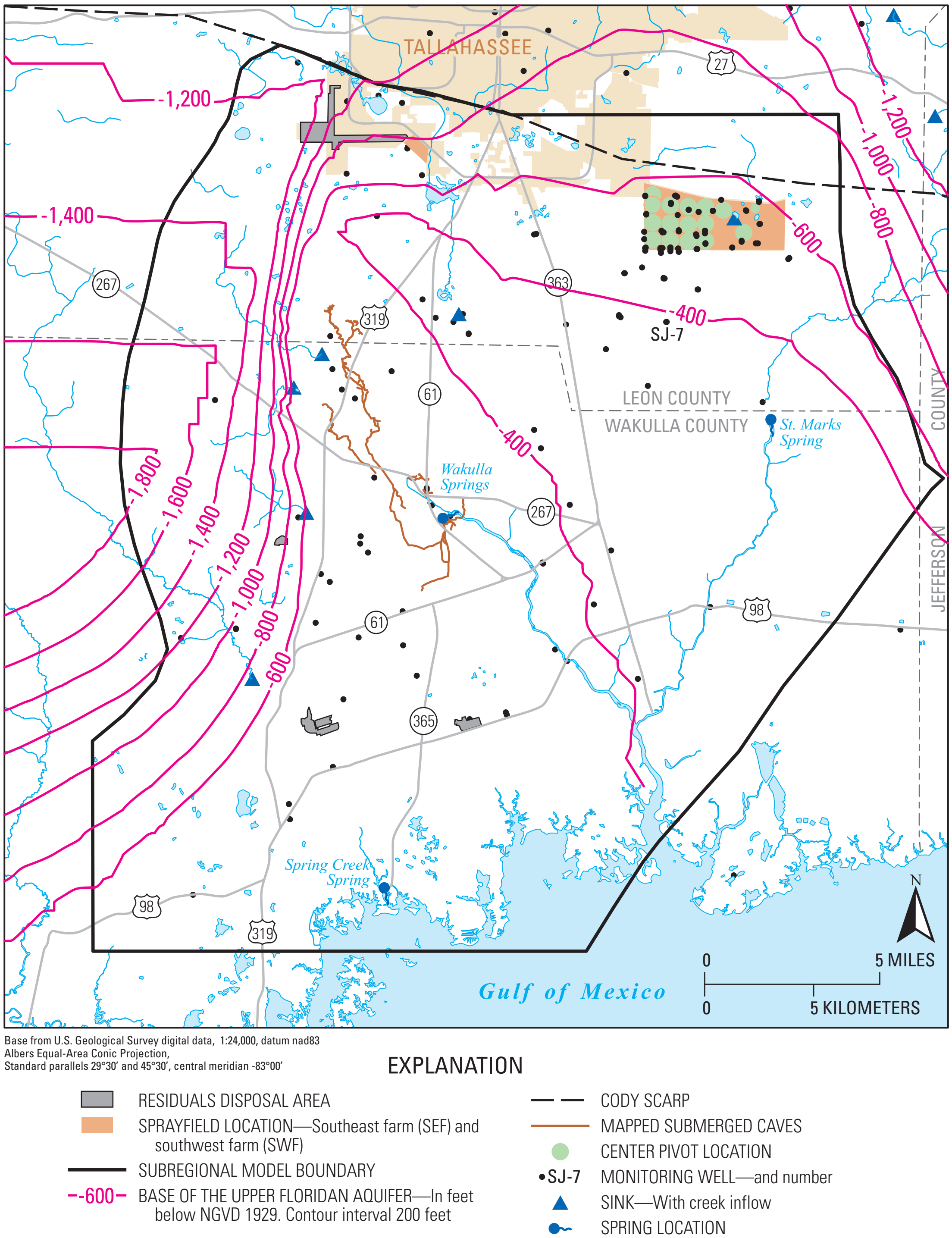


Figure 6. Base of the Upper Floridan aquifer used to set the bottom of model layer 2. (Contours modified from Miller, 1986.)

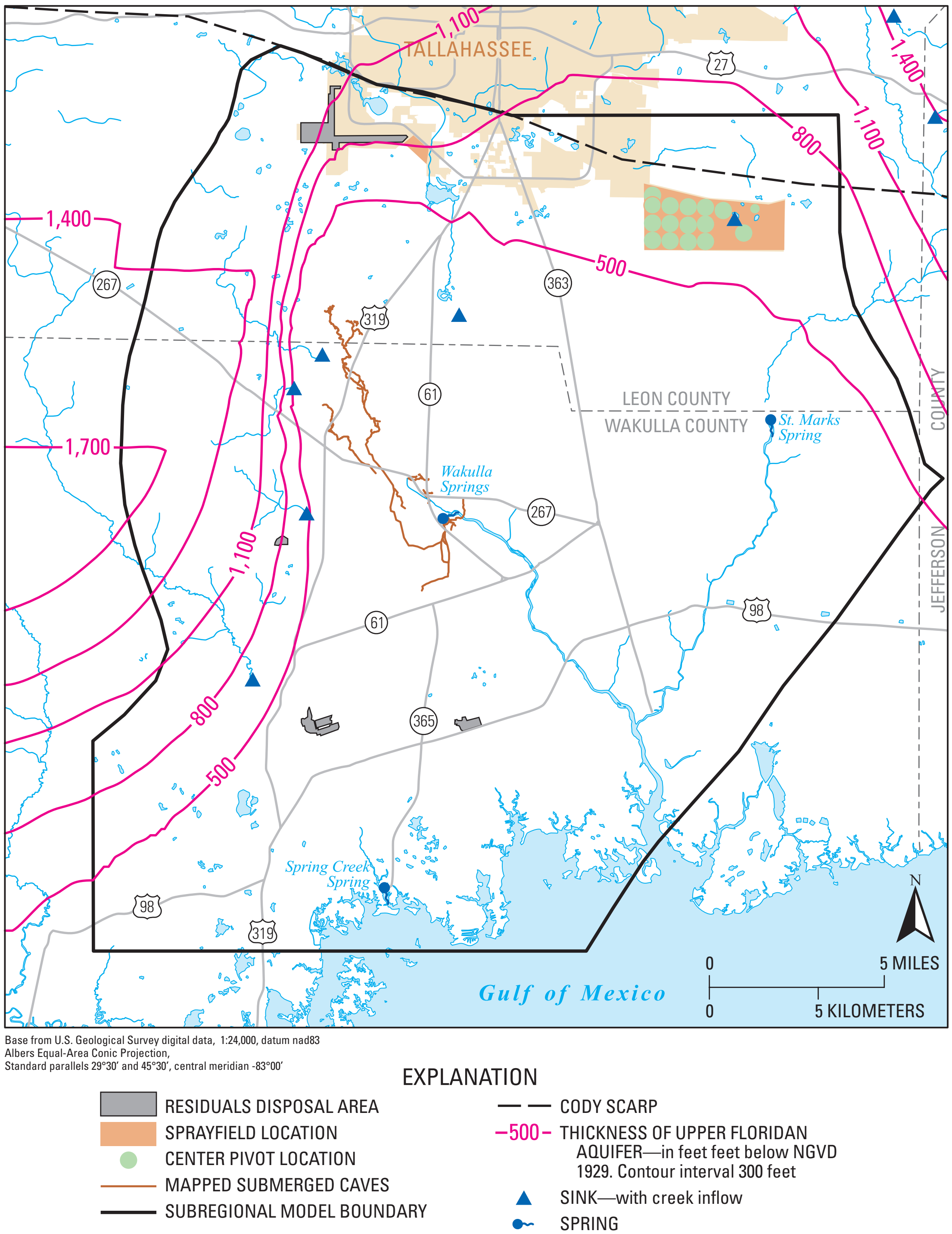


Figure 7. Thickness of the Upper Floridan aquifer.

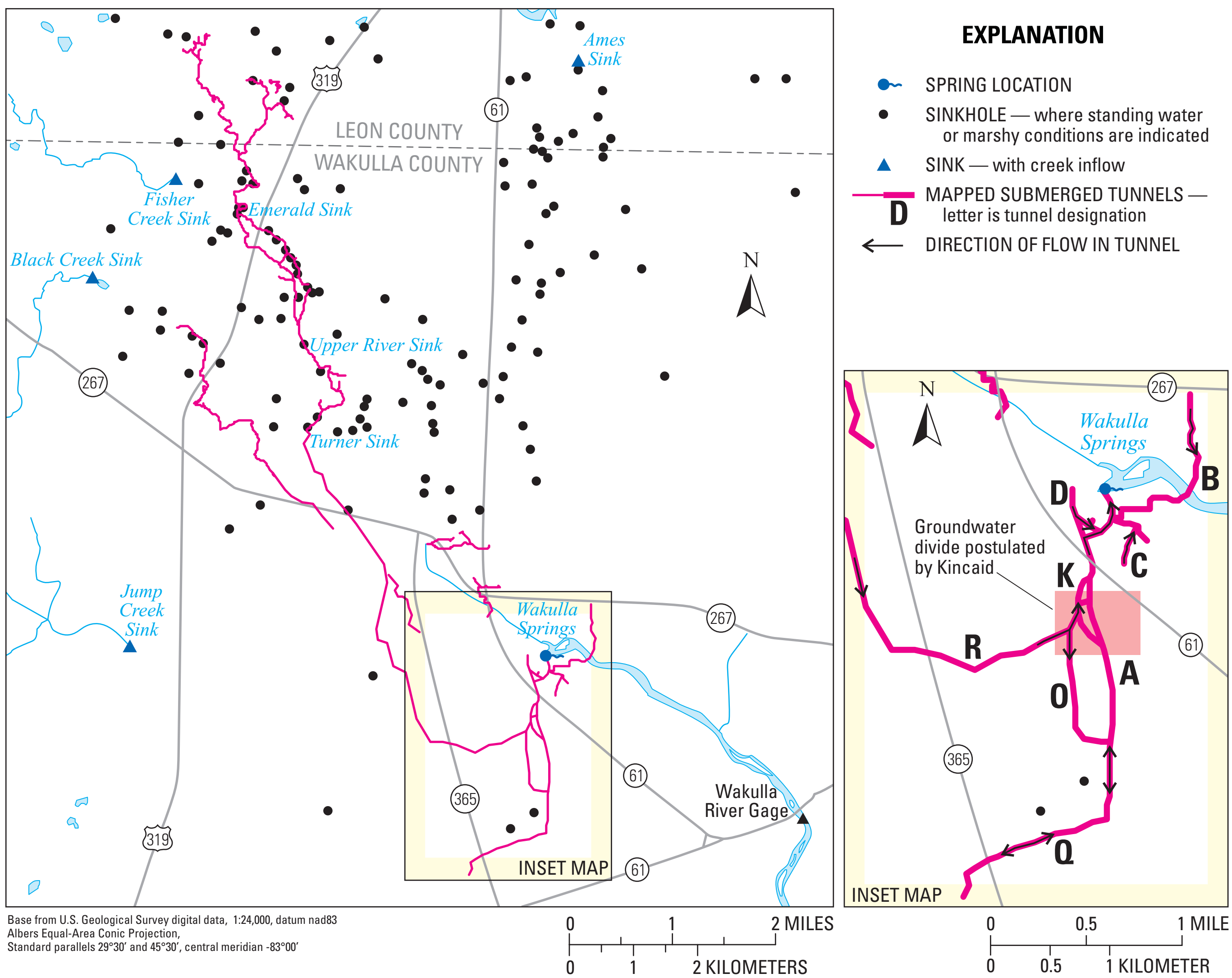


Figure 8. Location of the Wakulla Springs cave system.

Hazlett-Kincaid, Inc., written commun., 2006). Only a small proportion of the injected dyes was recovered during the tracer tests, which suggests the possibility that some of the groundwater may be bypassing Wakulla Springs.

Groundwater flow in the tunnels (conduit flow) that connect to Wakulla Springs is complex and is not completely understood. The flow in the R-tunnel is probably the simplest to understand. The R-tunnel is part of the extensive cave system that trends northwest from Wakulla Springs. Upper River Sink occurs where this cave system breaches land surface; the flow in this sink has been measured seven times in the period from 1932 to 1977 and averaged 165 ft^3/s (Rosenau and others, 1977). This finding indicates that the cave system (including the R-tunnel) is carrying a substantial quantity of water. Where the R-tunnel reaches the A-K-O tunnel junction, the flow could be substantially higher if the tunnels are gaining water all along their length. Flow at the junction of the R and A-K-O-tunnels has the possibility of going north to Wakulla Springs, south toward the Spring Creek Spring Group, or both. Sometimes, cave divers swimming southward in the A-tunnel from the spring entrance have observed that the groundwater flow in the cave is northward toward the spring vent, but reverses somewhere in the vicinity of the R-tunnel connection and can flow southward toward the Spring Creek Springs Group (fig. 8). A groundwater divide (fig. 8) in this area was postulated as early as 1999 by Kincaid (1999). Kincaid further noted that this divide is not stationary and can move as groundwater conditions change. If the groundwater divide were to shift to the south, then upon reaching the A-K-O-tunnel junction, all of the flow in the R-tunnel would flow northward to Wakulla Springs; conversely, if the divide were to shift to the north, then all of the flow in the R-tunnel would go southward toward the Spring Creek Springs Group. If the divide were located as shown in figure 8, the R-tunnel flow would split with some going northward and some going southward, which appears to have been the case when Kincaid postulated its existence. In a recent tracer test, a dye was introduced into Lost Creek Sink (fig. 1); this dye was later detected at some of the Spring Creek Springs Group and at Wakulla Springs (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2008). This finding suggests that the flow in the Q-tunnel can reverse completely and flow northward toward Wakulla Springs.

Rapid dissolution of the limestone is occurring within the study area as evidenced by these extensive cave systems. Cave maps of Wakulla Springs show that many of the caves lie between 300 and 400 ft below land surface (bls) (although some are much shallower and even breach the land surface as sinkholes). A cross-sectional conceptual model of ground-water flow for the study area is shown in figure 9. In this conceptual model, it was assumed that dissolution of the limestone is occurring at all levels of the aquifer, but is

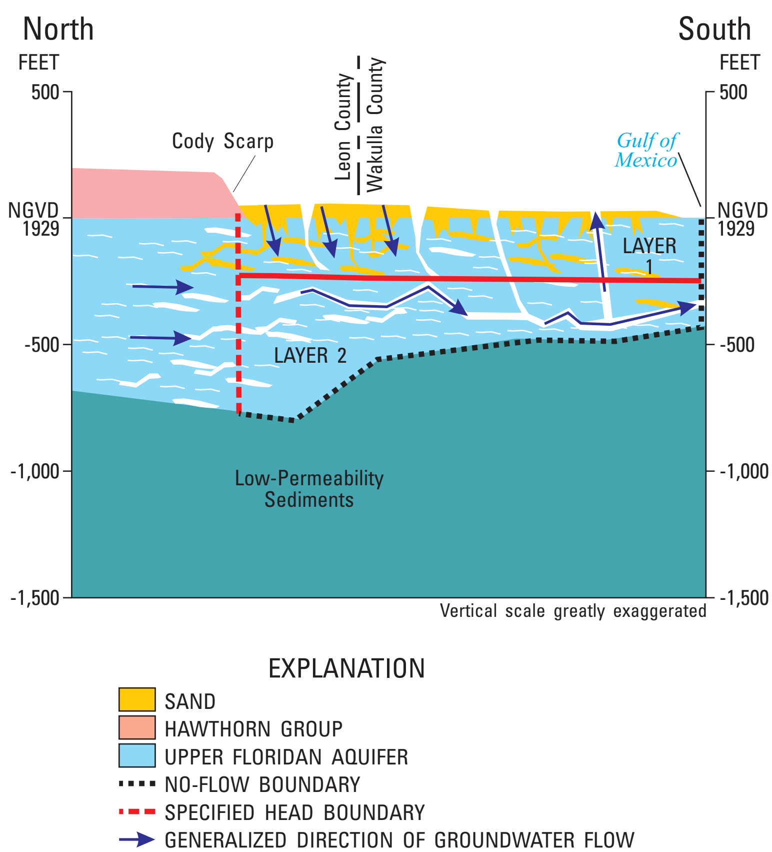


Figure 9. Generalized geologic cross section and model layers.

probably occurring most actively in the shallower part where the recharging rainwater first encounters limestone. The sands, silts, and clays that overlie the limestone tend to fill the shallow dissolution cavities from above; the deeper dissolution cavities are somewhat protected by their depth and are less likely to infill. Infilling of the shallower parts of the aquifer results in overall lower hydraulic conductivity and lower groundwater velocities. In contrast, the lower part of the aquifer has higher hydraulic conductivities and higher groundwater velocities.

Wakulla River discharge has been measured sporadically since 1929, and a permanent gage was installed in 2004. The Wakulla River gage is located approximately 3 mi downstream from the spring (fig.1). Essentially all of the flow measured at the gage comes from Wakulla Springs, with only a small amount coming from other springs that flow into the Wakulla River. The average discharge measured at that gage for the period 1929 to 2008 was 559 ft^3/s (table 1) with a standard deviation of 242 ft^3/s. A gage has been in operation on the St. Marks River since 1956 and is located approximately 1 mi downstream from the headspring (fig. 1); the average discharge at the St. Marks gage from 1956 to 2008 is 697 ft^3/s with a standard deviation of 350 ft^3/s. Discharge at the Spring Creek Springs Group has only been measured three times in the past (recently a gage was installed, but the rating curves have not been established). The Spring Creek Springs Group is located in a tidal estuary and is logistically difficult to measure because it requires a 13-hour measurement period to cover one full tidal cycle. The discharge for all three of the major springs has only been measured once simultaneously and that was in November 1991 (table 1) during a low rainfall period when the water clarity in all of the springs was good. During low rainfall periods, the water in the springs and rivers becomes very clear. For example, the bottom of Wakulla Springs, more than 100 ft deep, can sometimes be seen from the glass bottom boats during these conditions. Lack of clarity indicates that substantial quantities of surface water are entering the aquifer through sinkholes. During heavy rainfall periods, dark brown (tannic acid stained) surface water will flow into sinkholes and travel through the caves to the springs, causing the spring discharges to rise and the clarity to fall to a few feet or less.

The UFA in the region surrounding the study area shows no long-term changes in the potentiometric surface (Bush and Johnston, 1988; Davis and Katz, 2007), so the volume of groundwater flowing southward toward the springs should have been relatively constant. However, the discharge at Wakulla Springs appears to have experienced a long-term increase between 1928 and 2008 (fig. 10). Wakulla Springs is located upgradient from Spring Creek Springs Group, so it is possible that the flow in Wakulla Springs has increased by taking flow away from the Spring Creek Springs Group. There are two possible reasons for the long-term increase in Wakulla Springs flow. First, south Florida experienced a 9-in. sea level rise from 1932 to 2007 due to the warming of the seawater temperatures in the western part of the north Atlantic (Science and Technology Committee, 2007). If this same sea level rise occurred in north Florida, then additional head pressure would have occurred at the Spring Creek Springs Group, possibly resulting in more of the water in the R-tunnel flowing northward to Wakulla Springs. Second, the evolution of the submerged cave passages may have allowed Wakulla Springs to capture more flow in the same way that one river can capture flow from another river through erosion processes.

Rapid short-term changes are occurring at Wakulla Springs in addition to the increases in long-term discharges. Some of these changes could be caused by herbicide treatments used to kill hydrilla, an invasive plant that has colonized the Wakulla River. For example, immediately

Table 1. Measured discharges for Wakulla and St. Marks Rivers and the Spring Creek Springs Group.

[River gage locations shown in figure 1; ft^3/s, cubic feet per second; N/A, data not available; ≥, greater than or equal to; na, not applicable]

River gage	Measured discharge in November 1991 (ft^3/s)	Measured discharge during late May to early June 2006 (ft^3/s)	Average discharge for period of record (ft^3/s)
St. Marks	602	560	697[a]
Wakulla	350	750	559[b]
Spring Creek Springs Group	307	na	na
Total	1,259	≥ 1,310	na

[a]Period of record is 1956 to 2008.

[b]Period of record is 1929 to 2008.

before the treatment on April 18, 2006, the discharge in Wakulla Springs was about 350 ft^3/s, but it increased to about 750 ft^3/s after the treatment (fig. 11). Hydrilla grows in thick, aerially extensive mats that extend from the bottom of the river to the surface and can restrict river flow; the herbicide treatment kills the plants, thus removing this restriction. This increase in flow of about 400 ft^3/s occurred during a dry period when little or no surface water was recharging the UFA through sinkholes. Evidence for the lack of surface water flowing into the sinks resulted from examining the discharge record of the Sopchoppy River, which is adjacent to the study area (gage location is shown on fig.1). The Sopchoppy River is the closest river to the study area with an extensive record of discharge measurements (since 1961). During the rapid increase in Wakulla Springs flow during April 2006, flow in the Sopchoppy River was at one of the lowest levels since 1966 (discharge was less than 10 ft^3/s) due to below average rainfall. The Sopchoppy River, Lost Creek, Fisher Creek, and Black Creek all have similar catchment areas, so Lost Creek, Fisher Creek, and Black Creek likely had very low flows or were completely dry during the increase in discharge at Wakulla Springs. Figure 11 illustrates the similarity in flow pattern between Lost Creek and the Sopchoppy River.

At Wakulla Springs, the same occurrence of low-flow conditions prior to the herbicide application and approximate doubling of flow after the treatment was repeated for April 2007 and April 2008. The rapid change in flow in Wakulla Springs due to the hydrilla treatments demonstrates how small changes in the hydraulic conditions can result in large shifts in groundwater flow in the study area. When the hydrilla colonized the Wakulla River, it replaced the native eel grass. The eel grass also grew in thick mats that extend from the bottom of the river to the surface and could have acted as a restriction to flow. Therefore, the hydrilla treatments can

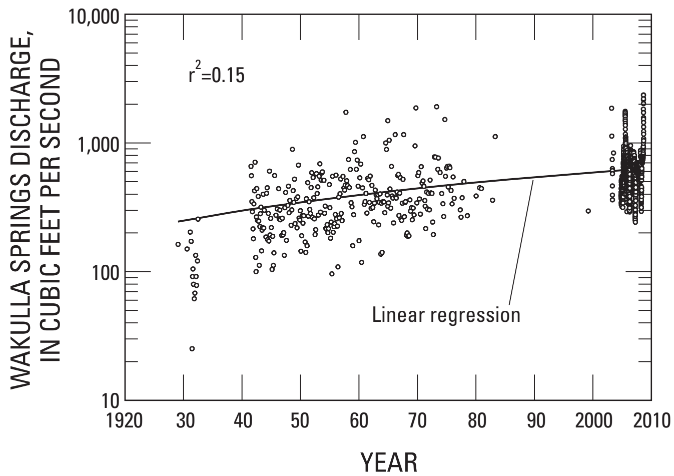


Figure 10. Wakulla Springs discharge from 1928 to 2008.

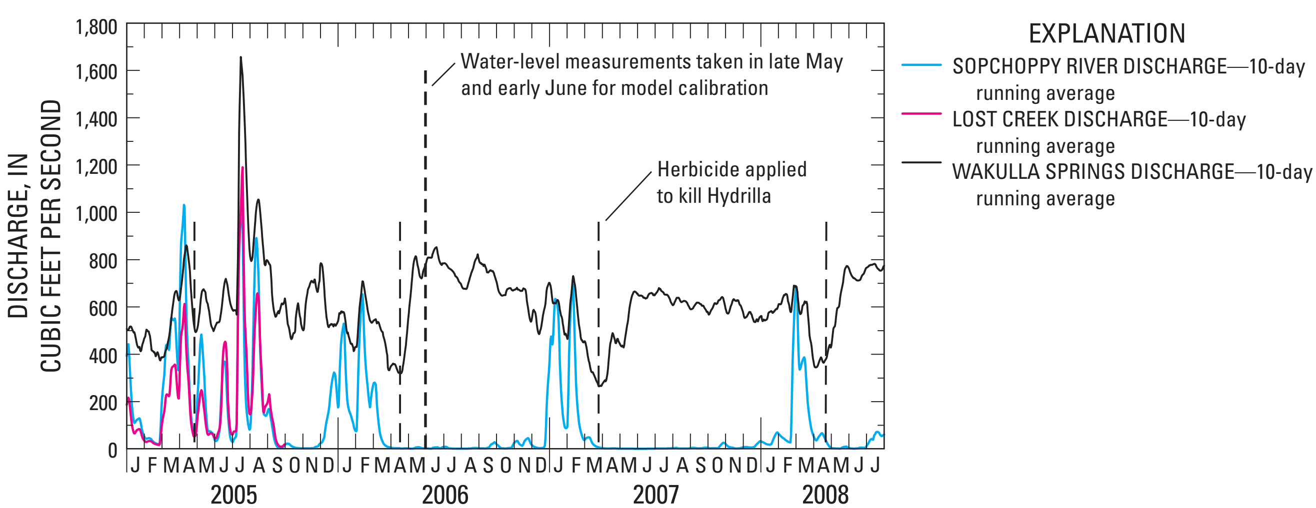
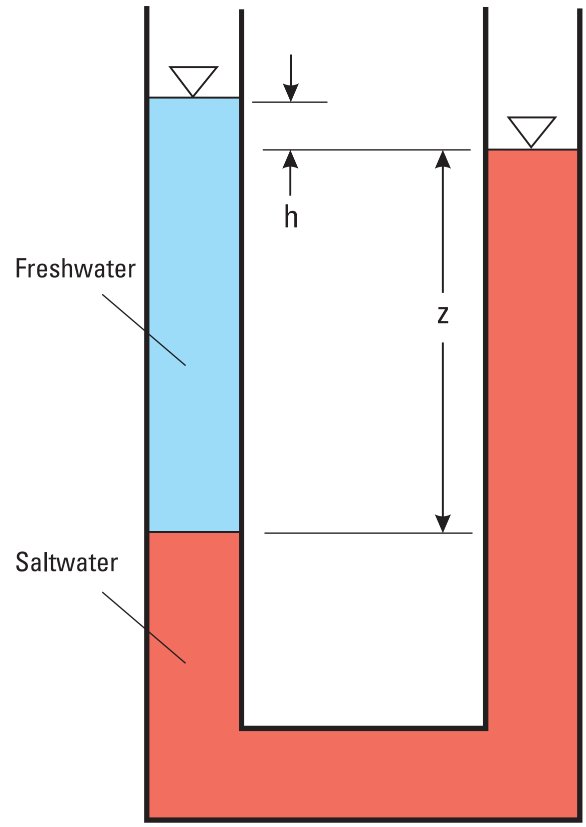


Figure 11. Wakulla Springs, Sopchoppy River, and Lost Creek discharges from January 2005 to August 2008.

remove an unwanted invasive species, but this action creates an unnatural state of lower density vegetation in the river that does not restrict flow and does not restore historic conditions. However, hydrilla treatments began in 2002, so these short-term changes are not the cause of the long-term increase in flow in Wakulla Springs.

Wakulla Springs can rapidly transition from low-flow to high-flow conditions due to several circumstances. After an herbicide treatment for hydrilla, flow increases in Wakulla Springs so that most, or all, of the flow in the R-tunnel goes to this spring. This occurrence would reduce the flow at Spring Creek Springs Group. Because less freshwater goes to the Springs Creek Springs Group, the hydraulic head at the springs drops slightly (the springs are in an estuary) and allows more saltwater to be pushed back into the spring vents, thus filling the vents with higher density saltwater. There has been limited exploration of the caves at the Spring Creek Springs Group, but the Wakulla caves are known to exceed 350 ft in depth. Assuming that the Spring Creek Spring Group caves are similar, a substantial vertical column of saltwater can be pushed back into the cave system. The saltwater can cause a higher equivalent freshwater head (fig. 12). If the cave is 300 ft deep and filled with pure seawater, then the equivalent freshwater head in the Spring Creek Springs Group will be 7.5 ft, which exceeds the head of 5 ft in Wakulla Springs.

In the spring months, growing hydrilla begins to obstruct flow in the Wakulla River, causing more water in the R-tunnel to divert to the Spring Creek Springs Group. If the additional freshwater flow to the Spring Creek Springs Group is enough to push out the saltwater, then the Spring Creek Spring Group can begin flowing again and may continue to flow assuming that a substantial amount of water from the R-tunnel was flowing south. If sea level rises, the head at the Spring Creek Springs Group may rise and push more saltwater into the Spring Creek Springs Group, thus causing Wakulla Springs to maintain higher flows for longer periods than in the past. Other causes, such as blockage in the caves, can reduce the flow in the Spring Creek Springs Group. Caves in the study area can carry a sediment bedload (just like a river does) and this can temporarily block a conduit. Lost Creek flows into the Lost Creek Sink about 5 mi northwest of the Spring Creek Springs Group and can be a source of sediments, as can vertical migration downward of the surface sediments.



Thickness of saltwater (z), in feet	Height of freshwater above saltwater (h), in feet
100	2.5
200	5.0
300	7.5
400	10.0

Figure 12. Hydrostatic balance between freshwater and saltwater illustrated by a U-tube (modified from Todd, 1980).

Data Collection and Field Methods

Field data were collected to use for model calibration purposes and consisted of water-level measurements, river discharge measurements, geologic coring, monitoring well installation, and groundwater- and surface-water quality sampling. Nitrate-N loading at land surface was then determined for each of the seven major sources:

1. Irrigation using wastewater and fertilizer application at the SEF and SWF sprayfields,
2. Atmospheric deposition,
3. Effluent discharges from OSDS,
4. Disposal of biosolids by land spreading (this was discontinued in 2005),
5. Creeks discharging into sinks,
6. Fertilizer application (separate from that applied at the sprayfields), and
7. Livestock wastes.

Well and Core Samples

Groundwater-level measurements were made in 108 wells in late May to early June 2006 to define the potentiometric surface of the UFA (app.; fig. 1). South of the SEF sprayfield, 10 new wells were installed as part of this study to infill gaps in the water level and water-quality coverage and to collect geologic cores (fig. 3; wells SE-22 and SE-53, SJ-1 to 10). Characteristics of all wells are given in the appendix. Surface-water gages maintained by the USGS on the Wakulla and St. Marks Rivers continuously measured discharges (gage locations shown on fig.1).

Water-quality sampling was conducted by the City and USGS for an extensive list of compounds to determine the effect of the SEF sprayfield on the UFA and Wakulla Springs. This work is being documented by Katz and others (2009) and only the data used for model calibration purposes will be discussed in this report. The wells, springs, and other sites sampled by the USGS, sampling dates, and the nitrate-N and chloride measurements, are included in table 2. In addition to water-quality sampling conducted specifically for this study, the City collects routine samples from many of the wells at the SEF sprayfield as part of their operating permit, and this water-quality data set also was used for model calibration. The USGS has sporadically sampled Wakulla Springs beginning in the 1960s and these data were used for this study.

The lithology and thickness of the UFA was not well described south of the SEF, so as part of the monitoring well drilling process a continuous core was collected from land surface to 476 ft bls at well SJ-7 well (fig. 3). The open hole was geophysically logged for fluid temperature, fluid resistivity natural gamma, spontaneous potential, 8, 16, 32, 64-inch (in.) formation resistivity, and diameter using a 3-arm caliper. The logs showed a substantial change in aquifer properties occurring in the interval from about 400 ft bls to the bottom at 476 ft bls. At these depths, the resistivity logs showed a lower resistivity in the water surrounding the borehole, indicating higher dissolved solids in the formation. The higher resistivity water (above about 400 ft bls) was interpreted to be part of the active freshwater flow system and the lower resistivity (below 400 ft bls) was interpreted not to be part of the freshwater flow system. In the interval from land surface to about 400 ft bls, the volume of rock recovered in the core barrel was often less than 50 percent (and sometimes zero), with numerous dissolution cavities being reported by the driller. Below about 400 ft bls, the cores showed little to no dissolution in the limestone, and the core recovery increased to 90 percent or more, indicating much lower effective

Table 2. Concentrations of nitrate-N and chloride in water samples from wells, springs, and Tallahassee sprayfield effluent.

[µS/cm; microsiemens per centimeter, °C; degrees Celsius, mg/L; milligrams per liter; <, less than]

Site identifier	Sampling date	Nitrate-N, in mg/L	Chloride, in mg/L
SJ-1	11/1/2005	1.6	13
SJ-2	11/1/2005	1.7	13
SJ-3	11/1/2005	0.36	4.4
SJ-4	11/1/2005	0.45	4.9
SJ-5	11/2/2005	0.31	5.7
SJ-6	11/2/2005	0.26	5.7
SJ-7	7/11/2006	0.21	5.6
SJ-8	7/11/2006	<0.06	4.9
SJ-9	7/11/2006	1.4	10
SJ-10	7/11/2006	1.3	9.5
SE-22A	10/29/2003	3.4	22
SE-22A	11/2/2005	3.8	24.2
SE-53	10/29/2003	5.5	33
SE-53	11/2/2005	4.8	34
Springs			
Wakulla Springs B- Tunnel	7/13/2006	0.90	8.2
Wakulla Springs	11/3/2005	0.54	7.7
Wakulla Springs	7/13/2006	0.49	7.7

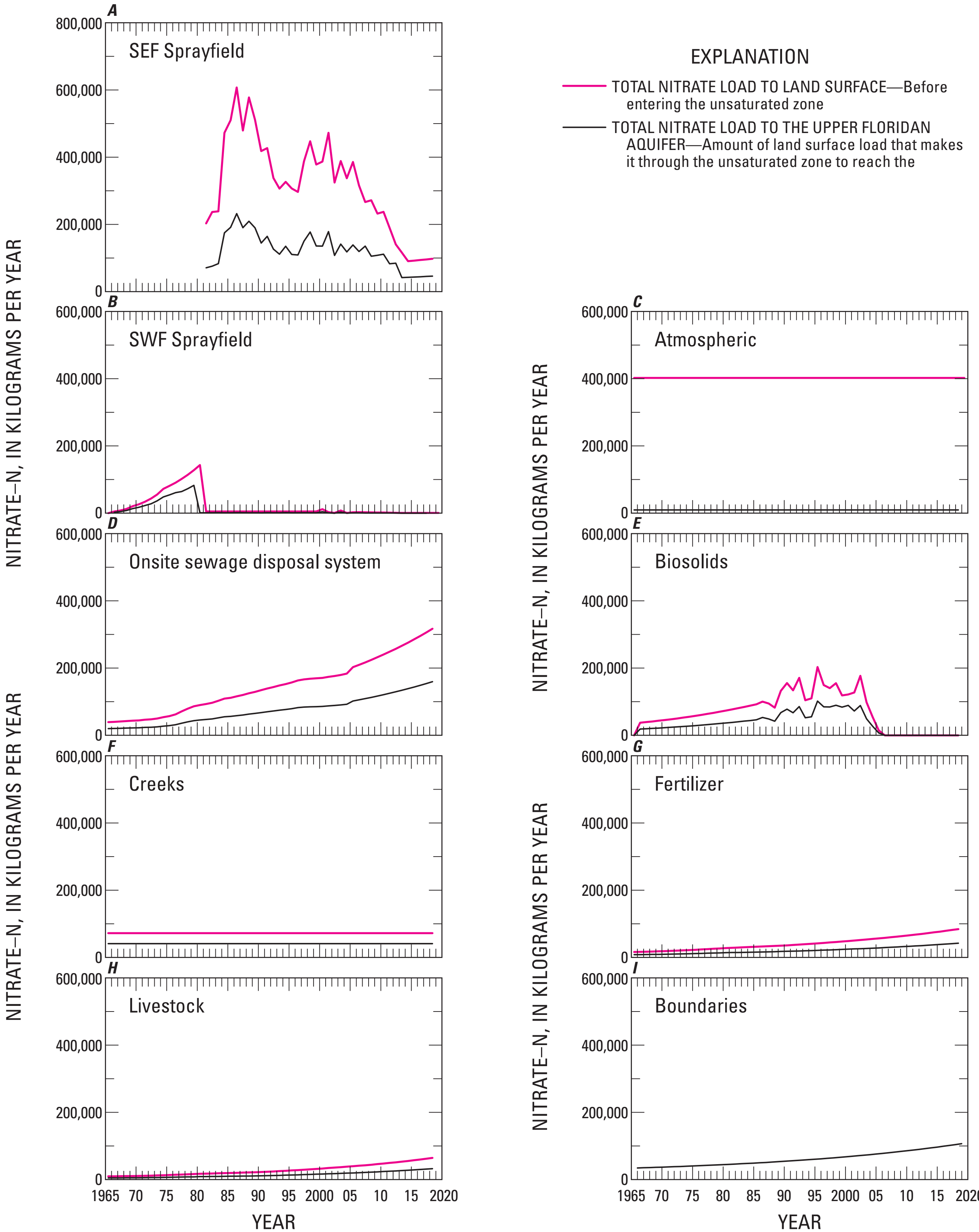


Figure 13. Nitrate-N loading to land surface and the Upper Floridan aquifer from 1966 through 2018.

porosity. Based on this discovery, the base of the freshwater flow system was assumed to be about 400 ft bls south of the SEF sprayfield, and was the supporting reason for revising Miller's (1986) map of the base of the UFA as discussed in the previous Hydrologic Setting section.

Nitrate-N Loading and Concentrations at Land Surface from Various Sources

Nitrate-N loading at land surface in this report refers to nitrate-N applied at or near land surface and is considered to be the mass entering the unsaturated zone. It represents an upper limit on the mass of nitrate-N that could reach the UFA. Nitrate-N is consumed by a range of biological processes (such as plant uptake or microbial processes) in the unsaturated zone; the mass that actually reaches the UFA will usually be less than the mass loaded at land surface. An eighth source of nitrate-N to the study area is the result of groundwater flowing across the boundaries (although this is not a loading to land surface). The load from each source was determined for each year from 1966 through about 2006 and extrapolated through 2018 based on population growth where applicable. Figure 13 summarizes the mass of nitrate-N loading per year at each source; it also shows the mass from each source that makes it through the unsaturated zone to reach the UFA, as determined from fate and transport modeling (discussed in a later section of this report).

Southeast and Southwest Sprayfields

The mass of nitrate-N in the wastewater effluent used for irrigation and fertilizer application is tracked by the City for both sprayfields. The total yearly mass of nitrate-N loaded to land surface at the SEF was calculated by summing the mass applied in the wastewater, the mass in rainfall, and the mass applied as fertilizer. At the SEF, the load peaked at about 600,000 kg/yr in 1986 (fig. 13*A*) when fertilizer application was highest; since 1986, the load has declined to about 320,000 kg/yr. This decline was due to a reduction and eventual elimination of fertilizer usage. A further decline to about 91,000 kg/yr is anticipated by 2013, based on planned improvements at the treatment plant that will reduce the wastewater nitrate-N concentration from about 12 mg/L to 3 mg/L.

The mass of nitrate-N loaded at land surface was converted to a concentration by dividing by the net recharge (net recharge is the sum of the irrigated volume plus rainfall volume minus the potential evapotranspiration). The SEF sprayfield nitrate-N concentration at land surface peaked at about 20 mg/L in the middle to late 1980s (fig. 14*A*). These relatively high values were a combination of the wastewater effluent concentration, ranging from 10 to 15 mg/L, and the heavy application of fertilizer. Dilution by rainfall reduced the nitrate-N concentrations somewhat and was greatest during heavy rainfall years. A steady decline in nitrate-N concentrations occurred from the mid-1980s until 2006; this

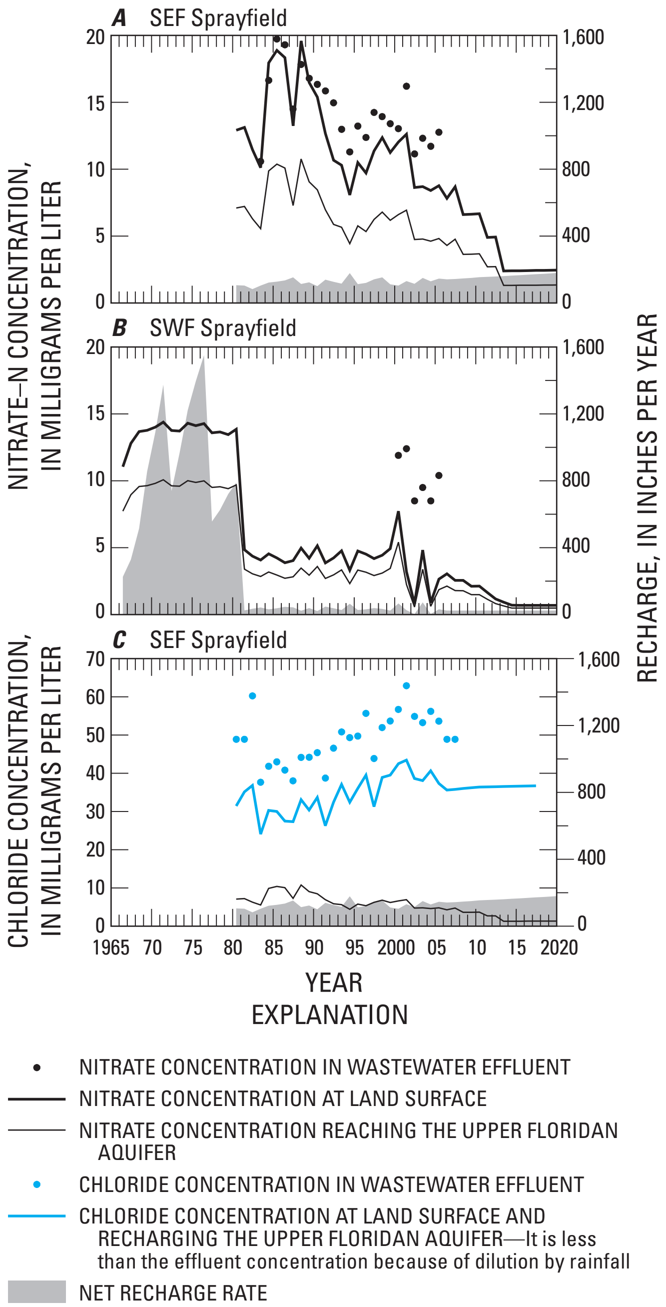


Figure 14. Nitrate-N and chloride concentrations and recharge rates at the Southeast Farm (SEF) and Southwest Farm (SWF) sprayfields. (Data from Jamie Shakar, City of Tallahassee, written commun., 2005).

was a result of an ongoing reduction in fertilizer usage. After 2006, the nitrate-N concentration is anticipated to decline further because of the complete elimination of fertilizer application and improvements at the wastewater treatment plant. The concentration of nitrate-N in the wastewater effluent is anticipated to be reduced to 3 mg/L by 2013; with rainfall dilution, the concentration at land surface will be about 2.5 mg/L. The net recharge rate at the SEF sprayfield ranged from a low of 83.4 in/yr in 1983 to 140.8 in/yr in 2006, and is anticipated to reach 175 in/yr in 2018 (fig. 14*A*) due to the increasing volumes of wastewater resulting from population growth.

The SWF sprayfield nitrate-N load at land surface was initially low in 1966 when disposal first began and peaked at about 140,000 kg/yr in 1980. The nitrate-N load abruptly decreased as wastewater effluent was diverted to the newly opened SEF sprayfield and has been under 10,000 kg/yr since 1980 (fig.13*B*). This facility was a pilot project to test irrigation techniques. Wastewater was sprayed on the land surface, thus resulting in high recharge rates because the land area available was relatively small.

The nitrate-N concentrations at land surface at the SWF sprayfield were within the 10 to 15 mg/L range during the highest recharge years of 1966 through 1980 (fig. 14*B*); from 1980 through 2007, the concentration was generally less than 5 mg/L. The nitrate-N concentration in the wastewater effluent from 1966 through 2007 generally stayed within the 10 to 15 mg/L range; irrigation rates were so high (exceeding 1,000 in/yr at times) that dilution by rainfall was minor. In contrast, irrigation rates from 1980 through 2007 were low (between 20 and 75 in/yr) and dilution by rainfall was important, yielding nitrate-N concentrations at land surface of about 5 mg/L or less. The concentration in the wastewater effluent is anticipated to be about 3 mg/L; the concentration at land surface will be about 0.7 mg/L based on assumed irrigation rates with rainfall dilution.

Atmospheric Deposition

Atmospheric deposition is one of the largest sources of nitrate-N loading to land surface. The dissolved inorganic nitrogen (nitrate-N plus ammonia) ranged from 0.15 mg/L to 0.28 mg/L and averaged 0.22 mg/L in 1999 (Chellette and others, 2002). Assuming a long-term average rainfall of 60 in/yr, a concentration of 0.22 mg/L, and a total area of 463 mi^2, the load at land surface was estimated to be about 400,000 kg/yr (fig. 13*C*); however, plants uptake most of this nitrate-N that is thinly spread over a large area.

Effluent Discharges from Onsite Sewage Disposal Systems

The yearly nitrate-N loading to land surface from OSDSs was determined by estimating the total number of OSDSs in the study area and multiplying that number by the nitrate-N load per OSDS. The actual number of OSDSs in Leon and Wakulla Counties was available for the years 1970 to 2005 (fig.15); however, the locations were available only in 2005 (fig. 16).

There were 39,043 OSDSs in Leon County in 2005 that included 8,026 in the study area. For years when the actual number of OSDSs in Leon County was not available, the number was estimated by using the county population number from the U.S. Census data and applying the proportion of 1 OSDS for every 6.838 county residents (this was the actual proportion in 2005). In the study area, there were 0.2056 OSDSs for every OSDS in the county (also the proportion in 2005) (fig. 15*A*). Chellette and others (2002) estimated that there were 2.42 people per OSDS in Leon County, with a water use of 55 gallons per person per day. The nitrate-N concentration in the effluent from OSDSs is hard to assess. According to a literature review by Otis and others (1993), total nitrogen in the effluent influent ranges from 35 to 100 mg/L. The U.S. Environmental Protection Agency (1980) estimated that the total nitrogen concentration in OSDS effluent ranges from 25 to 100 mg/L. For this study, the nitrate-N concentration in the effluent at the drain field (the concentration after all forms of nitrogen are converted to nitrate-N) was assumed to be 60 mg/L.

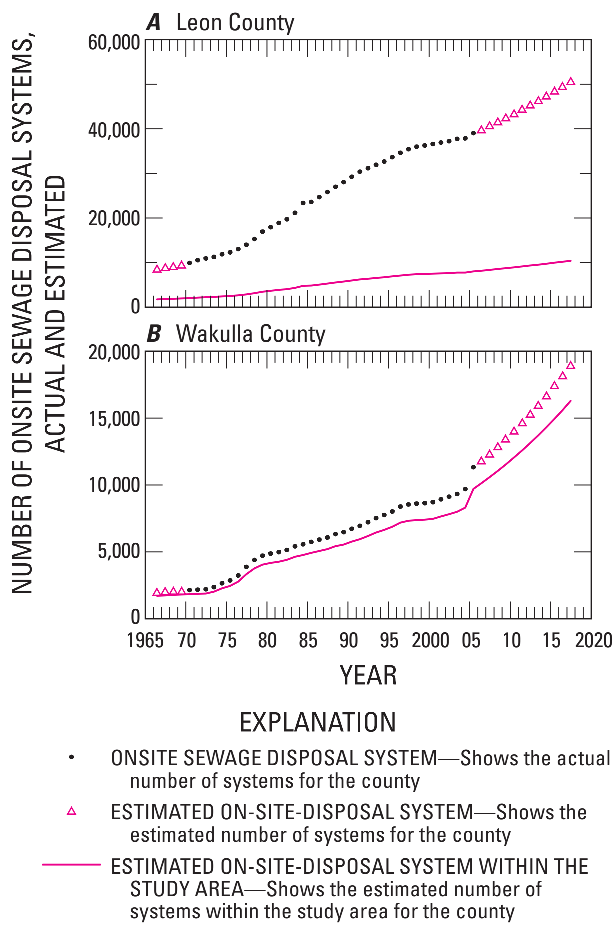
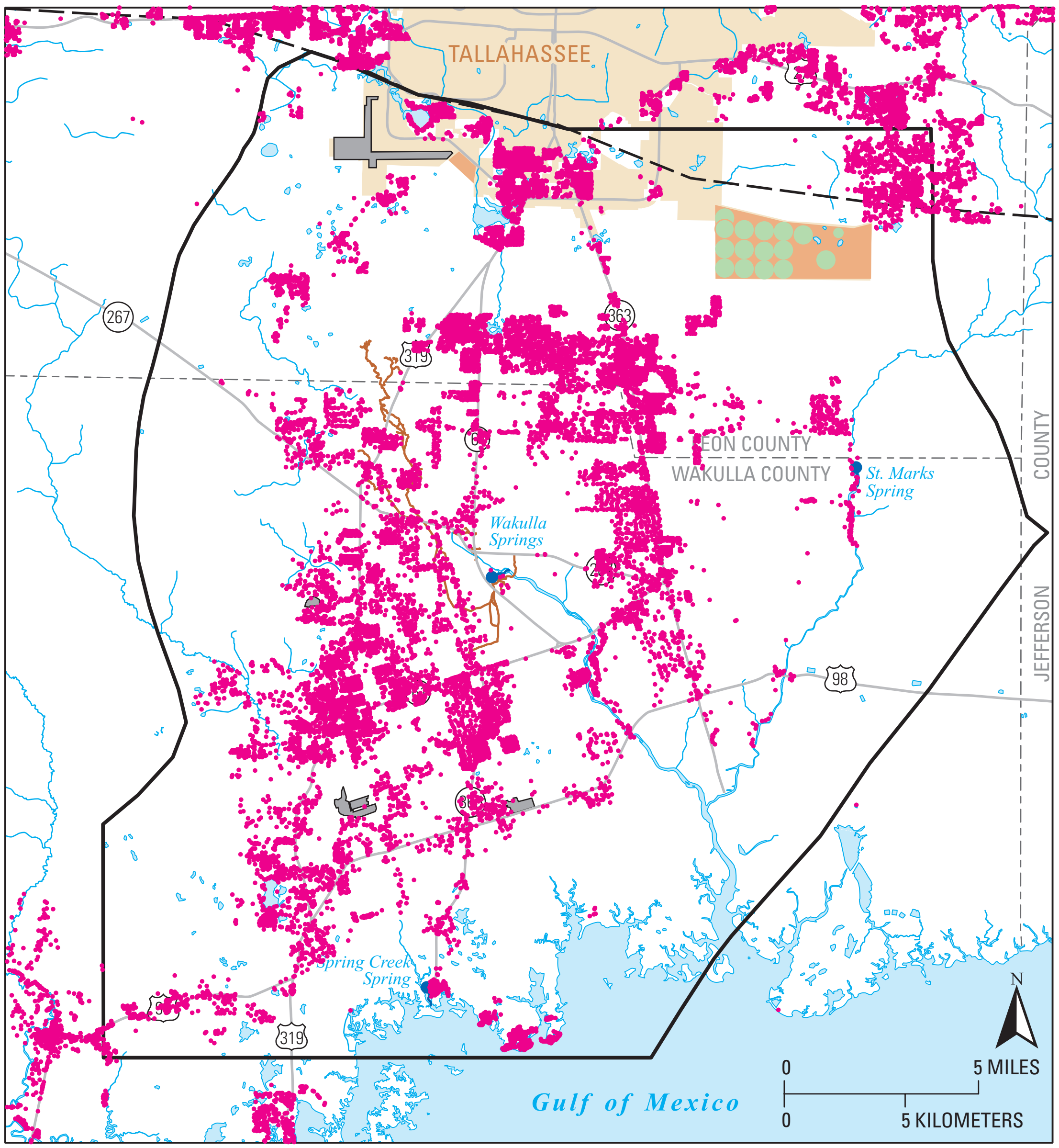


Figure 15. Actual and estimated number of onsite sewage disposal systems in *A*, Leon and *B*, Wakulla Counties from 1966 to 2018.



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

EXPLANATION

- RESIDUALS DISPOSAL AREA
- SPRAYFIELD LOCATION
- MODEL-SUBREGIONAL BOUNDARY
- CODY SCARP
- MAPPED SUBMERGED CAVES
- CENTER PIVOT LOCATION
- OSDS—onsite sewage disposal system
- SPRING LOCATION

Figure 16. Locations of onsite sewage disposal systems in Leon and Wakulla Counties in 2005.

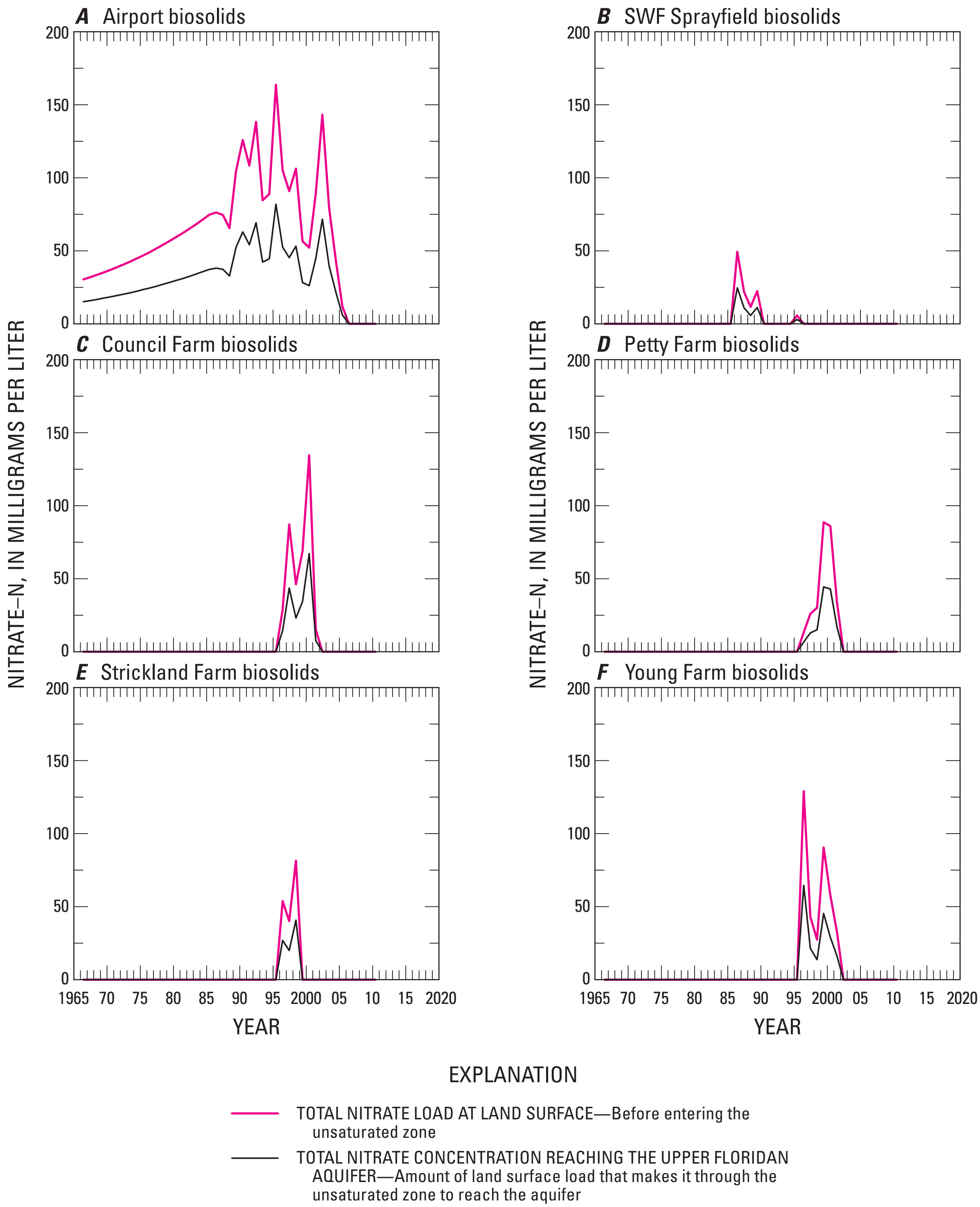


Figure 17. Land surface nitrate-N concentration and concentration recharging the Upper Floridan aquifer from biosolids disposal for the *A*, Tallahassee airport, *B*, Southwest Farm (SWF) sprayfield, and *C*, Council, *D*, Petty, *E*, Strickland, and *F*, Young farm sites (shown on fig. 1).

The number of OSDSs in the Wakulla County part of the study area was calculated using the same method as for Leon County (fig. 15*B*). In 2005, there were 11,334 OSDSs in Wakulla County that included 9,714 OSDSs in the study area, thus giving a proportion of 0.8571 OSDSs in the study area for every OSDS in Wakulla County. Chellette and others (2002) estimated 2.57 people per OSDS, a water use of 55 gallons per person, and a nitrate-N concentration in the effluent of 60 mg/L. Wakulla County is in the process of constructing sanitary sewers, so the estimated number of future OSDSs may be too high if a substantial number of additional sites are connected. In addition, Wakulla County has passed an ordinance requiring advanced OSDSs, which will reduce the concentration of nitrate-N going to the drain fields and will reduce the actual nitrate-N load. If this ordinance results in all the new OSDSs being advanced, and the conversion of a substantial number of existing OSDSs, then the actual load from OSDSs will be less than the load calculated here.

The total nitrate-N load at land surface (the load at the drain field) in both counties was calculated by multiplying the number of OSDSs, the number of persons per system (2.42 for Leon County and 2.57 for Wakulla County), a water use of 55 gallons per person, and a nitrate-N concentration of 60 mg/L. The result was 40,000 kg/yr of total nitrate-N in 1966, increasing to about 230,000 kg/yr in 2006. About 350,000 kg/yr of total nitrate-N is anticipated by 2018 fig.13*D*).

Disposal of Biosolids by Land Spreading

From 1966 to 2005, the City disposed of wastewater biosolids by land application, which consisted of spreading a thin layer across a large area. Most of the land application occurred at the City airport site (fig. 1); however, smaller volumes were disposed of from 1996 to 2005 at four sites (Council, Petty, Strickland, and Young farms; fig. 1). A total of 37,000 kg N/yr was applied in 1966 at all sites combined and this mass increased until it peaked at about 200,000 kg N/yr in 1995 (fig. 13*E*). Application of biosolids began to decrease in 1995 when the City started converting biosolids to fertilizer, thus reducing the amount disposed by land spreading. Disposal of biosolids stopped completely after 2005 when all of the biosolids were converted to fertilizer.

The airport location was not irrigated, so nitrate-N transport through the unsaturated zone was facilitated by rainfall infiltration only. The concentration at land surface was calculated by dividing this mass by the volume of net recharge at the site (fig. 17), which was based on an infiltration rate of 18 in/yr (Davis and Katz, 2007). The nitrate-N concentration at land surface sometimes approached or exceeded 100 mg/L at all but the SWF sprayfield site.

Creeks Discharging into Sinks

Munson Slough (discharging to Ames Sink), Fisher Creek (discharging to Fisher Creek Sink), Black Creek (discharging to Black Creek Sink), and Lost Creek (discharging to Lost Creek Sink) discharge surface water directly into the UFA within the study area (fig. 1). The average annual creek discharges are 30, 3, 10, and 60 ft^3/s, respectively (Chellette and others, 2002). The average total Kjeldahl nitrogen (TKN) concentrations measured during 2000 and 2001 were: Munson Slough at 0.51 mg/L, Fisher Creek at 0.74 mg/L, Black Creek at 1.00 mg/L, and Lost Creek at 0.74 mg/L (Chellette and others, 2002). Lost, Black, and Fisher Creek watersheds are predominantly within the Apalachicola National Forest and are relatively undisturbed, while the Ames Sink watershed is largely within the urbanized southern part of the City. It was assumed that about 65 percent of the total TKN was converted to nitrate-N. The nitrate-N load from creek discharges was calculated by multiplying the discharge of each creek by its nitrate-N concentration. The sum of these loads total about 70,000 kg/yr (fig. 13*F*).

Fertilizer Application

Chellette and others (2002) determined that the nitrate-N fertilizer countywide application rate for Leon County was 197,000 kg/yr in 1999; about 44,000 kg/yr was attributed to the SEF sprayfield while the remaining 153,000 kg/yr was attributed to residential use. Only the domestic-use value is used herein, because the fertilizer-use value for at the SEF sprayfield was included in its nitrate-N budget. The Leon County population in 1999 was estimated at 234,000, so the countywide application rate was 0.65 kg/yr per person. The Leon County population and countywide residential nitrate-N fertilizer load (based on 0.65 kg/yr per person) are shown in figure 18*A*. The ratio of the part of the study area in Leon County to the total area of the county is 0.2; the nitrate-N fertilizer load in the Leon County part of the study area was determined by multiplying this ratio by the countywide load (fig. 18*A*). The estimated nitrate-N load from fertilizer at land surface in the Leon County part of the study area was about 12,000 kg/yr in 1966, increasing to 35,000 in 2006, and is anticipated to reach about 45,000 kg/yr in 2018.

Chellette and others (2002) determined that the nitrate-N fertilizer load in the unconfined part of Wakulla County (which is the same as was used in this study) was 18,000 kg/yr in 1999. The Wakulla County population in 1999 was estimated at 22,000, so the countywide application rate was 0.82 kg/yr per person. The nitrate-N fertilizer load for other years was calculated by multiplying the population by this ratio (fig. 18*B*).The estimated nitrate-N load from fertilizer was about 4,600 kg/yr in 1966, increasing to 23,000 in 2006, and is anticipated to reach about 39,000 kg/yr in 2018. The total estimated nitrate-N load from fertilizer to land surface in the entire study area was about 17,000 kg/yr in 1966, increasing to 58,000 in 2006, and is anticipated to reach about 84,000 kg/yr in 2018 (fig. 13*G*).

Livestock Wastes

Chellette and others (2002) estimated that nitrate-N loading from livestock within the unconfined part of Leon County (which is the same area as the Leon County part of the study area) was 10,000 kg/yr in 2000. The Leon County population in 2000 was estimated to be about 240,000, so the nitrate-N loading rate from this source was about 0.042 kg/yr per person. The nitrate-N loading for other years was calculated by multiplying the population by this ratio. The estimated nitrate-N load from livestock to land surface in the Leon County part of the study area was about 3,800 kg/yr in 1966, increasing to 11,000 in 2006, and is anticipated to reach about 15,000 kg/yr in 2018 (fig. 19*A*).

Similarly, Chellette and others (2002) determined that the nitrate-N loading from livestock within the unconfined part of Wakulla County (which is the same area as the Wakulla County part of the study area) was 23,000 kg/yr in 2000. The Wakulla County population in 2000 was estimated to be about 23,000, so the nitrate-N loading from livestock was 1.0 kg/yr per person. The nitrate-N loading for other years was calculated by multiplying the population by this ratio. The estimated nitrate-N load was about 5,900 kg/yr in 1966, increasing to 30,000 in 2006, and is anticipated to reach about 50,000 kg/yr in 2018 (fig. 19*B*). The total nitrate-N load from animal wastes to land surface in the Leon and Wakulla County part of the study area was estimated to be about 9,700 kg/yr in 1966, increasing to 41,000 in 2006, and is anticipated to reach about 65,000 kg/yr in 2018 (fig. 13*H*).

During the calculation of these livestock nitrate-N loads, it was assumed that the livestock load would increase with population. This is a reasonable assumption for Wakulla County through 2018 because of its rural nature. There are no large commercial livestock operations in the county and livestock is generally held by individuals or small farms. An increase in population could result in more livestock (although it may not increase directly in proportion with population). The Leon County part of the study area also is rural and could have increased livestock for the next few years. Recently, a large property near the St. Marks River springs (fig. 1) was developed to pasture horses. Similar to Wakulla County, the

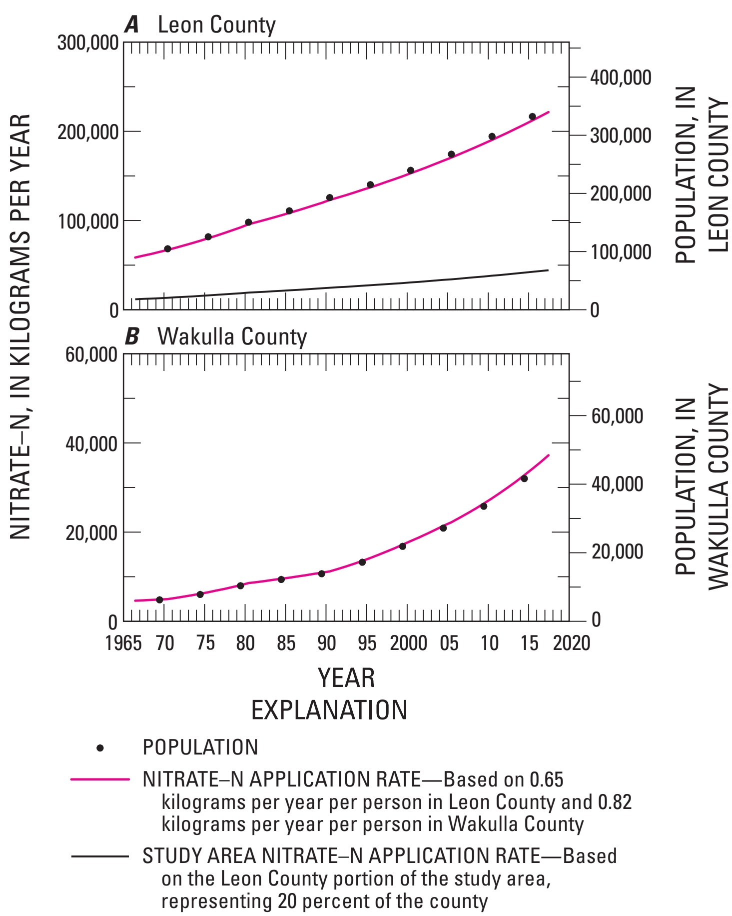


Figure 18. Nitrate-N load from domestic fertilizer application on *A*, Leon, and *B*, Wakulla Counties.

increase in population could result in an increase of livestock (although it may not increase directly in proportion with population). Fortunately, from a total mass perspective, the nitrate-N from livestock is the smallest input, so an error in its calculation should not markedly bias the result.

Nitrate-N and Chloride Concentrations in the Upper Floridan Aquifer and Wakulla Springs

As part of this study, changes in nitrate-N concentrations in groundwater and springs over time were documented. As anticipated, some sources have had better monitoring than other sources. The best data set was probably collected at the City sprayfields because monitoring wells were installed and sampled at both sprayfields before they became operational. Selected wells have been sampled ever since, and new wells have been added as the SEF sprayfield expanded. In addition, the 10 new monitoring wells that were installed and sampled downgradient from the SEF sprayfield are part of this study. The four wells selected as examples are SE-22, SE-53, SJ-1, and SJ-9 (fig. 3). Well SE-22 was installed before the SEF sprayfield became operational in November 1980 and is located on the downgradient edge of center pivots 1-7; SE-53 was installed before center pivots 10 and 13 became operational in March 1986 and is on the downgradient edge of these two center pivots; wells SJ-1 and SJ-9 were installed in 2005 and 2006, respectively, and are located approximately 1 and 2 mi downgradient from the sprayfield (fig. 3). The nitrate-N concentration in well SE-22 began to increase from the background levels of 0.2 mg/L within months of center pivots 1-7 becoming operational (fig. 20), peaking in the late 1980s at about 8 mg/L (coinciding with the highest levels of fertilizer application), and stabilizing at about 5 mg/L after 1995. This well had the highest nitrate-N concentration of any well along the downgradient boundary of the sprayfield. The chloride concentrations also began to increase from background levels of 5 mg/L within months of the sprayfield becoming operational, and have continued to increase ever since (fig. 20). The nitrate-N concentrations in well SE-53 began to increase from a background level of about 0.2 mg/L within

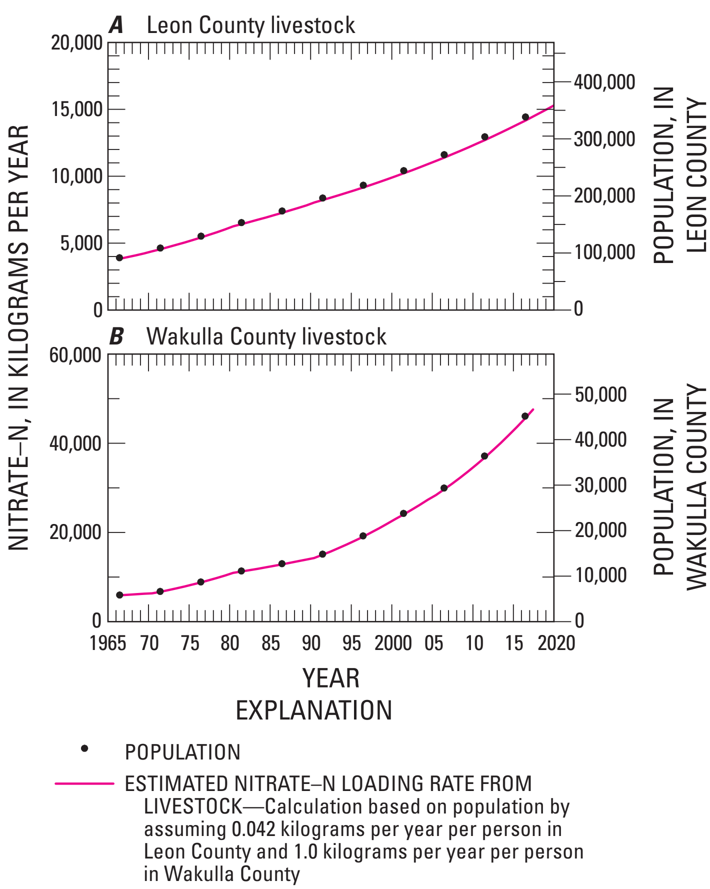


Figure 19. Nitrate-N loading from animal wastes on *A*, Leon, and *B*, Wakulla Counties.

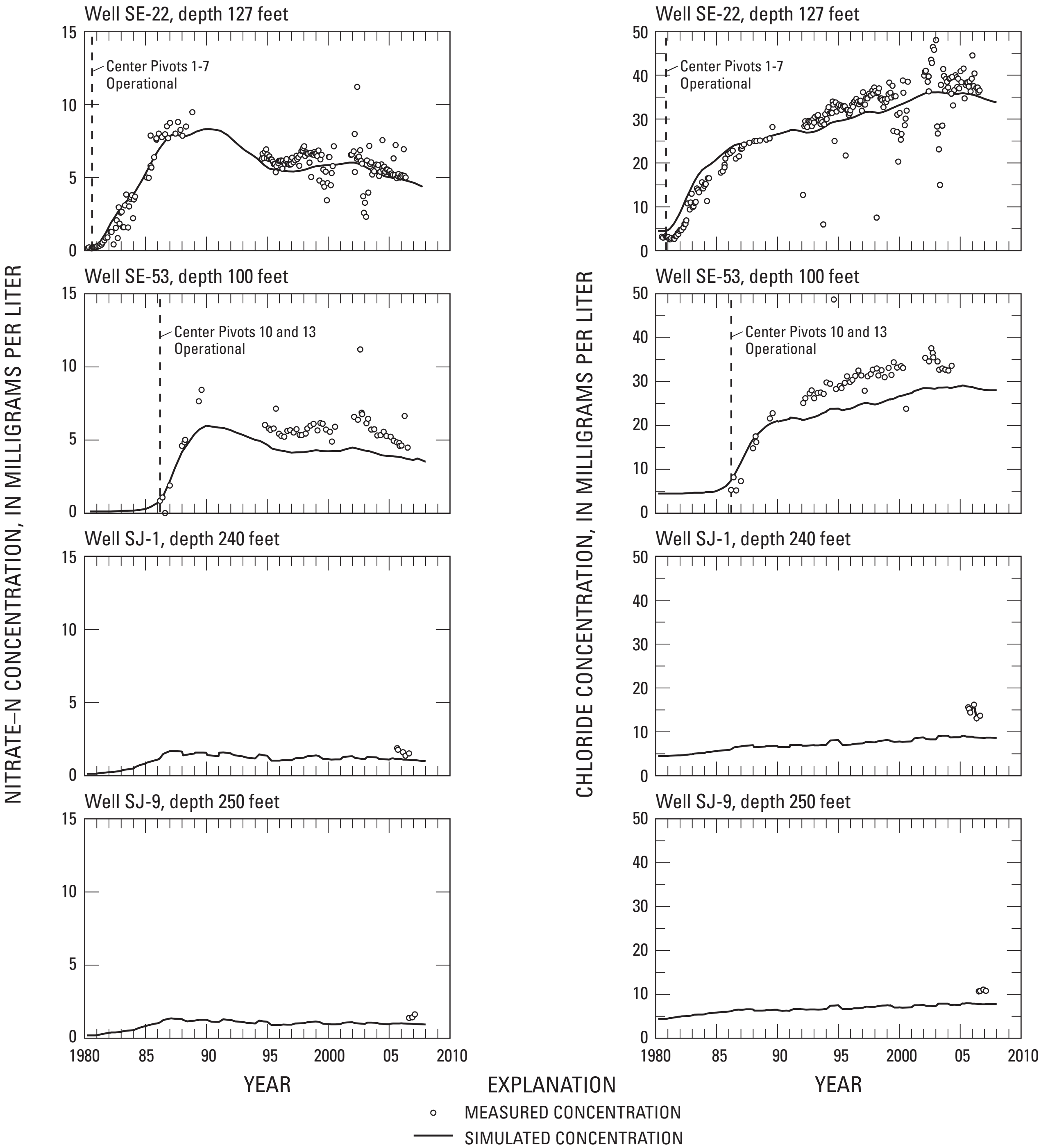


Figure 20. Measured and simulated nitrate-N and chloride concentrations in wells SE-22, SE-53, SJ-1, and SJ-9 (well locations shown on fig. 3).

months of center pivots 10 and 13 becoming operational, peaking in the late 1980s at about 7 mg/L, stabilizing at about 6 mg/L from 1990 to 2003, and declining to about 5 mg/L by 2006. The nitrate-N concentrations in the two new wells SJ-1 and SJ-9 were measured during the period between 2005 and 2006. The nitrate-N concentrations in well SJ-1 (about 1 mi south of the SEF sprayfield boundary) averaged 1.63 mg/L in five measurements; the concentrations in well SJ-9 (about 2 mi south of the SEF boundary) averaged 1.48 mg/L in three measurements (fig 20). Both of these wells showed substantially lower nitrate-N concentrations than did wells at the SEF sprayfield. Correspondingly, the chloride concentrations in both of these wells were substantially lower than values measured at the SEF sprayfield.

Some limited groundwater-quality monitoring also occurred at the airport and SWF sprayfield biosolids disposal area (fig. 3*B*). Well SF-02, located at the southern end of the airport biosolids spreading area (fig. 3), had nitrate-N concentrations ranging between about 9 and 23 mg/L from 1985 to 1990 (fig. 21*A*). This variability was probably because the varying amounts of disposal volume each year and the practice of rotating the points of disposal prevented excessive loading in any one area. The nitrate-N concentration in monitoring well LS-25 at the southern boundary of the SWF sprayfield showed a wide variation, ranging between about 3 and 10 mg/L between 1992 and 2006 (fig. 21*B*). The variability was probably due to the combination of a variable center pivot irrigation schedule and the irregular land spreading of biosolids.

The nitrate-N concentration in Wakulla Springs has been monitored for many years and was about 0.2 mg/L in 1966, increasing to 1.7 mg/L in the early 1990s, then declining to

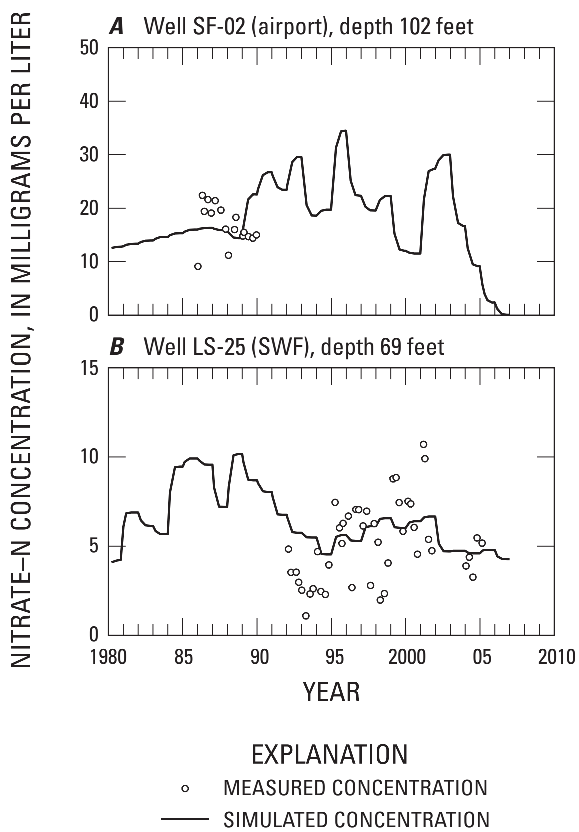


Figure 21. Measured and simulated nitrate-N concentrations in wells *A*, LS-25 and *B*, SF-02 (well locations shown on fig. 3).

about 0.5 mg/L in 2007. The chloride concentration has been steadily increasing during the same period (fig. 22). The A-tunnel had the lowest concentration of nitrate-N of all the tunnels and was generally less than 0.5 mg/L from 2004 to 2006. The B- and C-tunnels had the highest concentrations of nitrate-N of all the tunnels. In the B-tunnel, nitrate-N was between 0.90 and 0.95 mg/L from 2004 to 2006; the chloride concentration was about 9.0 mg/L during the same period. The nitrate-N concentration in the C-tunnel was between 0.85 and 0.90 mg/L from 2004 to 2006. The chloride concentration was about 9.0 mg/L during the same period.

The measured nitrate-N concentrations from 2004 to 2006 in Wakulla Springs, A-, B-, C-, and D-tunnels also are shown on table 3. The concentration in Wakulla Springs is the result of the mixture of waters from A-, B-, C-, and D-tunnels. The concentration of nitrate-N in the B-tunnel equaled or exceeded 0.9 mg/L and the concentration in C-tunnel was at or near 0.9 mg/L from 2004 to 2006. The D-tunnel had concentrations that were very near or above 0.8 mg/L, except for the last measurement of 0.63 mg/L in April 2005. In contrast, the nitrate-N concentrations in the A-tunnel were below 0.5 mg/L, except for the last measurement of 0.55 mg/L in April 2005. The nitrate-N concentration in Wakulla Springs has always been between the relatively high levels in the B-, C- and D-tunnels and the relatively low levels in the A-tunnel. Low flow from Wakulla Springs during November 2004 produced discharges of 411 ft^3/s and nitrate concentrations of 0.70 mg/L; low flow from Wakulla Springs during April 2005 produced discharges of 366 ft^3/s and nitrate-N concentrations of 0.75 mg/L. In contrast, high flow from Wakulla Springs during November 2005 produced discharges of 624 ft^3/s and nitrate concentrations of 0.54 mg/L; high flow from Wakulla County during July 2006 produced discharges of 710 ft^3/s and nitrate-N concentrations of 0.49 mg/L. This finding indicates that during periods of low flow, the nitrate-N concentration in Wakulla Springs tended toward the levels in the B-, C-, and D-tunnels. During periods of high flow, the concentrations tended toward levels in the A-tunnel. These data support the groundwater divide postulated by Kincaid (1999), in which the divide can shift to the south, resulting in more water from the A/R-tunnel going northward to Wakulla Springs. During these high flows in Wakulla Springs, the surface-water flow in the Sopchoppy River was at some of the lowest levels since gaging began in 1964, thus indicating that there was virtually no surface water flowing into the local sinks. Therefore, the changing flow and nitrate-N concentrations in Wakulla Springs was not the result of greater surface-water influx, but the result of a changing volume of groundwater in the A-tunnel moving northward toward Wakulla Springs rather than southward toward the Spring Creek Springs Group.

Table 3. Nitrate-N concentration in Wakulla Springs vent and tunnels from 2004 to 2006.

[mg/L; milligrams per liter; ft^3/s; cubic feet per second, ns, not sampled]

Sampling date	Wakulla River flow, in ft^3/s	Nitrate-N concentration at indicated location, in mg/L				
		Wakulla Spring vent	A-Tunnel	B-Tunnel	C-Tunnel	D-Tunnel
4/12/2004	ns	.62	0.41	.91	.85	.82
8/2/2004	ns	.65	.45	.93	.89	.79
11/1/2004	411	.70	.49	.95	.90	.86
1/31/2005	522	.63	.40	.90	.86	.82
4/25/2005	366	.75	.55	.90	.90	.63
11/3/2005	624	.54	ns	ns	ns	ns
7/13/2006	710	.49	ns	.90	ns	ns

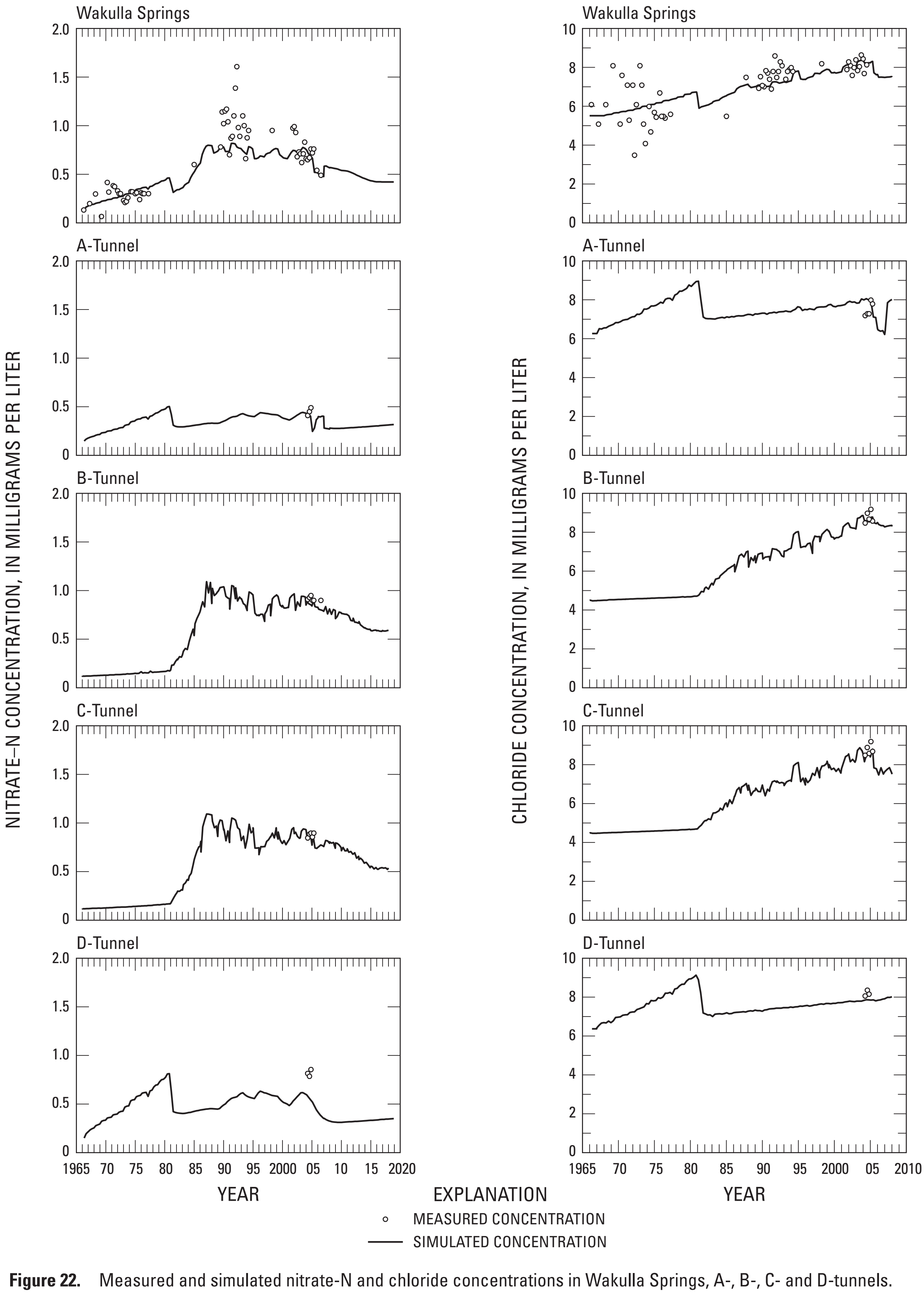


Figure 22. Measured and simulated nitrate-N and chloride concentrations in Wakulla Springs, A-, B-, C- and D-tunnels.

Model Development

Movement of nitrate-N in groundwater was simulated using computer models that required a two-step process. The first step was to develop and calibrate a model to simulate groundwater flow in the study area. The second step was to develop and calibrate a solute transport model to simulate nitrate-N movement. The output of the groundwater flow model was used as an input to the solute transport model. Hence, it was necessary to develop the groundwater model first.

Groundwater Flow Model Description and Calibration

The development of the groundwater flow model was another two-step process. The first step was to use recently collected data to recalibrate an existing regional steady-state groundwater flow model, which extends out to the natural groundwater boundaries (fig. 1). The second step was to develop a finer grid subregional transient model to simulate groundwater flow within the study area, with the boundary conditions at the perimeter of the subregional model set using the regional model. The transient subregional model was constructed to simulate the period from January 1, 1966, through December 31, 2018. The start date of January 1, 1966, was selected because the SWF sprayfield began operations that year. The end date of December 31, 2018, was selected because the planned reduction in nitrate-N to 3 mg/L in the wastewater effluent by 2014 will have had time to be fully reflected in the nitrate-N levels in Wakulla Springs. Both the regional and subregional models used the USGS Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) computer code (Harbaugh and others, 2000).

The regional model, documented by Davis and Katz (2007), was recalibrated for this study. This model encompasses the entire springsheds for the St. Marks River springs, Wakulla Springs, and the Spring Creek Springs Group (fig.1), and will be referred to in this report as the regional model. The regional model has four layers that encompass most of the simulated area. Layers 1 and 2 simulate the surficial aquifer and the low-permeability Hawthorn clays that overlie the UFA, layer 3 represents the upper 200 ft of the UFA, and layer 4 extends from layer 3 to the bottom of the UFA aquifer (fig. 4). The regional model has 241 rows and 265 columns. The largest cells are 10,290 × 10,290 ft, and the smallest cells are 400 × 400 ft. The simulated water levels determined by the regional-scale model are used to set the water levels in specified-head cells at the boundaries of the subregional model (described next). The regional model has a coarser grid than the subregional model, so the heads were linearly extrapolated where required.

The subregional model was inset within the regional model (fig. 1). It consists of only two layers because of the near absence of the overlying surficial aquifer and Hawthorn clays. The subregional model grid consists of 288 rows and 258 columns (fig. 23) with the UFA divided into two model layers; all of the model cells are 500 ft × 500 ft horizontally. The UFA tops, bottoms, and thicknesses are the same as for the regional model. Rivers were simulated using the Drain Package (Harbaugh and others, 2000). The Wakulla and St. Marks Rivers begin as very large springs, but small springs also contribute along their way to the Gulf of Mexico, thus indicating that both of these rivers are gaining water over their entire length. The Drain Package can simulate this activity without allowing the rivers to lose water to the aquifer (which does not appear to be happening). Transient groundwater flow was simulated so that the changing volume of recharge at the two sprayfields could be simulated; in areas other than the sprayfields, recharge rates were steady state and taken from the regional model. Transient stress periods for the model were updated yearly, except where substantial hydrologic changes occurred at midyear, such as when center pivots 1-7 at the SEF sprayfield became operational (table 4). The starting heads for the transient model were established by running the model as steady state for the hydrologic conditions in 1966, which was the first year of the transient simulation. The subregional model was used to simulate two groundwater flow scenarios because of the uncertainty about how much groundwater was flowing to Wakulla Springs and the Spring Creek Springs Group. In scenario 1, the simulation starting date was January 1, 1966, and the ending date was December 31, 2018 (table 4). In this scenario, groundwater discharge from Wakulla Springs and Springs Creek Springs Group was approximately equal (where groundwater flow in the R-tunnel divided at the A/K-tunnels with some water going to Wakulla Springs and some water going to the Spring Creek Springs Group). An exception to this scenario was the interval from May 5, 2005, to January 1, 2007, when all of the flow in the A-, K-, and R-tunnels went to Wakulla Springs. In scenario 2, the simulation starting date was January 1, 2007, and ended on December 31, 2018, and all of the flow in the A-, K-, and R-tunnels went to Wakulla Springs. This was a continuation of the conditions that occurred in scenario 1, from May 1, 2005, to January 1, 2007. Hydrologic conditions can cause groundwater flow in the A-, K-, and R-tunnels to shift quickly from going to Wakulla Springs to going to the Spring Creek Springs Group and back again. If this occurs repeatedly in the interval from January 1, 2007, to December 31, 2018, which is likely, then neither scenario will be exactly correct, but the two scenarios should bracket the actual conditions.

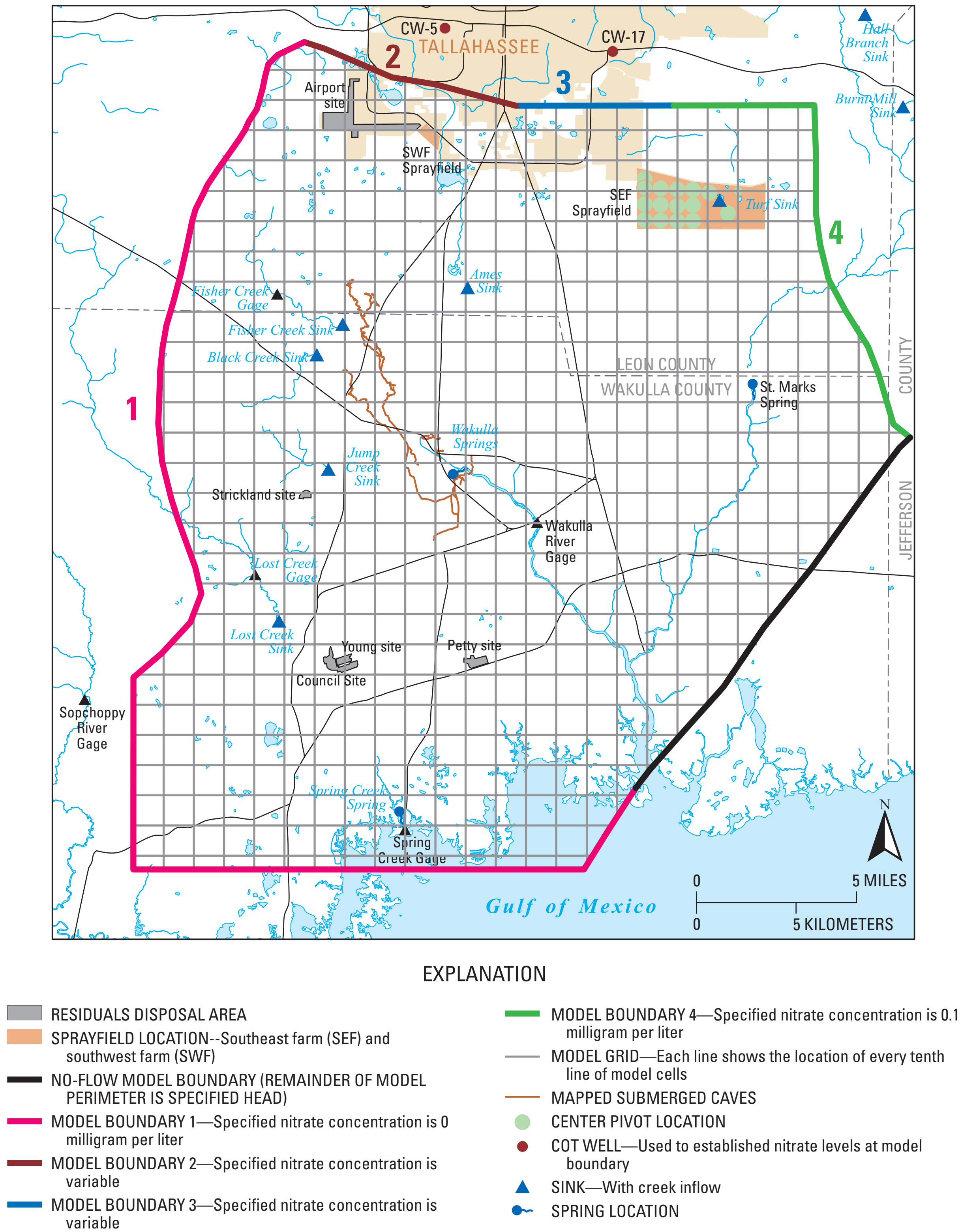


Figure 23. Finite-difference grid (every tenth cell boundary shown) and general locations for boundary conditions for the subregional groundwater flow and solute transport models.

Table 4. Transient stress periods for the subregional groundwater flow and solute transport models from January 1, 1966, to December 31, 2018.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; --, not simulated]

Start date of stress period	Stress period length, in days	Scenario 1: 1/1/1966 through 12/31/2018	Scenario 2: 5/1/2005 through 12/31/2018
1/1/1966	365	Start of scenario 1. SWF sprayfield becomes operational. Almost all flow in A/R-tunnel is going to Spring Creek Springs Group	--
1/1/1967	365		--
1/1/1968	366		--
1/1/1969	365		--
1/1/1970	365		--
1/1/1971	365		--
1/1/1972	366		--
1/1/1973	365		--
1/1/1974	365		--
1/1/1975	365		--
1/1/1976	366		--
1/1/1977	365		--
1/1/1978	365		--
1/1/1979	365		--
1/1/1980	305		--
11/1/1980	61	SEF sprayfield becomes operational when center pivots 1-7 begin operation in November 1980	--
1/1/1981	365		--
1/1/1982	59		--
3/1/1982	306	SEF sprayfield center pivots 8, 9, 11, and 12 begin operation in March 1982	--
1/1/1983	365		--
1/1/1984	366		--
1/1/1985	365		--
1/1/1986	59		--
3/1/1986	306	SEF sprayfield center pivots 10 and 13 begin operation in March 1986	--
1/1/1987	365		--
1/1/1988	366		--
1/1/1989	365		--
1/1/1990	365		--
1/1/1991	365	Model calibrated to water-level and discharge data collected in November 1991	--
1/1/1992	366		--
1/1/1993	365		--
1/1/1994	365		--
1/1/1995	365		--
1/1/1996	366		--
1/1/1997	365		--

Table 4. Transient stress periods for the subregional groundwater flow and solute transport models from January 1, 1966, to December 31, 2018—Continued.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; --, not simulated]

Start date of stress period	Stress period length, in days	Scenario 1: 1/1/1966 through 12/31/2018	Scenario 2: 5/1/2005 through 12/31/2018
1/1/1998	365		--
1/1/1999	90		--
4/1/1999	275	SEF sprayfield center pivots 14-16 begin operation in April 1999	--
1/1/2000	366		--
1/1/2001	365		--
1/1/2002	365		--
1/1/2003	365		--
1/1/2004	366		--
1/1/2005	120		--
5/1/2005	245	Almost all flow in A/R-tunnel going to Wakulla Springs	--
1/1/2006	365	Model calibrated to water-level and discharge data collected in late May to early June 2006	--
1/1/2007	365	Flow in A/R-tunnel is going to both Wakulla Springs and Spring Creek Springs Group	Start of Scenario 2. Almost all flow in A/R-tunnel diverted to Wakulla Springs. The nitrate-N distribution and water levels from Scenario 1 at time 1/1/2007 was the starting distribution for Scenario 2.
1/1/2008	366		
1/1/2009	365		
1/1/2010	365		
1/1/2011	365		
1/1/2012	366		
1/1/2013	365		
1/1/2014	365		
1/1/2015	365		
1/1/2016	366		
1/1/2017	365		
1/1/2018	365		
12/31/2018	365	End of simulation	End of simulation

Subregional Model Geometry

The top of model layer 1 is the same as the top of the UFA (fig. 5) and its thickness is a uniform 200 ft; the bottom of model layer 1 is shown in fig. 24. The top of model layer 2 coincides with the bottom of model layer 1 and the bottom of model layer 2 is the bottom of the UFA (fig. 6); the thickness of model layer 2 is variable (fig. 25), exceeding 1,000 ft in the west but thinning to about 200 ft in the central and coastal areas. The thin veneer of sands, silts, and clays present at land surface was not included in the simulation of layer 1.

Boundary Conditions

The lateral boundary conditions for both layers 1 and 2 are shown in figure 23. The southeastern perimeter is a no-flow boundary because it follows a groundwater flow line as delineated by the regional model. Specified heads were assigned to the remainder of the model perimeter; the head values were taken from the regional groundwater flow model. The regional flow model was steady state, so the specified head values were not changed during the subregional model simulations.

Simulated Hydraulic Conductivities

The calibrated horizontal hydraulic conductivities in layer 1 ranged from 10 to 10,000 ft/d (fig. 26) and in layer 2 ranged from 10 to 5,000,000 ft/d (fig. 27). The highest conductivities in layer 2 occurred where submerged caves were simulated. Caves were simulated to be present in the model using the following criteria:

1. Where caves were known to exist based on maps created by divers;
2. Where numerous sinkholes indicated the presence of heavy dissolution in the subsurface;
3. Where a tracer test from Turf Sink to Wakulla Springs showed a traveltime of 40 days, indicating that either a cave, or at least a very permeable pathway exists (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006);
4. Where high tannic flows into Lost Creek Sink result in outflows of tannic water at the Spring Creek Springs Group, indicating a direct connection; and
5. Where cave divers observed that the water was flowing southward at times and the cave continued from the southernmost tip of the mapped Wakulla Springs caves toward the Spring Creek Springs Group.

The high conductivities in the simulated caves generally cause groundwater to flow toward them and they tend to transmit a large quantity of water, which results in high groundwater velocities. The vertical hydraulic conductivities were set equal to the horizontal hydraulic conductivities because the aquifer consists of very permeable limestone with no known clay (or other horizontal low permeability) layers. For reasons discussed earlier, caves were assumed to be predominantly in the deeper part of the aquifer and were generally simulated in layer 2. However, where springs occurred, caves were simulated in layer 1.

Simulated Recharge to the Upper Floridan Aquifer

Recharge to the UFA within the study area comes from several sources. These sources are defined in order of importance as:

1. Inflow across the lateral boundaries of the study area,
2. Net precipitation (rainfall minus evapotranspiration),
3. Creek flow into sinkholes,
4. Irrigation at the SEF and SWF sprayfields, and
5. Discharges from OSDSs (table 5).

Simulated groundwater flowing across the model boundaries was the single largest source of groundwater to the model and totaled 926 ft^3/s (table 5). This inflow was simulated using constant head cells along the perimeter, as discussed earlier.

The second largest source of recharge to the model, 500 ft^3/s, was from net precipitation (fig. 28; table 5). The net precipitation rates were taken from the steady-state regional groundwater model and also were steady state; an exception was at the SEF and SWF sprayfields where the rates were transient. Net precipitation was a constant 18 in/yr throughout most of the study area, but was as low as 1.8 in/yr in the southwest corner where shallow clays impeded infiltration. At the SWF sprayfield, the simulated recharge rate exceeded 1,000 in/yr in the period before the SEF sprayfield became operational (November 1980) and was generally less than 50 in/yr afterwards (fig. 14). At the SEF sprayfield, the simulated recharge rate generally ranged from between 100 and 200 in/yr. Recharge was simulated using the Recharge Package (Harbaugh and others, 2000). The application rate at the SWF sprayfield was about 1 ft^3/s in 1966 (when it became operational), increasing to 11 ft^3/s in 1980 and then decreasing substantially after the SEF began operations. The application rate at the SEF sprayfield was about 11 ft^3/s in November 1980 and is anticipated to reach about 30 ft^3/s by 2018.

The third largest source of recharge to the model was creeks discharging into sinks. The simulated recharge to the UFA from all creeks combined was 103 ft^3/s. Creek inflows were simulated using the Well Package (Harbaugh and others, 2000); the simulated groundwater inflow rates for the individual creeks are shown in table 5.

A relatively minor source of water to the UFA was the discharge from OSDSs. These were simulated using the Well Package (Harbaugh and others, 2000). In 2005, there were 8,026 OSDSs in the Leon County part of the study area (fig.15) and 9,714 OSDSs in the Wakulla County part of the study area. The only year when the actual number and locations of all OSDSs was documented was 2005; for other years, only the estimated number of OSDS was known. Based on the work by Chellette and others (2002), an average discharge rate of 133 gallons per day (gal/d) per OSDS was calculated for Leon County and about 141 gal/d per OSDS for Wakulla County. Since it was not feasible to reconstruct the distribution of all OSDSs for each year of the modeling, the locations of all OSDSs known in 2005 were simulated for the entire period. The correct total volume of discharge from the OSDSs was simulated for each stress period using the following method:

1. The number of OSDSs for each year was multiplied by 133 gal/d per system for Leon County and 141 gal/d per system for Wakulla County, thus providing the total OSDS recharge for each county (fig. 29);
2. The total discharge was then divided by 8,026 for Leon County and 9,714 for Wakulla County to give the discharge rate assigned each OSDS simulated for that year.

Within the Leon County part of the study area, the simulated OSDS inflow increased from 0.3 ft^3/s (which occurred in 1966) to 2.3 ft^3/s (which occurred in 2018), and inflow in Wakulla County increased from 0.34 ft^3/s (which occurred in 1966) to 3.7 ft^3/s (which occurred in 2018; table 5).

Subregional Model Calibration

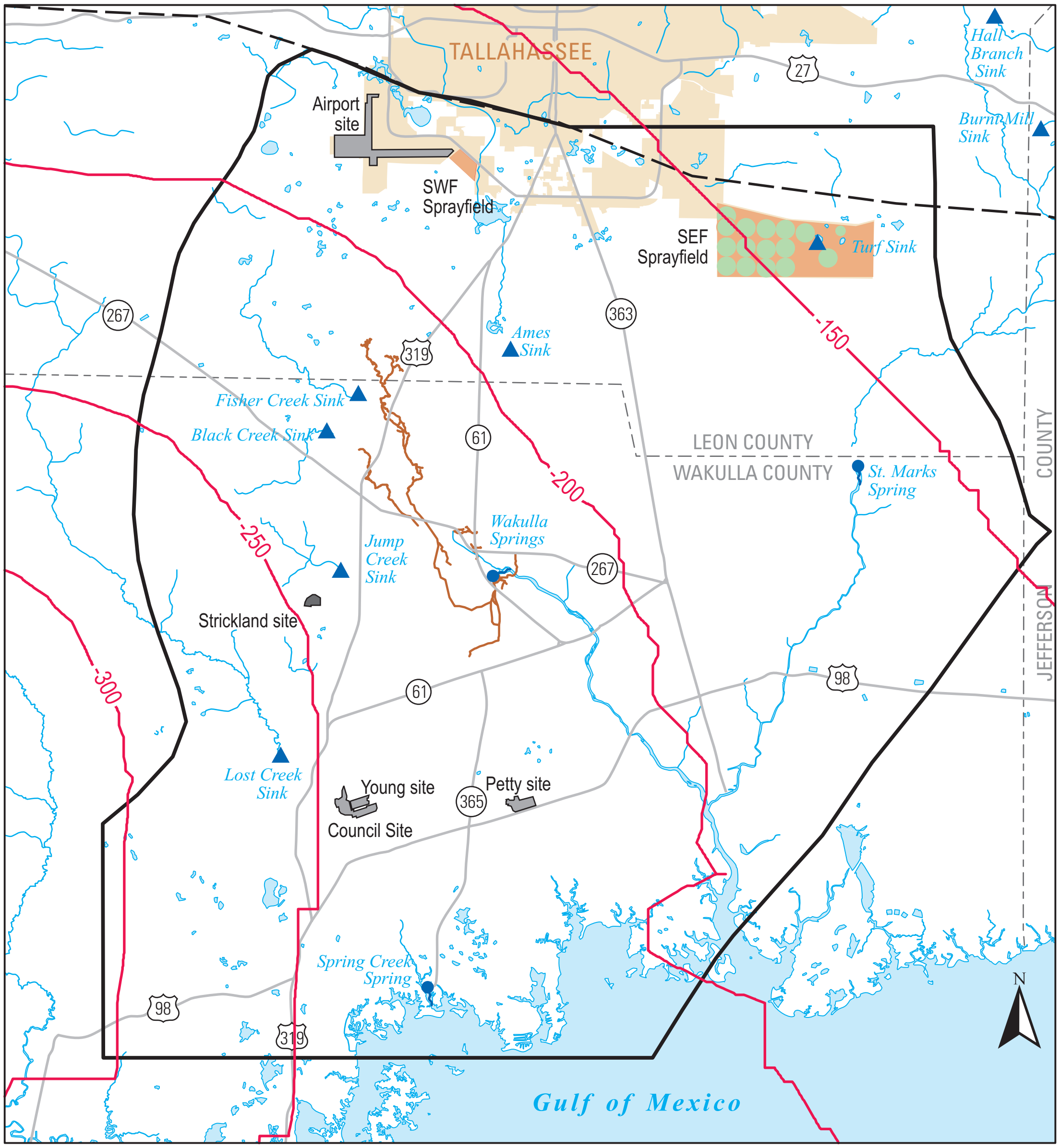
The subregional model simulated transient groundwater flow from 1966 when the first City sprayfield began operation, through 2018 when effects of upgrades at both City sprayfields should have had time to work their way through the groundwater flow system. Since 1966, comprehensive water-level and river discharge measurements have occurred twice — once in November 1991 and again in late May to early June 2006. Thus, the subregional groundwater model was calibrated to these data sets. The transient model was run from 1966 through 1991 and the results were compared to the November 1991 data set; the model run was then continued through 2006 and the results were compared to the late May to early June 2006 data set.

The model was calibrated using a trial and error process and consisted mostly of varying the hydraulic conductivities, especially the conductivities of the simulated conduits. The subregional model used the same aquifer parameters as the regional model, except for a few modifications. The most important modification in the subregional model was the simulation of submerged conduits using the high hydraulic conductivity zones in layer 2 (fig. 27). These zones could be included in the finer grid subregional model, but not in the larger grid regional model, and were necessary to match the changing flows observed in Wakulla Springs, as well as the high groundwater flow velocities measured by tracer tests.

Table 5. Simulated sources of recharge to the Upper Floridan aquifer.

[ft^3/s, cubic feet per second; OSDS, onsite sewage disposal system; SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield]

Groundwater input source		Groundwater flow rate, in ft^3/s	
Flow across model boundaries:			
Zone 1		98	
Zone 2		67	
Zone 3		40	
Zone 4		721	
Subtotal for boundaries		926	
Recharge from net precipitation		500	
Creek inflows:	Ames Sink	30	
	Black Creek Sink	3.0	
	Fisher Creek Sink	10	
	Lost Creek Sink	60	
Subtotal for creeks		103	
		Min	Max
OSDS flows –Leon County		0.0	2.3
OSDS flows –Wakulla County		0.4	3.7
SWF Sprayfield		1	11
SEF Sprayfield		11	30
Totals		1,531	1,576



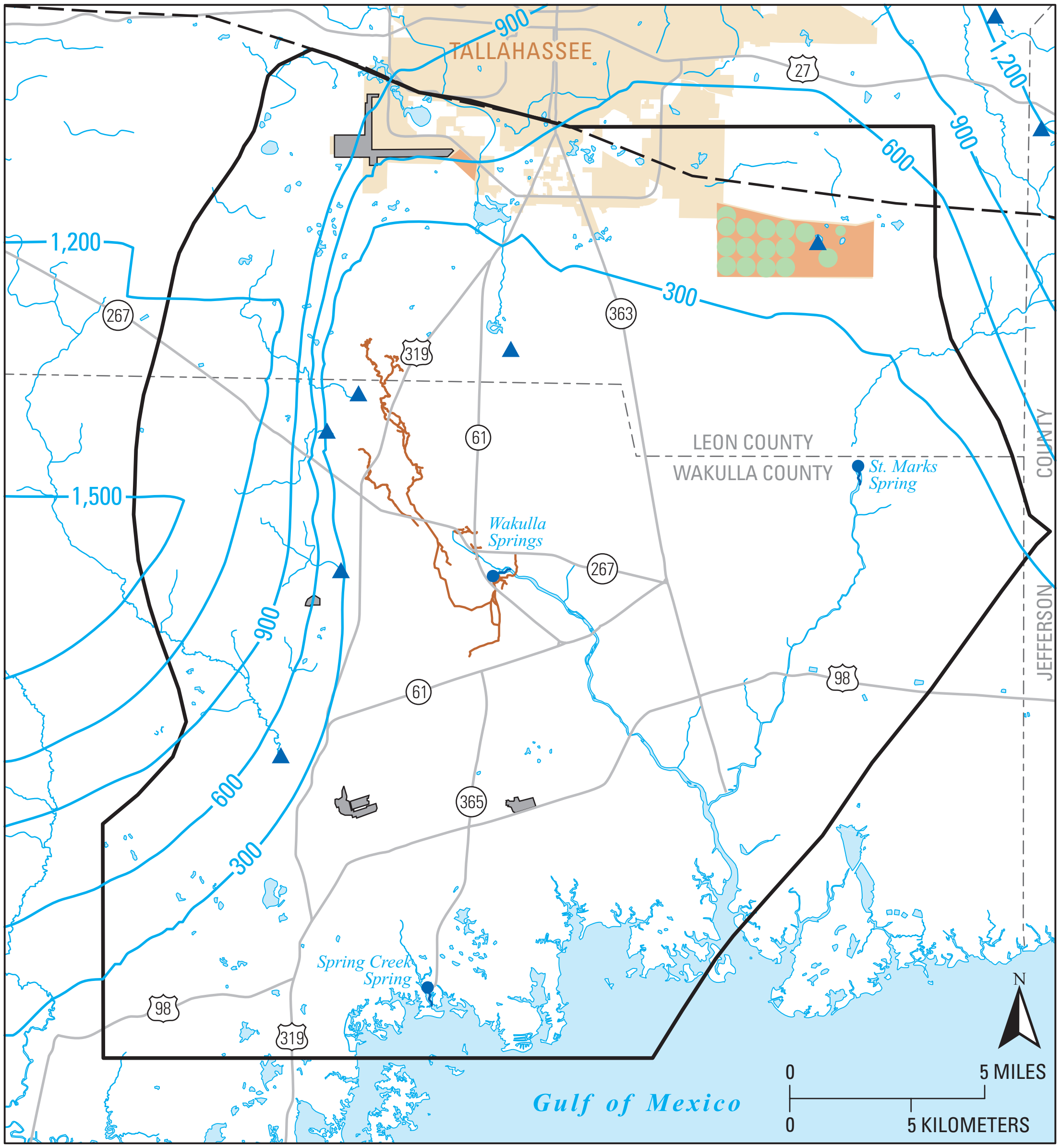
Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

0 5 MILES
0 5 KILOMETERS

EXPLANATION

RESIDUALS DISPOSAL AREA
SPRAYFIELD LOCATION—Southeast farm (SEF) and southwest farm (SWF)
SUBREGIONAL MODEL BOUNDARY
–100– BASE OF MODEL AREA 1—Altitude in feet above NGVD 1929. Contour interval 50 feet
CODY SCARP
MAPPED SUBMERGED CAVES
CENTER PIVOT LOCATION
SINK—With creek inflow.
SPRING LOCATION

Figure 24. Bottom of model layer 1.



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

EXPLANATION

RESIDUALS DISPOSAL AREA
SPRAYFIELD LOCATION
CENTER PIVOT LOCATION
MAPPED SUBMERGED CAVES
SUBREGIONAL MODEL BOUNDARY
CODY SCARP
300 THICKNESS OF LAYER 2—In feet. Contour interval 300 feet
SPRING
SINK—with creek inflow

Figure 25. Thickness of model layer 2.

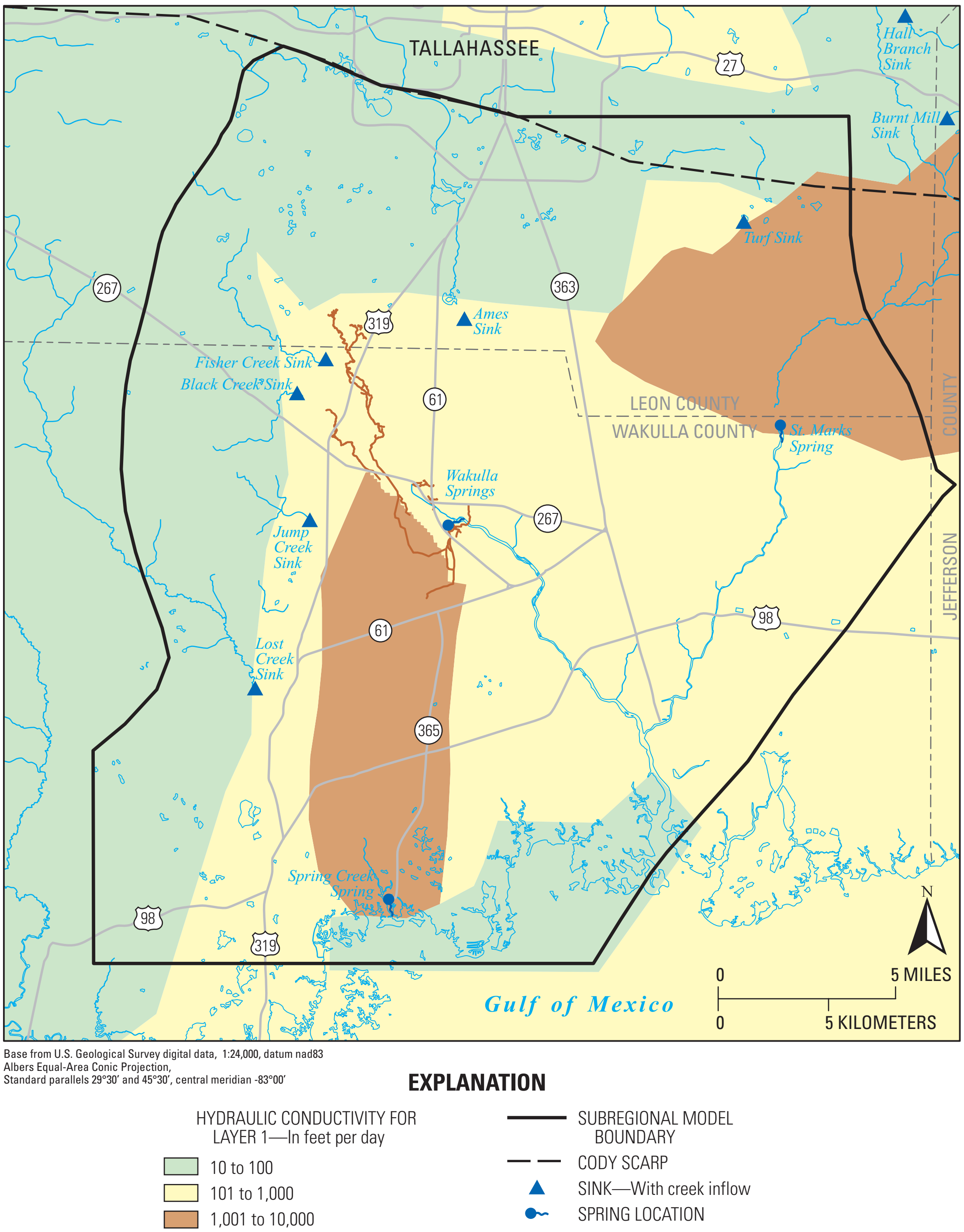


Figure 26. Simulated horizontal hydraulic conductivity for layer 1.

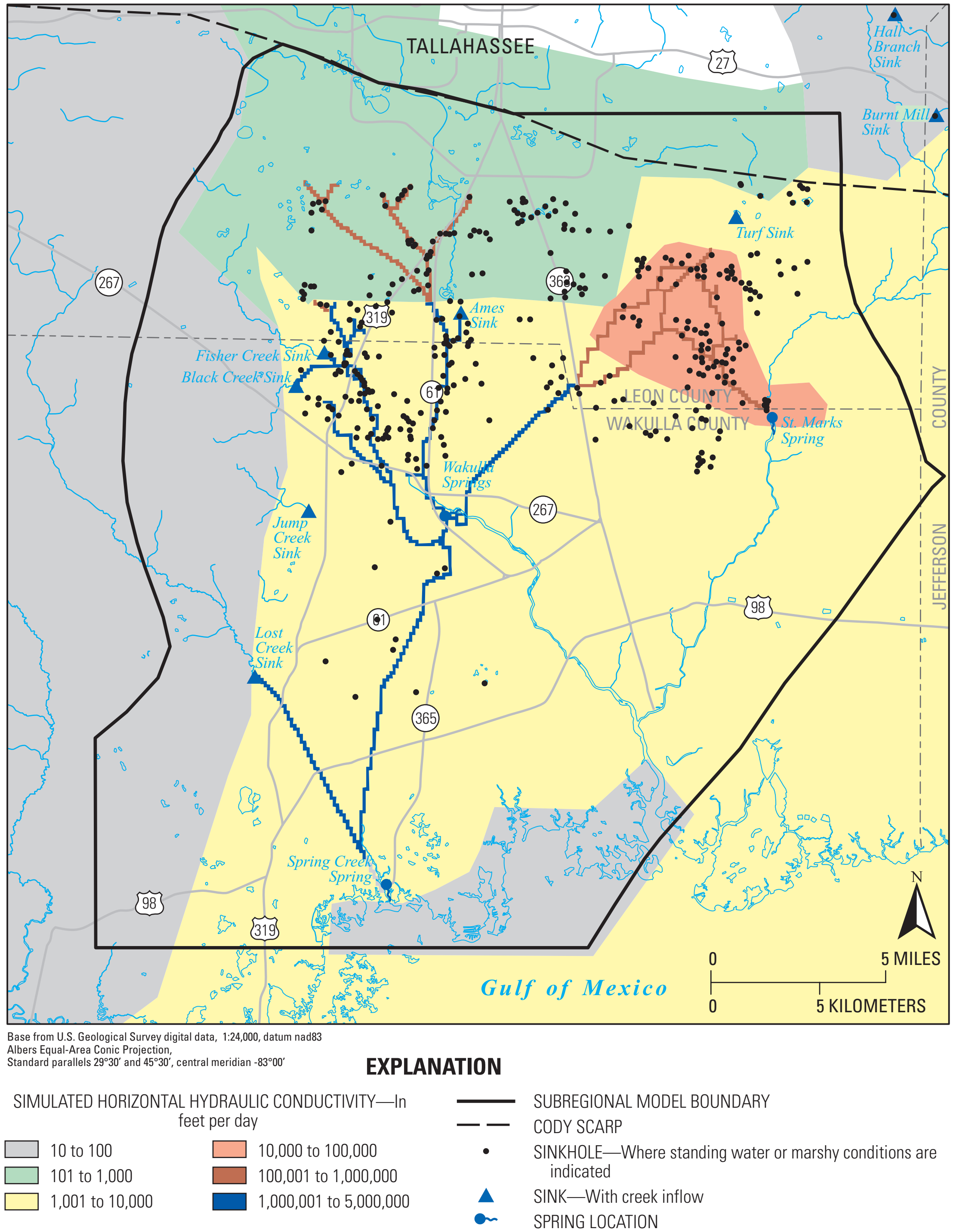
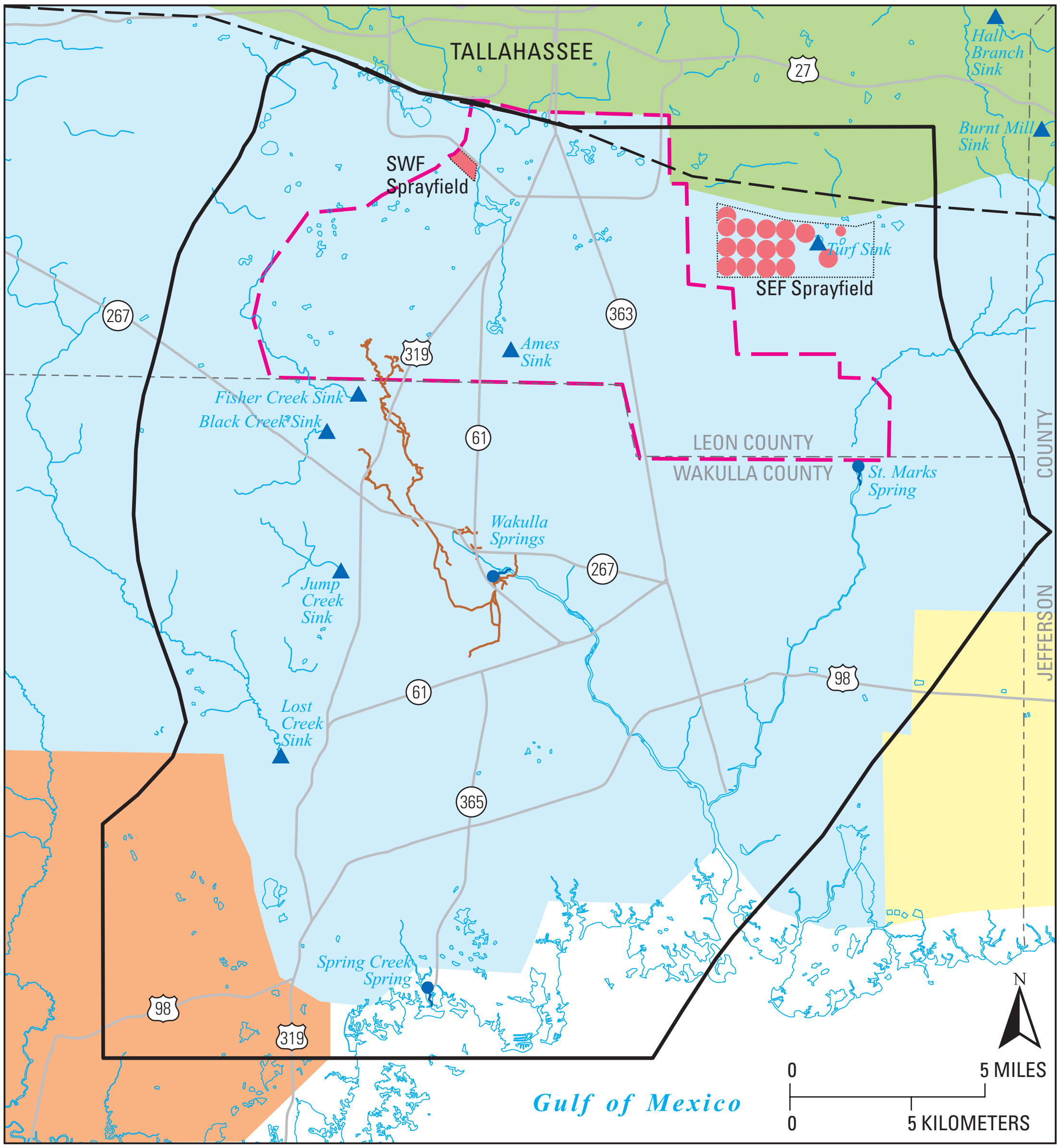


Figure 27. Simulated horizontal hydraulic conductivity for layer 2.



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

EXPLANATION

RECHARGE RATE—In inches per year

- No recharge
- Recharge is variable
- 1.8
- 4.0
- 8.0
- 18

- RECHARGE AREA WHERE FERTILIZER AND LIVESTOCK LOAD WAS ADDED TO RAINFALL LOAD
- SUBREGIONAL MODEL BOUNDARY
- CODY SCARP
- SPRAYFIELD BOUNDARY—Southeast farm (SEF) and southwest farm (SWF)
- SINK—With creek inflow
- SPRING LOCATION

Figure 28. Simulated net recharge rates to the Upper Floridan aquifer.

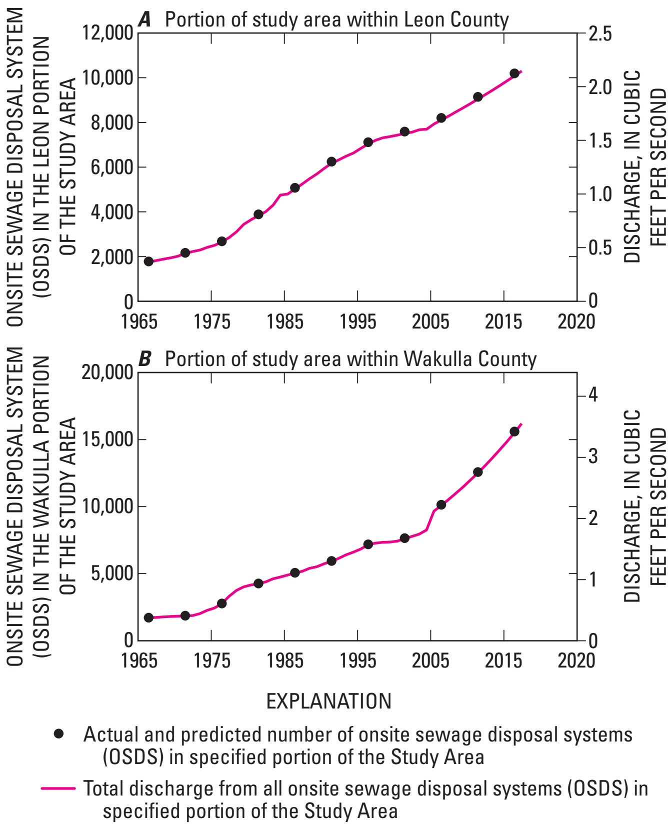


Figure 29. Total onsite sewage disposal system (OSDS) discharges for Leon and Wakulla Counties.

In addition, OSDSs were not simulated in the regional model, but were simulated in the subregional model. However, the small volume of water added by the septic tanks did not raise the simulated water levels or discharges and therefore, had little effect on the calibration. But, they did affect the nitrate-N simulation.

The simulated and measured water levels for the November 1991 data set are shown on figure 30. The model matched 12 of 13 model heads within the calibration criterion of 5 ft and all of the discharges within 7 percent (table 6). The relatively wide range in calibration criterion occurred because not all of the well altitudes were surveyed to an accuracy of 0.01 ft, so there could have been an error of as much as a couple of feet.

For the late May to early June 2006 data set, the model matched 55 of 61 model heads (fig. 31) within the calibration criterion of 5 ft, and the measured flows at Wakulla Springs and St. Marks River springs were within 2 percent of the simulated values (table 6). Most of the wells that were outside of the calibration criterion were confined to one small region on the east side of the SEF (wells shown in yellow on fig. 31) and a rapidly changing groundwater gradient was present in this area making it difficult to match. The increase in the simulated flow to Wakulla Springs and the decrease in the simulated flow to the Spring Creek Springs Group in the model were caused by lowering the simulated stage in Wakulla Springs and raising the simulated stage in the Spring Creek Springs Group in May 2005.

The need to understand how there could be an increase in flow at Wakulla Springs and a decrease in flow at the Spring Creek Springs Group resulted in two additional steady-state simulations where:

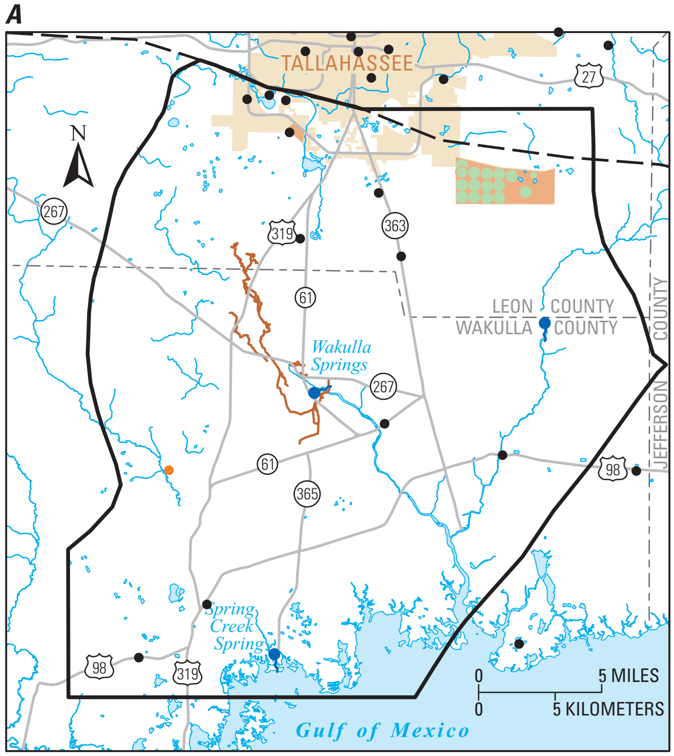
1. The simulated stage at Wakulla Springs was 5 ft and simulated stage at the Spring Creek Springs Group was 0 ft;

2. The simulated stage at Spring Creek Springs Group was increased to 6 ft, thus simulating a new equivalent freshwater head for the springs as discussed earlier.

Table 6. Measured and simulated discharges for the 1991 and 2006 data sets.

[Gaging station locations shown on figure 1; all gains are in cubic feet per second; na, data not available; ≥, greater than or equal to]

Spring discharge	Measured discharge in November 1991	Simulated discharge in November 1991	Percent difference for 1991 Scenario	Measured discharge during late May to early June 2006	Simulated discharge during late May to early June 2006	Percent difference for late May to early June 2006 Scenario
St. Marks	602	589	-3	560	570	2
Wakulla	350	368	5	750	763	2
Spring Creek Springs Group	307	329	7	na	11	na
Total	1,286	2	≥1,310	1,344		



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

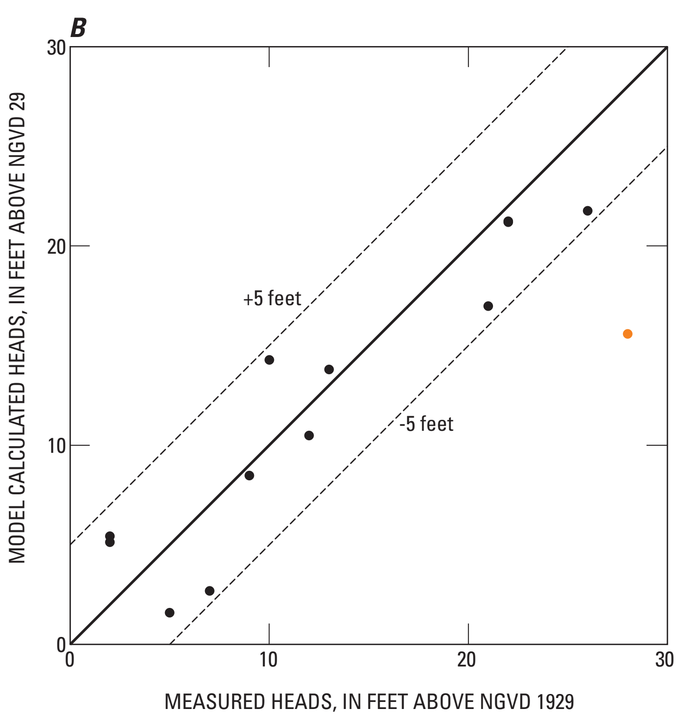


Figure 30. Location of *A*, wells and *B*, comparison of measured and simulated heads in 1991.

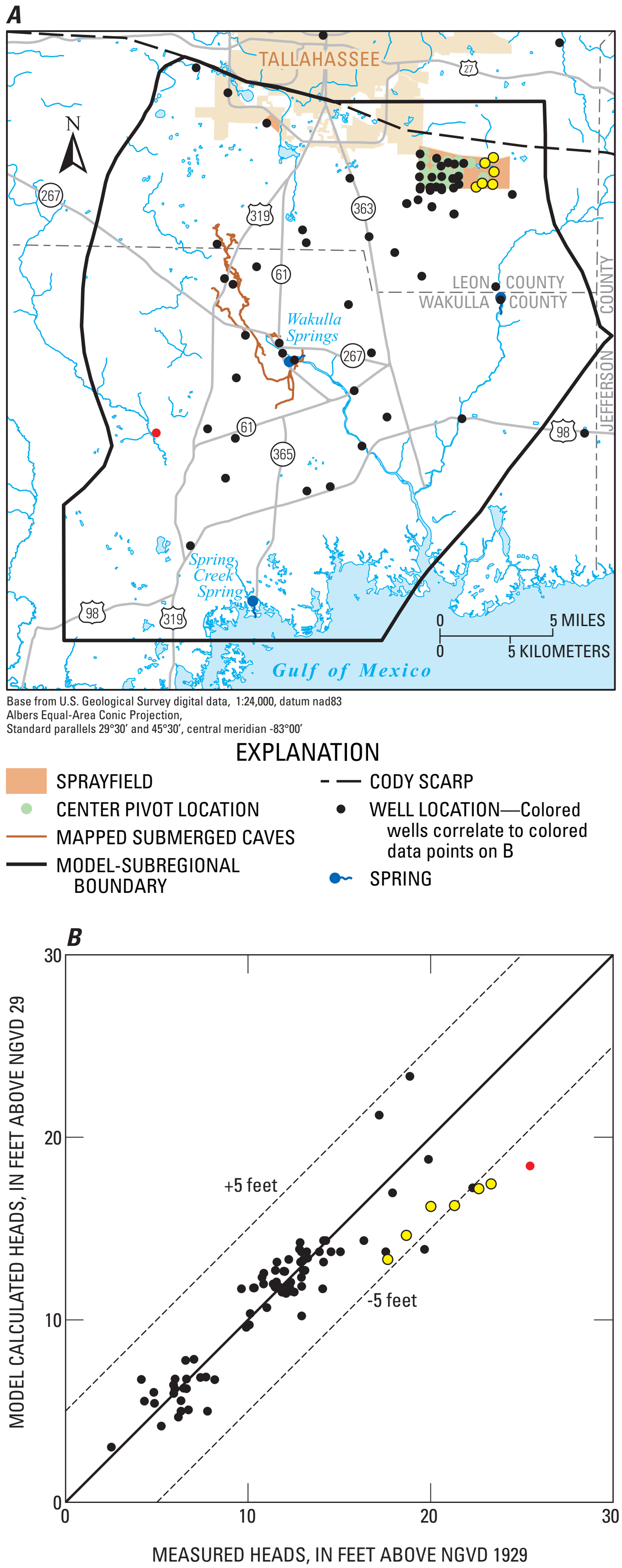


Figure 31. Location of *A*, wells, and *B*, comparison of measured and simulated heads for the late May to early June 2006 data set.

When the stage in Wakulla Springs is 5 ft and the stage in the Spring Creek Springs Group is 0 ft, almost all of the flow in the R-tunnel goes southward to the Spring Creek Springs Group, thus bypassing Wakulla Springs (fig.32*A*). However, when the stage in Wakulla Springs is 5 ft and the stage in the Spring Creek Springs Group is 6 ft, all of the flow in the R-tunnel goes northward to Wakulla Springs (fig. 32*B*).

Simulated Effective Porosity

Effective porosity, in a model simulation, governs the velocity of groundwater movement. In a groundwater flow simulation, MODFLOW calculates the volume of water moving from model cell to model cell, but assumes that groundwater fills the entire cell. The effective porosity restricts the groundwater movement to the percentage of the cell that is assumed to be interconnected by porosity and causing the velocity of groundwater to move at more realistic rates. Effective porosity is difficult to assess accurately, especially in karst terrains. The simulated effective porosity for layer 1 is a uniform 0.01; the simulated effective porosities for layer 2 are shown in figure 33. Actual groundwater flow velocities within some of the submerged caves were measured by tracer tests and these were used during model calibration to determine the simulated effective porosities. As discussed earlier, the groundwater traveltimes from Ames Sink and Fisher Creek Sink to Wakulla Springs were about 20 and 10 days, respectively (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006); from Turf Sinks to Wakulla Springs, the traveltime was about 40 days (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006). Particle tracking techniques available in MODPATH (Pollock, 1989) were used to measure the traveltime (10 days) from Fisher Sink to Wakulla Springs and matched the simulated traveltime using a simulated effective porosity of 0.015; the measured traveltimes to Wakulla Springs from Ames Sink (20 days) and Turf Sink (40 days) were matched using a simulated effective porosity of 0.03.

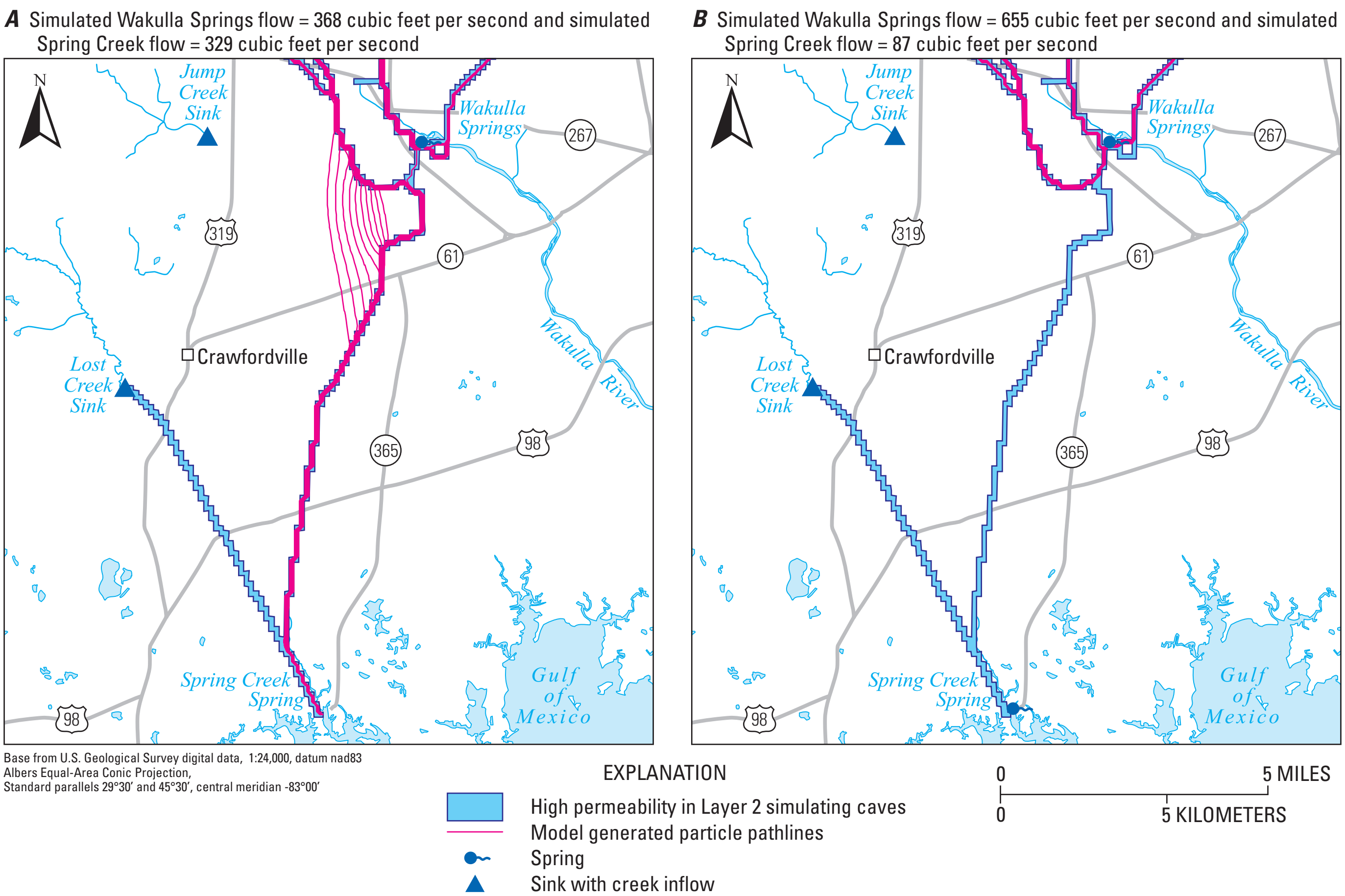


Figure 32. Particle pathlines showing groundwater flow directions with the *A*, simulated Wakulla Springs stage at 5 ft and the Spring Creek Springs Group stage at 0 ft, and *B*, simulated Wakulla Springs stage at 5 ft and Spring Creek Springs Group stage at 6 ft.

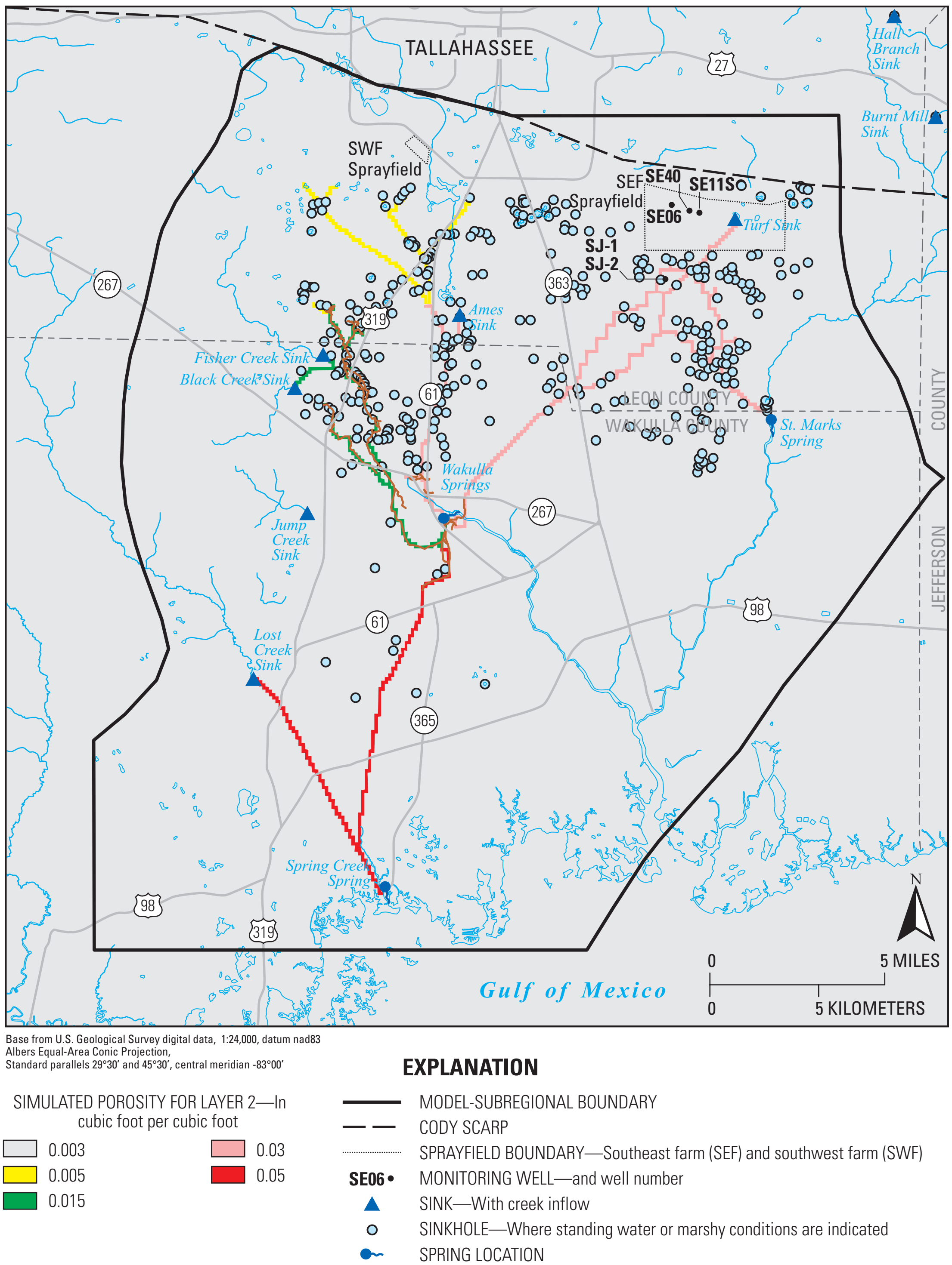


Figure 33. Simulated porosity for layer 2.

The traveltime was measured in an area where a sinkhole did not exist (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006). Dyes were injected into wells SE-06, SE-40, and SE-11S at the SEF sprayfield; the dyes reached their first peak in monitoring wells SJ-1 and SJ-2 in about 20 days (fig. 34). The simulated pathlines from these injection wells to the monitoring wells occurred mostly outside of a simulated cave, with only a small part of the path being in a simulated cave. An effective porosity of 0.003 in the area outside of the simulated cave was measured, and an effective porosity of 0.03 in the simulated cave matched this measured traveltime (fig. 34). The lower effective porosity of 0.003 in the area outside of the simulated caves was necessary to produce a sufficiently fast groundwater velocity to reach the monitoring wells at the measured traveltimes. This effective porosity of 0.003 was applied to all of the simulated areas outside of simulated caves in layer 2.

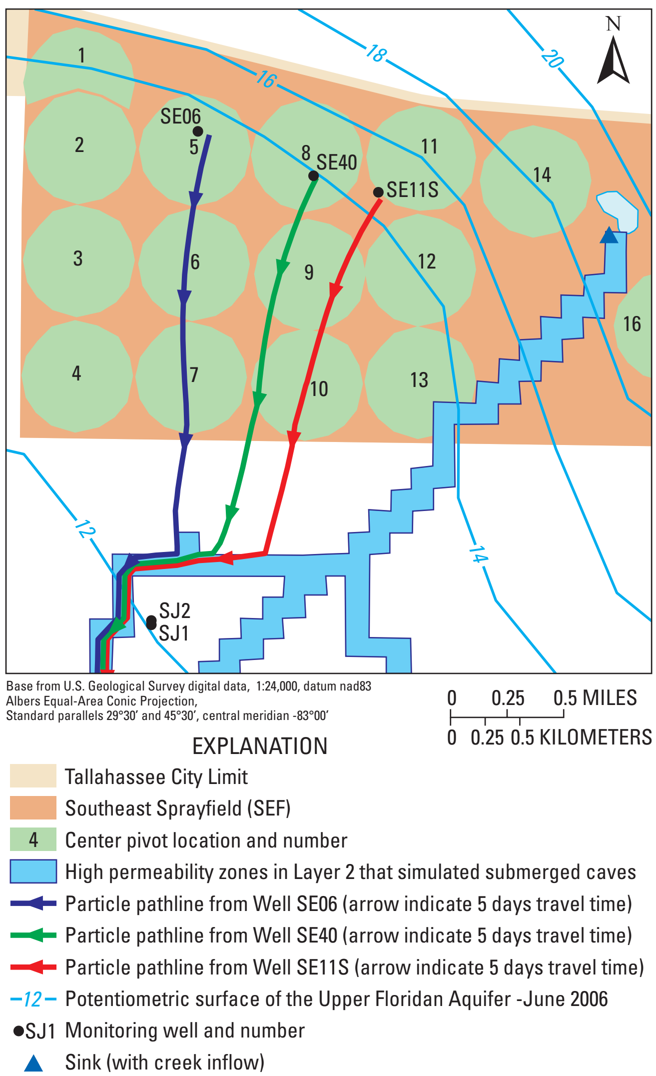


Figure 34. Particle tracking from monitoring wells SE-06, SE-11S, and SE-40.

Fate and Transport Model and Calibration

Fate and transport modeling was used to estimate the nitrate-N load to Wakulla Springs from all of the individual sources in the study area and to project future nitrate-N loading to Wakulla Springs. To improve the overall accuracy of the modeling, chloride was simulated because it is not susceptible to breaking down in the unsaturated zone or aquifer as nitrate-N. Nitrate-N was simulated to enter the UFA from eight sources:

1. Center pivot irrigation using wastewater effluent and fertilizer usage at the SEF and SWF sprayfields,
2. Effluent discharges from OSDSs,
3. Inflow at model boundaries,
4. Disposal of biosolids by land spreading (this was discontinued in 2005),
5. Creeks discharging to sinks,
6. Fertilizer application,
7. Livestock wastes, and
8. Atmospheric deposition.

The calibration strategy was to match, as closely as possible, the known temporal and spatial distributions of nitrate-N and chloride. The model code used for the fate and transport simulation was the Modular Three-Dimensional Multi-Species Transport Model (MT3D) (Zheng and Wang, 1998). The MT3D uses the groundwater flow field generated by MODFLOW in combination with user-specified solute concentrations (and user-specified aquifer properties specific to solute transport) to calculate solute movement. The subregional-model grid used for the transient groundwater flow model was used for the fate and transport model. The solute transport modeling covered the 52-year period from 1966 through 2018. Similar to the groundwater flow model, the solute input parameters were updated yearly, except when a substantial change occurred at midyear (table 4).

Hydrodynamic Dispersion

In addition to the aquifer properties discussed in the model development section, the transport model required the extra parameter of hydrodynamic dispersion. Hydrodynamic dispersion of a dissolved chemical occurs as a result of local variation in groundwater velocity around the mean advective velocity and molecular diffusion. Dispersion will cause a contaminant plume to spread, thus resulting in lower concentrations away from the source area. Dispersivities are usually difficult to quantify accurately in the field. Gelhar and others (1992) performed a critical review of field-scale dispersion studies to define reasonable dispersivity values at various model scales. Using data that these authors described as the most reliable, a reasonable value for longitudinal dispersivity (in the direction of the flow axis) for this scale model was 32 ft; for transverse dispersivity (perpendicular to the flow axis in the horizontal plane) it was 16 ft; and for vertical dispersivity (perpendicular to the flow axis in the vertical plane) it was 0.16. These values were applied to the entire model domain. The initial nitrate-N and chloride concentration distributions were established by running the model in steady state, using conditions for 1966.

Simulation of Nitrate-N and Chloride Concentrations from Various Sources

The fate and transport model was calibrated using a trial and error process in which the input concentrations were varied until the model matched the measured groundwater concentrations as closely as possible. As discussed earlier, the loading rates (or concentrations) to land surface for each of the nitrate-N sources was estimated, and this value was used as an upper limit on the concentration that could make it through the unsaturated zone and reach the UFA. For this reason, the calibration procedure for each source will be discussed separately, along with it particular problems and concerns.

Southeast and Southwest Farm Sprayfields

To calibrate nitrate-N at the SEF and SWF sprayfields, it was assumed that the concentrations at land surface (fig. 14) reached the UFA. This resulted in the model-calculated nitrate-N concentrations being higher than the measured values in the monitoring wells. The concentrations applied at land surface were then reduced by an increasingly greater percentage until the model-predicted concentrations matched the measured values. A reduction of 45 percent (representing a 45-percent uptake in the unsaturated zone; table 7) resulted in the best match to the measured data. Examples of the match for monitoring wells SE-22, SE53, SJ-1, and SJ-9 are shown on figure 20.

The calibration strategy for chloride assumed no breakdown in the unsaturated zone (fig. 20). Data from wells SE-22 and SE-53 exist prior to the SEF sprayfield becoming operational in November 1980 and these wells have consistently had some of the highest nitrate-N and chloride concentrations measured.

The simulated and measured nitrate-N concentrations at the SEF sprayfield for model layer 1 for July 2006 are shown on figure 35; the most extensive round of groundwater sampling was performed in 2006. As expected, the highest nitrate-N concentrations occurred within the SEF sprayfield, and concentrations of nitrate-N decreased southward in the direction of groundwater flow. The simulated concentrations in layer 2 were lower (fig. 36), thus indicating that dilution is occurring, or, that some of the nitrate-N is being prevented from getting into the deeper parts of the UFA.

An examination of the increase in nitrate-N and chloride concentrations in well SE-22 reveals an interesting discovery of how the nitrate-N and chloride concentrations evolved over time. This well has some of the highest nitrate-N and chloride

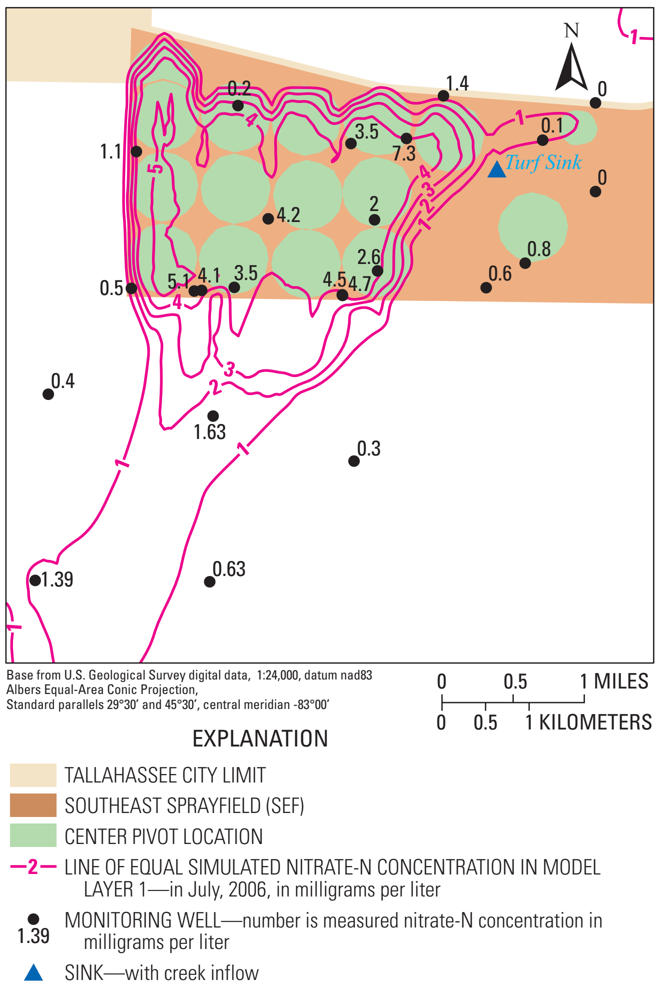


Figure 35. Simulated and measured nitrate-N concentrations at the Southeast Farm (SEF) sprayfield in model layer 1 in 2006.

concentrations and has been monitored since before the SEF sprayfield began operation. Center pivots 1-7, located immediately upgradient from SE-22, began operation in November 1980. Soon afterward, the measured chloride in SE-22 began to increase, but it took about 10 years for the concentration in SE-22 to reach the concentration of the wastewater effluent being applied at land surface (fig 37*A*). This finding indicates that the recharge rates were sufficiently high and that the irrigated wastewater had completely replaced the water in the UFA in the area around well SE-22 (this well is screened from 102 to 127 ft bls). The measured nitrate-N concentration in SE-22 always stayed substantially lower than the concentration applied at land surface (by about half), thus further indicating that nitrate-N was being taken up in the unsaturated zone.

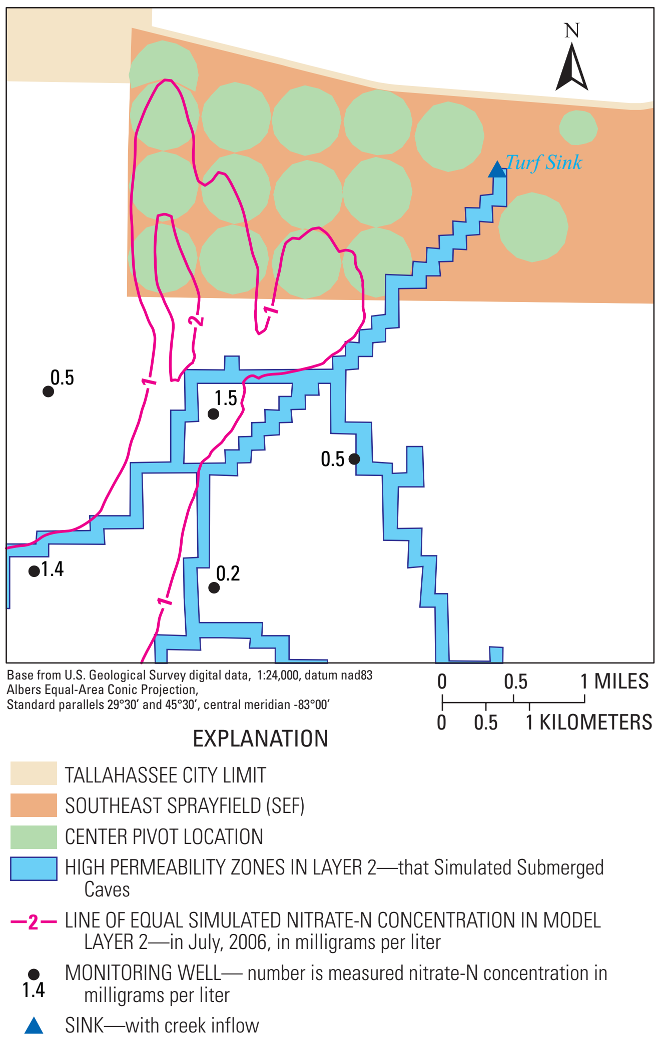


Figure 36. Simulated and measured nitrate-N concentrations at the Southeast Farm (SEF) sprayfield in model layer 2 in 2006.

The calibration strategy at the SWF sprayfield was the same as for the SEF sprayfield. The SWF sprayfield was initially a pilot project, running from 1966 to 1980, and since then has only been used sporadically; the volume of water disposed of at the SEF and SWF sprayfields is shown in figure 38. The simulated and measured nitrate-N concentrations in the SWF sprayfield well LS-25, located on the downgradient edge of the sprayfield, are shown on figure 21. A reduction of 30 percent (representing a 30-percent uptake in the unsaturated zone) resulted in the best match to well LS-25. Because of the erratic nature of the chloride data and low recharge rates at the SWF sprayfield, there was no attempt to match the chloride data. Instead, for the chloride model, it was assumed the chloride concentration in the wastewater effluent was a constant 50 mg/L.

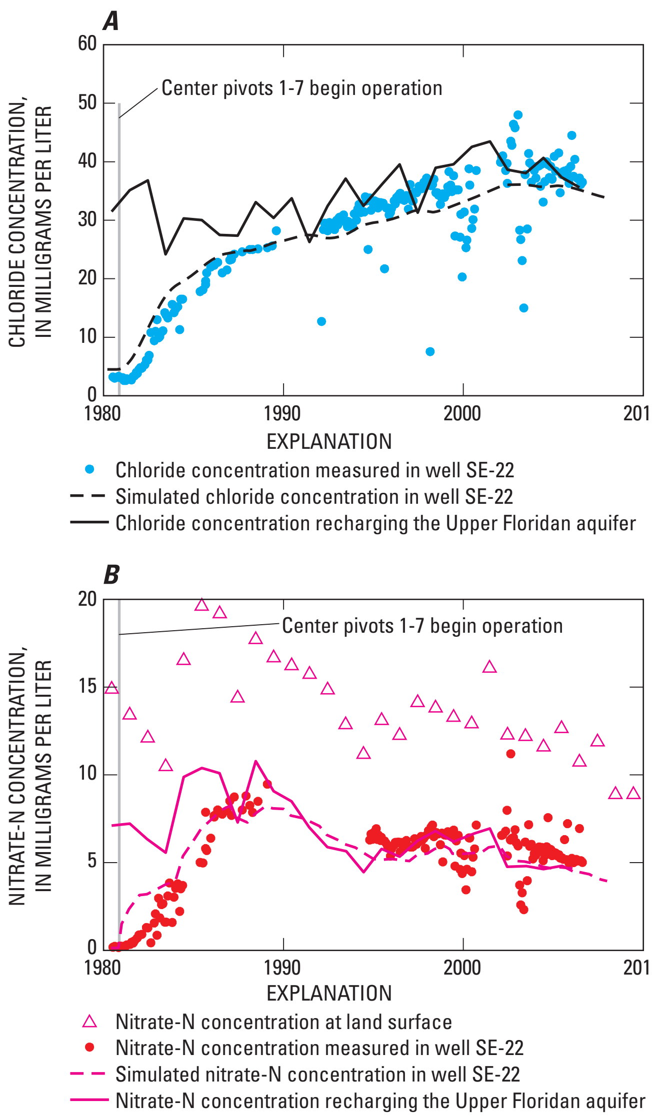


Figure 37. Measured and simulated *A*, chloride and *B*, nitrate-N concentrations at well SE-22 (location of well SE-22 is shown on figure 3).

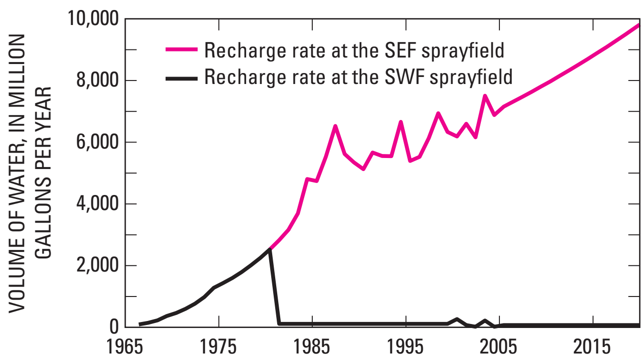


Figure 38. Volume of recharge at the Southeast Farm (SEF) and Southwest Farm (SWF) sprayfields.

Effluent Discharges from Onsite Sewage Disposal Systems, Fertilizer Application, and Livestock Wastes

The concentration of nitrate-N in the effluent from OSDSs was estimated using literature derived values. Katz and others (2010) found that in Wakulla County, the nitrate-N concentration in drain field effluent averaged about 60 mg/L and at the water table below the drain field the concentration was about 30 mg/L. Citing six papers, Horsley and Witten (2000) gave a nitrate-N range of 23 to 40 mg/L in samples taken from the leaching area and from groundwater directly below the leaching area. Based on this range, the simulated nitrate-N concentration in effluent reaching the UFA from all the OSDSs was 30 mg/L.

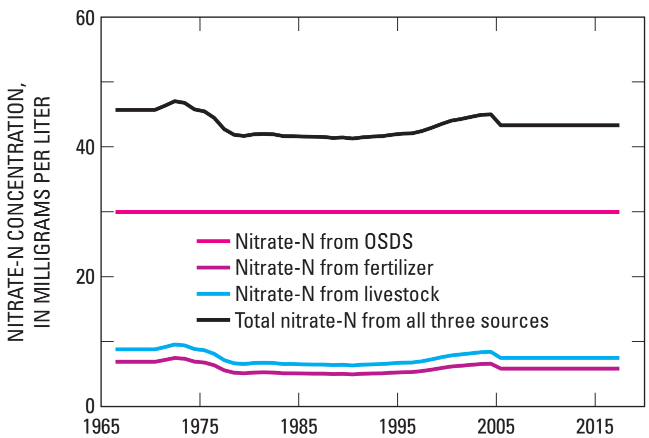


Figure 39. Simulated nitrate-N concentrations reaching the Upper Floridan aquifer at each onsite sewage disposal system (OSDS) location in Wakulla County (concentrations are the sum of OSDS, fertilizer, and livestock nitrate-N).

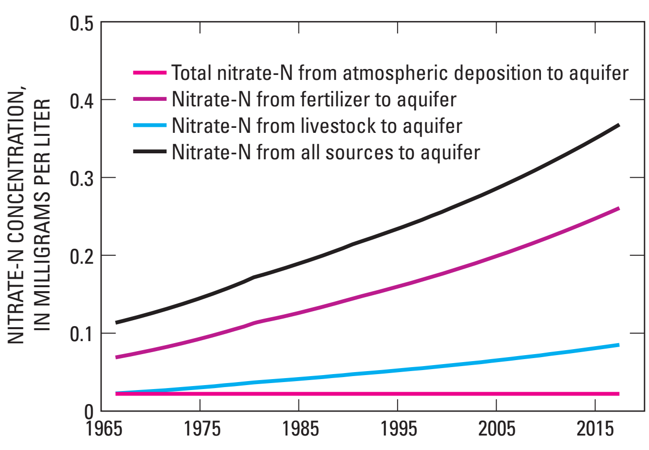


Figure 40. Simulated nitrate-N concentrations in recharge from atmospheric deposition, fertilizer, livestock, and total sources in the Leon County part of the study area (excluding the uninhabited areas).

Wakulla County is generally rural, and most homes use an OSDS. There are no large-scale livestock or farming operations, so fertilizer use is largely domestic and livestock operations are small and widespread. Therefore, each home using an OSDS will be a source of nitrate-N from its own OSDS, and may have contributing sources from fertilizer or livestock. Since it was not possible to separate out the nitrate-N load for fertilizer and livestock for the actual sites where it occurred, the nitrate-N load was spread evenly to all sites with an OSDS in Wakulla County. Leon County was handled differently and will be discussed next. OSDSs were simulated in the flow model using an injection well and the simulated concentration of nitrate-N in the injected water was 30 mg/L; in addition, the load from fertilizer and livestock wastes was added because these also were domestic sources. For each stress period, the mass of nitrate-N from the OSDS, fertilizer, and livestock was totaled and then divided by the injected volume to get the concentration of nitrate-N at each site with an OSDS. In reality, the nitrate-N from livestock and fertilizer only increased the nitrate-N concentration in the effluent by a small amount (fig. 39). The chloride concentration at each OSDS was set at 50 mg/L, which was the average concentration in the effluent from the wastewater treatment plant. This concentration assumes that the origin of the water to the OSDS and the wastewater treatment plant were similar.

Leon County is generally residential and most homes have sewers; homes with OSDSs are only a small subset of this part of the study area. The nitrate-N concentration from each OSDS was simulated at 30 mg/L; the load from fertilizer and livestock was not added as in Wakulla County. Because there was no way to apportion the nitrate-N load from fertilizer and livestock to individual home sites, it was uniformly applied to the populated part of Leon County within the study area (fig. 28). This apportioning was accomplished in the simulations by adding it to the atmospheric deposition load in that area (fig. 40). The uninhabited areas were excluded from the addition of nitrate-N loading from fertilizer and livestock. A nitrate-N reduction of 50 percent was assumed to occur in the unsaturated zone for fertilizer and livestock wastes, the same value used for OSDSs. However, uptake from these sources was the hardest to assess accurately and there were no locations that had monitoring data to compare with the model results. The loading to land surface from fertilizer and livestock wastes is relatively low (fig. 13), so even some error in the percentage reaching the UFA would not have a large impact on the simulated concentrations reaching Wakulla Springs. The chloride concentration at each OSDS was set at 50 mg/L.

Inflow at Model Boundaries

Specified nitrate-N and chloride concentrations were applied to the specified-head cells along the perimeter of the model to account for the movement of solutes into the study area by groundwater inflow. Specified concentrations were assigned in four zones along the model boundaries (fig. 23). In zones 1 and 4, the nitrate-N concentrations were a constant value of 0 and 0.1 mg/L, respectively. In zone 2, the nitrate-N concentration increased over time and values were derived from the upgradient municipal water-supply well CW-5 (fig. 41*A*). In zone 3, the concentration also increased over time and values were derived from the upgradient municipal water-supply well CW-17. Chloride concentrations were a constant 15 and 5 mg/L for zones 1 and 4, respectively. In zone 2, the concentrations increased over time and were derived from the upgradient municipal water-supply well CW-5 (fig 41*B*). In zone 3, chloride also increased over time based on the upgradient municipal water-supply well CW-17.

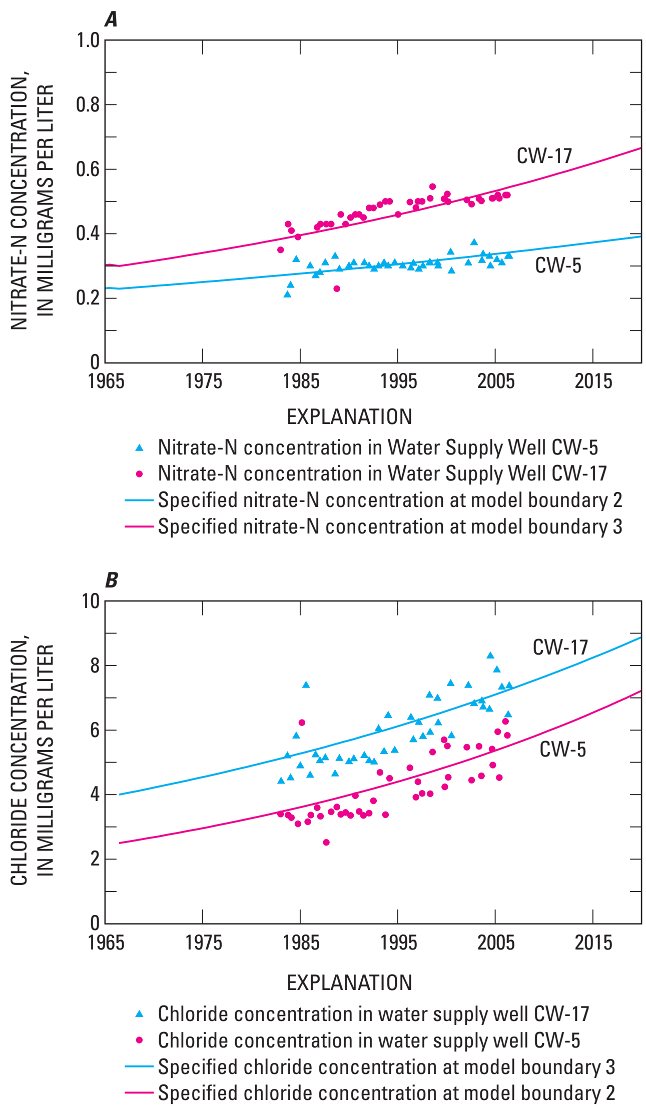


Figure 41. Nitrate-N and chloride in water-supply wells CW-5 and CW-17, located near the model boundaries.

Disposal of Biosolids by Land Spreading

The calibration strategy for nitrate-N at the airport biosolids disposal site was to start with the concentrations at land surface (fig. 17) and assume these concentrations reached the UFA. The concentrations were then reduced by an increasingly greater percentage until the model predicted concentrations matched the monitoring well values. A reduction of 50 percent (representing a 50-percent uptake in the unsaturated zone; table 7) provided the best match to the measured data for monitoring SF-02 (fig. 21). The high variability in nitrate-N concentrations probably resulted from the biosolids being spread in different parts of the disposal area at different times to even out the impact. The other biosolids disposal sites did not have monitoring wells, so the reduction in land-surface concentrations of 50 percent was applied to them as well. Biosolids were not considered an important source of chloride.

Creeks Discharging into Sinks and Atmospheric Deposition

The nitrate-N calibration strategy for atmospheric deposition and discharging creeks was to start with the literature-derived values and modify them during calibration as needed. The concentration of nitrate-N reaching the UFA from atmospheric deposition was set at 0.022 mg/L, based on the work of Chellette and others (2002). The nitrate-N concentration in the creeks flowing into sinks was discussed earlier and was set at 0.33 mg/L for Munson Slough, 0.48 mg/L for Fisher Creek, 0.65 mg/L for Black Creek, and 0.48 mg/L for Lost Creek. At the beginning of the simulation (1966), all of the other nitrate-N source concentrations were low to nonexistent, so atmospheric deposition and creek inflows had their maximum effect on the concentration in Wakulla Springs. As seen in figure 22, the model matched the 1966 nitrate-N and chloride concentrations in Wakulla Springs, indicating that, at least at this point in time, the simulated input concentrations were reasonable for these two sources. The chloride concentration for both atmospheric deposition and creek inflows was set at 5 mg/L.

Nitrate-N and Chloride Concentrations in Wakulla Springs

The final check on the calibration strategy was to compare the simulated nitrate-N and chloride concentrations to the measured values in Wakulla Springs. The simulated and measured nitrate-N and chloride concentrations in Wakulla Springs, A-, B-, C-, and D-tunnels are shown in figure 22. The simulated and measured values matched fairly well for nitrate-N in Wakulla Springs from 1966 to 1987. The model

Table 7. Percentage of nitrate-N removed in the unsaturated zone as recharging water moves from land surface to the Upper Floridan aquifer.

[SEF, Southeast Farm sprayfield; SWF, Southwest Farm sprayfield; OSDS, onsite sewage disposal system]

Source of nitrate-N	Simulated percentage of nitrate-N removed in the unsaturated zone	Justification for using simulated value	Problems
SEF Sprayfield	45	Numerous monitoring wells with long-term data were used to calibrate the fate and transport model.	High recharge rates at the sprayfield may make this value not applicable to other parts of the study area.
SWF Sprayfield	30	A limited number of monitoring wells with data was used to calibrate the fate and transport model.	High recharge rates at the sprayfield may make this value not applicable to other parts of the study area.
OSDSs	50	Preliminary data from one ongoing study. Consistent with literature review by Horsley and Witten (2000).	Insufficient field to independently verify with model.
Biosolids disposal	50	A limited number of monitoring wells with data was used to calibrate the fate and transport model.	Limited number of monitoring wells with data.
Fertilizer	50	Applied the value determined at biosolids airport disposal area.	Insufficient field data to independently verify with model.
Livestock	50	Applied the value determined for biosolids disposal.	Insufficient field data to independently verify with model.
Atmospheric deposition	98	Simulation matched the nitrate-N levels in Wakulla Springs in 1966 when other sources were minor. Monitoring well data in undeveloped areas showed little or no nitrate-N.	Only sporadic measurements. No long-term studies in the study area.

underpredicted the measured values from 1985 to 1995 during the high fertilizer usage years at the SEF. Therefore, more fertilizer may have been applied than reported, or, a greater proportion was making it through the unsaturated zone. From mid-2005 to 2007, both the simulated and measured values decreased from about 0.7 to 0.5, as shown by the last two sample points. The simulated chloride concentrations matched the measured values throughout the simulation. The reason for the high amount of variability in measured values from 1965 to about 1975 is not known. The highest measured and simulated nitrate-N and chloride concentrations were in the B- and C-tunnels. The B-tunnel heads north from Wakulla Springs, toward the SEF sprayfield (fig. 8). The lowest nitrate-N concentrations, both simulated and measured, were in the A-tunnel (fig. 22). The A-tunnel is located near and receives water from the R-tunnel; the R-tunnel trends to the northwest and runs under sparsely populated areas (fig. 8). Water-quality samples have been collected in all of the tunnels and Wakulla Springs only during the period between April 2004 and April 2005. The nitrate-N concentration in Wakulla Springs has always been higher than in the A-tunnel, but lower than in the B-, C-, and D-tunnels. The simulated nitrate-N concentration in Wakulla Springs varies depending on the volume of the contribution from the A-tunnel relative to that of the B-, C-, and D-tunnels. If the contribution of flow to Wakulla Springs from the A-tunnel is small, then the nitrate-N level in Wakulla Springs is relatively high, reflecting the higher levels found in the other tunnels. If the contribution from the A-tunnel is large, then the nitrate-N level in Wakulla Springs is relatively low, reflecting the lower levels found in the A-tunnel. In 1980, the rapid drop in nitrate-N and chloride concentrations at Wakulla Springs and in some tunnels was caused by the reduction in wastewater disposal at the SWF sprayfield and the increase of wastewater disposal at the SEF sprayfield.

Simulated Future Nitrate-N Concentrations in Wakulla Springs

The calibrated fate and transport model was used to predict nitrate-N concentrations in the UFA and Wakulla Springs through 2018. This year was chosen because planned reductions in nitrate-N applied at the sprayfields (from about 12 mg/L to 3 mg/L) will have had time to work through the groundwater flow system and be evident in Wakulla Springs. Because groundwater flow conditions could vary, two scenarios were simulated. In scenario 1, the flow in the R-tunnel divided at the junction with the A/K-tunnels so that from January 1, 1966, to May 1, 2005, part of the water went to Wakulla Springs and part of the water went to the Spring Creek Springs Group. From May 1, 2005, through January 1, 2007, all of the flow in the R-tunnel went to Wakulla Springs through the A/K-tunnels. After January 1, 2007, the flow reverted to the conditions present before May 1, 2005 (fig. 42). It is uncertain

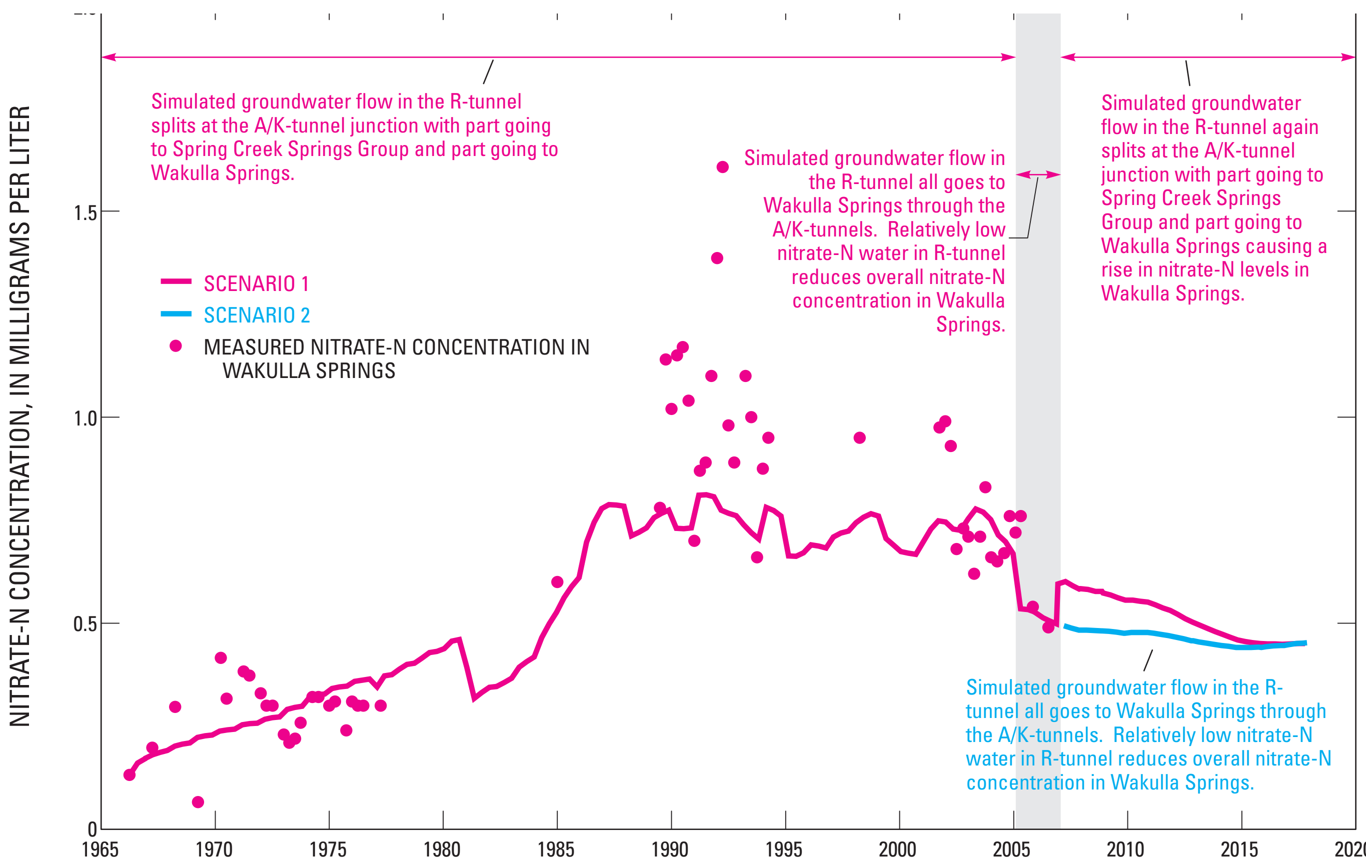


Figure 42. Simulated nitrate-N loads in Wakulla Springs from 1966 through 2018.

whether the condition simulated in scenario 1 after January 1, 2007, will predominate, or, if the predominant condition will be that all of the flow in the R-tunnel goes to Wakulla Springs. To cover a range of possibilities, a scenario 2 simulation was run covering just the period from January 1, 2007, through December 31, 2018. In this simulation, all of the flow in the R-tunnel goes to Wakulla Springs. This causes the anticipated concentrations in Wakulla Springs to remain lower due to the continued addition of low nitrate-N water from the R-tunnel (fig. 42).

The simulated nitrate-N concentrations in Wakulla Springs in scenario 1 decreased to less than 0.5 mg/L by about 2014 (fig. 42). This decrease occurred because of the simulated nitrate-N reduction at the sprayfields and occurred even though nitrate-N from some of the other sources (particularly OSDSs) is increasing. The nitrate-N concentration in scenario 2 also trended downward because of two factors:

1. The loading from both sprayfields decreased, as in scenario 1; but,
2. This was offset by an increased load coming in from the area southwest of Wakulla Springs that is having rapid population growth.

Simulated Nitrate-N Concentration Distribution in the Upper Floridan Aquifer at Selected Times

As part of the fate and transport model simulation, the nitrate-N concentration distribution was calculated several times each year. Selected examples are discussed next, which are the distributions at the ends of the years 1967, 1986, 2004, 2006, 2007, and 2018. The discussion will be of scenario 1 unless scenario 2 is specified.

End of 1967

The simulated nitrate-N concentrations in layer 1 showed an increase at the end of 1967 below the SWF sprayfield facility and the biosolids disposal area (fig. 43). This increase is substantial as 1967 was the first full year of site operations. In areas not impacted by these two sources, the concentrations were low, with only sporadic high concentrations in areas with numerous OSDSs. The nitrate-N concentrations in layer 2 were even lower and occurred only below the biosolids disposal area and SWF sprayfields (fig. 44).

End of 1986

The nitrate-N loading at the SEF sprayfield reached its highest level in 1986 due to heavy fertilizer usage. In layer 1, the simulated nitrate-N concentrations below this facility reached about 8 mg/L (fig. 45). The highest concentrations in layer 1 occurred below the airport biosolids disposal site, peaking at about 45 mg/L. The actual nitrate-N load to the UFA was higher at the SEF sprayfield because of the high irrigation rates; at the airport biosolids site, only rainfall occurred to transport the nitrate-N to the aquifer. Widespread nitrate-N concentrations less than 1 mg/L in areas of layer 1 were predominantly the result of OSDSs. The airport biosolids disposal site and SEF sprayfield also caused the highest simulated nitrate-N concentrations in layer 2, with concentrations at the airport disposal site reaching 4 mg/L and those at the SEF sprayfield reaching 3 mg/L (fig. 46). The simulated nitrate-N plume that started at the SEF sprayfield extended all the way to Wakulla Springs.

End of 2004

The simulated nitrate-N concentration in model layer 1 below the SEF sprayfield had decreased to about 8 mg/L by the end of 2004 because of the near elimination of fertilizer usage, even though the load from wastewater effluent was increasing (fig. 47). The simulated distribution of nitrate-N below the airport biosolids disposal had decreased to about 28 mg/L, thus reflecting the ongoing reduction of disposal amounts. Low-level concentrations of nitrate-N were far more widespread than in 1986, because of increasing numbers of home sites with OSDSs. The simulated nitrate-N concentration in model layer 2 below the SEF sprayfield had decreased by the end of 2004 to about 5 mg/L, thus reflecting the reduction in fertilizer usage and greater dilution occurring in layer 2 (fig. 48). The concentration below the airport biosolids disposal site was about 8 mg/L. Low-level concentrations of nitrate-N also were more widespread in layer 2, reflecting the increasing concentrations in layer 1. The effect of increasing nitrate-N loading due to groundwater inflow from outside the study area is evidenced by the simulated low-level nitrate-N concentrations entering along the northern model boundary (fig. 48).

End of 2006

The flow in Wakulla Springs and the Spring Creek Springs Group was nearly the same from January 1, 1966, to May 1, 2005. From May 1, 2005, to January 1, 2007, Wakulla Springs fully captured the flow in the R-tunnel, pulling in groundwater from the west and southwest. This resulted in some reorientation of the nitrate-N concentrations in layer 1, but they were minimal because groundwater flow in this layer is largely downward. The simulated distribution of nitrate-N below the airport biosolids disposal site in layer 1 decreased to about 4 mg/L, reflecting the elimination of biosolids disposal in 2005 (fig. 49); concentrations below the SEF sprayfield of a little less than 5 mg/L were still present. The reorientation of concentrations was more dramatic for layer 2, where nitrate-N concentrations that had been going to the Spring Creek Springs Group (as seen on fig. 48) were instead going to Wakulla Springs (fig. 50). Relatively low concentrations of nitrate-N were more widespread than in 2004, showing the increasing effect of OSDSs in both layers 1 and 2.

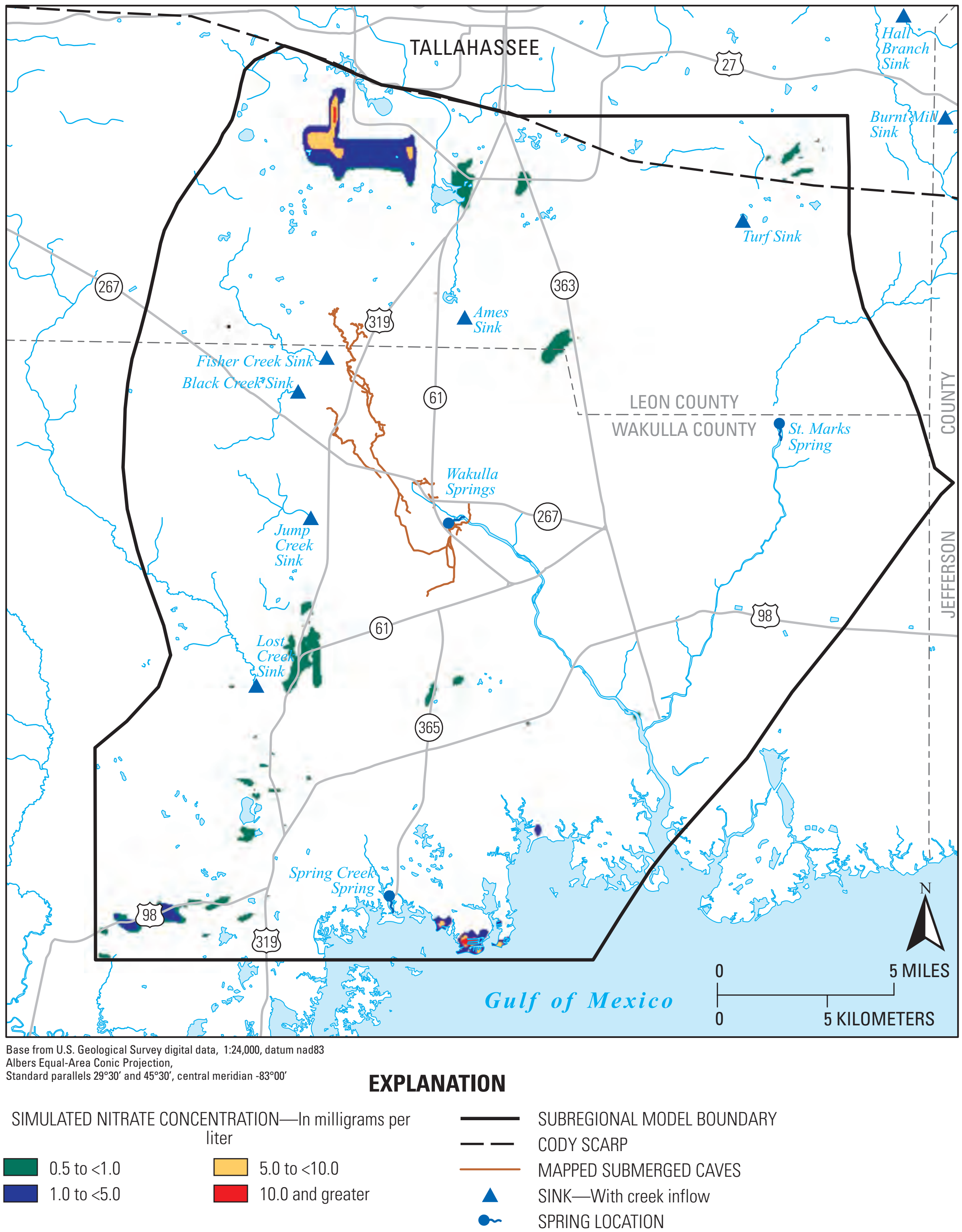


Figure 43. Simulated nitrate-N concentrations in the Upper Floridan aquifer in model layer 1 at the end of 1967.

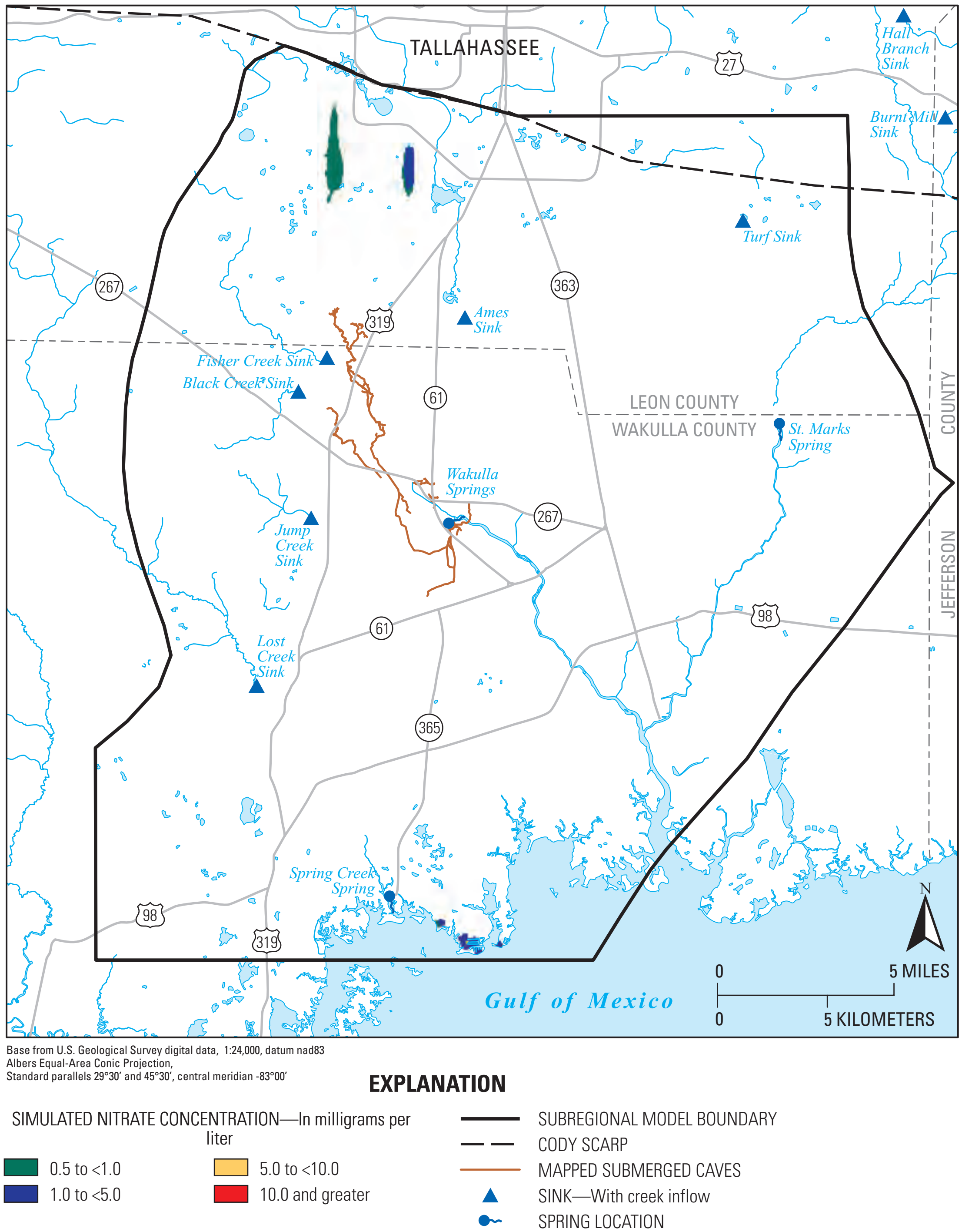


Figure 44. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 2 at the end of 1967.

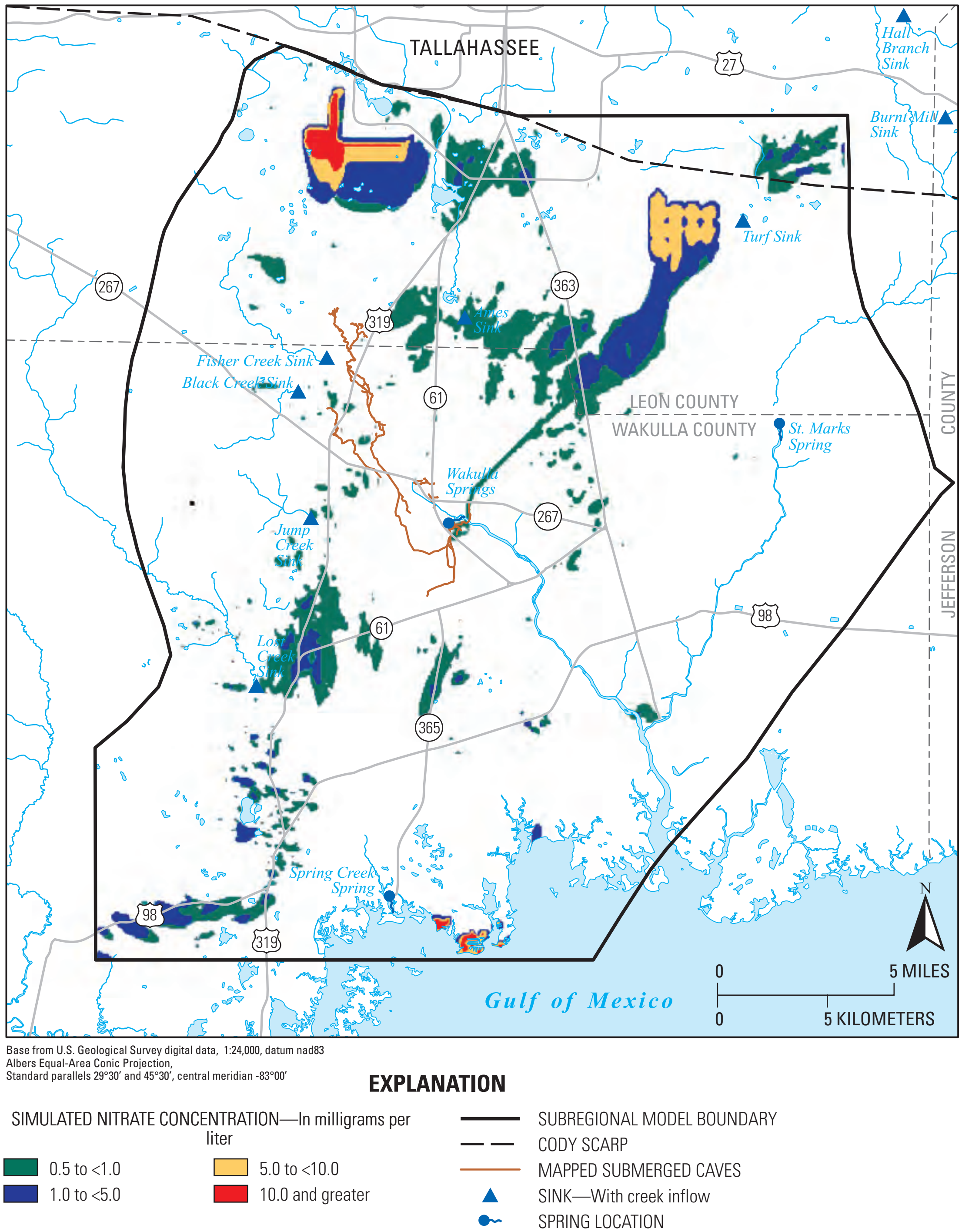


Figure 45. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 1 at the end of 1986.

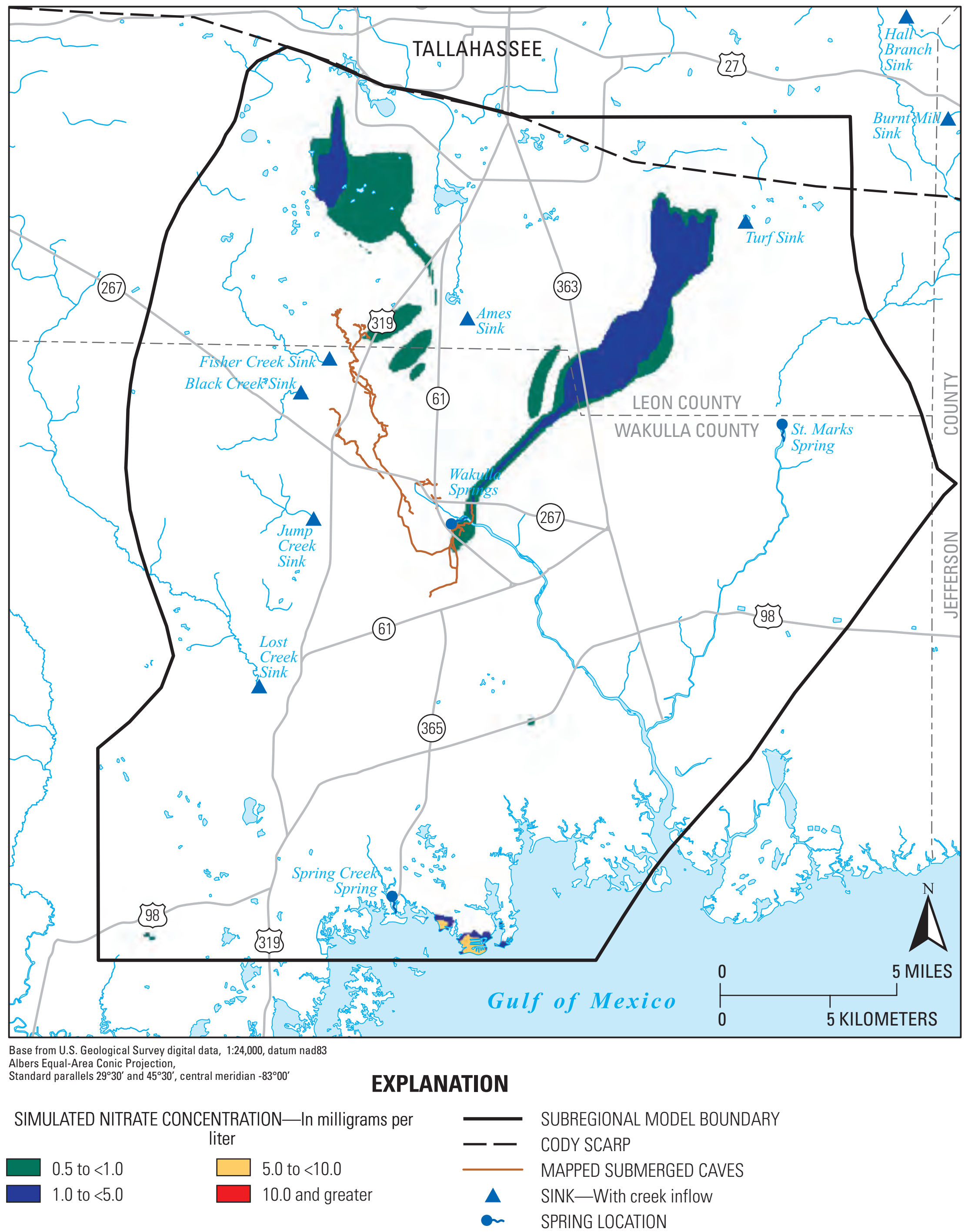


Figure 46. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 2 at the end of 1986.

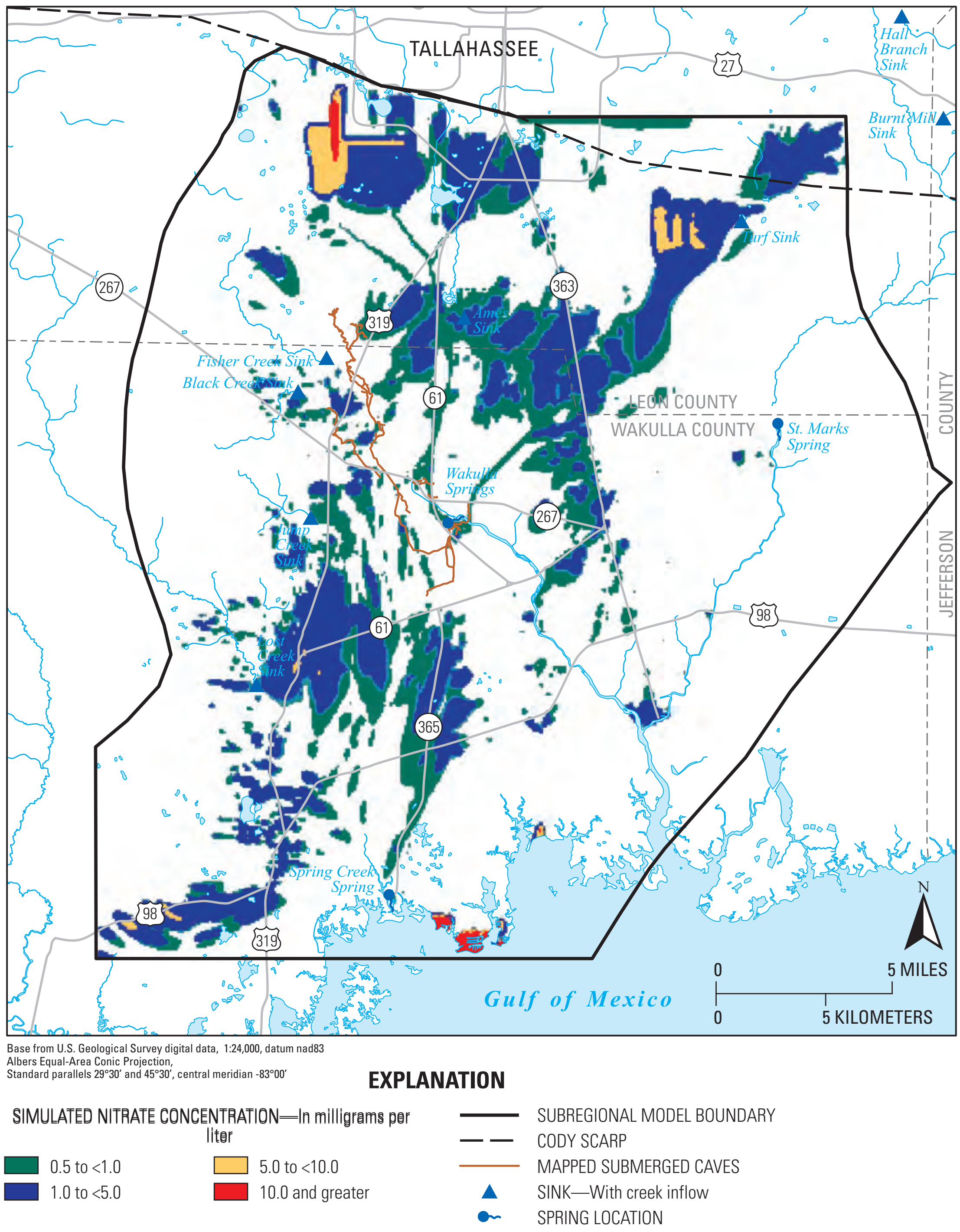


Figure 47. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 1 at the end of 2004.

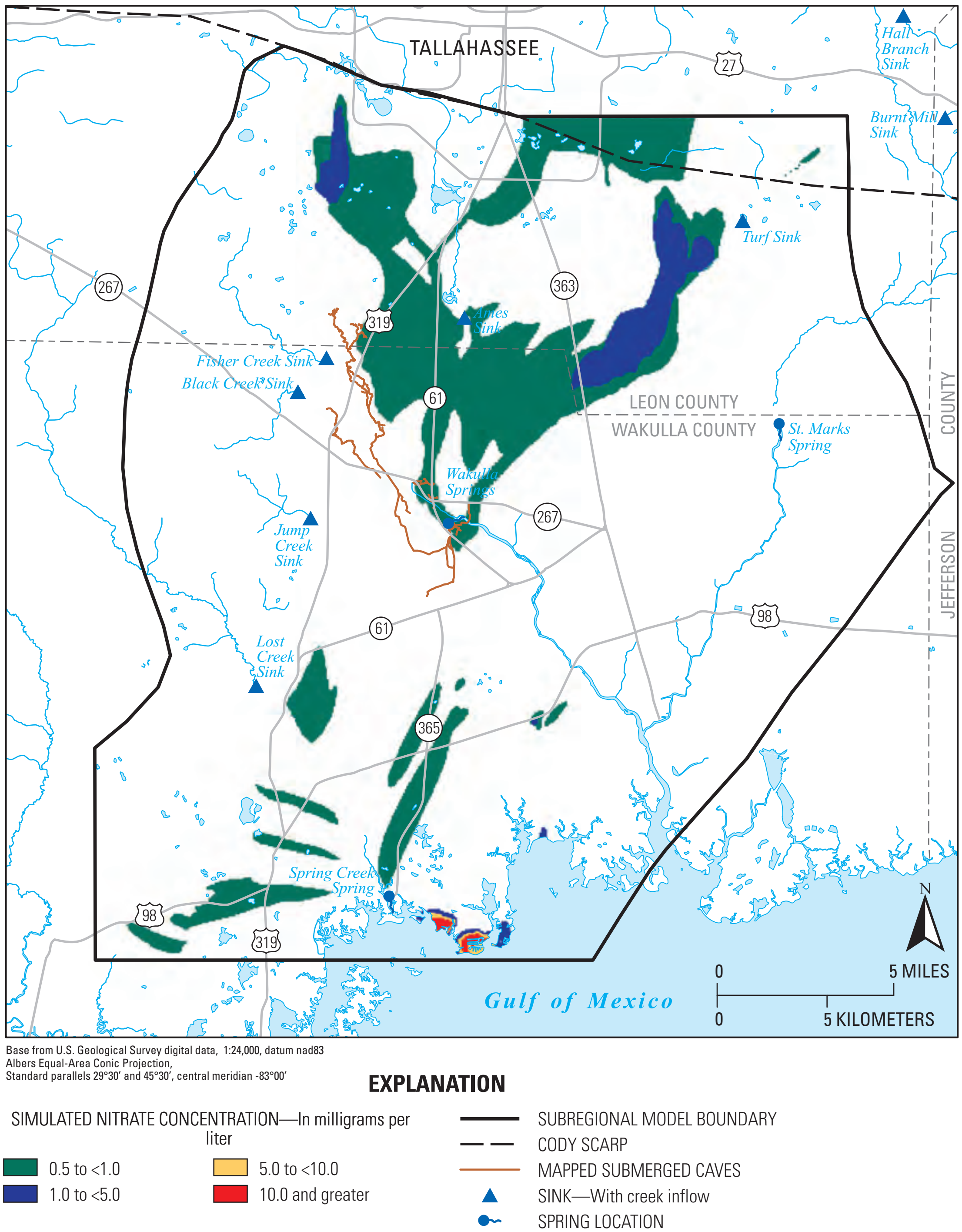
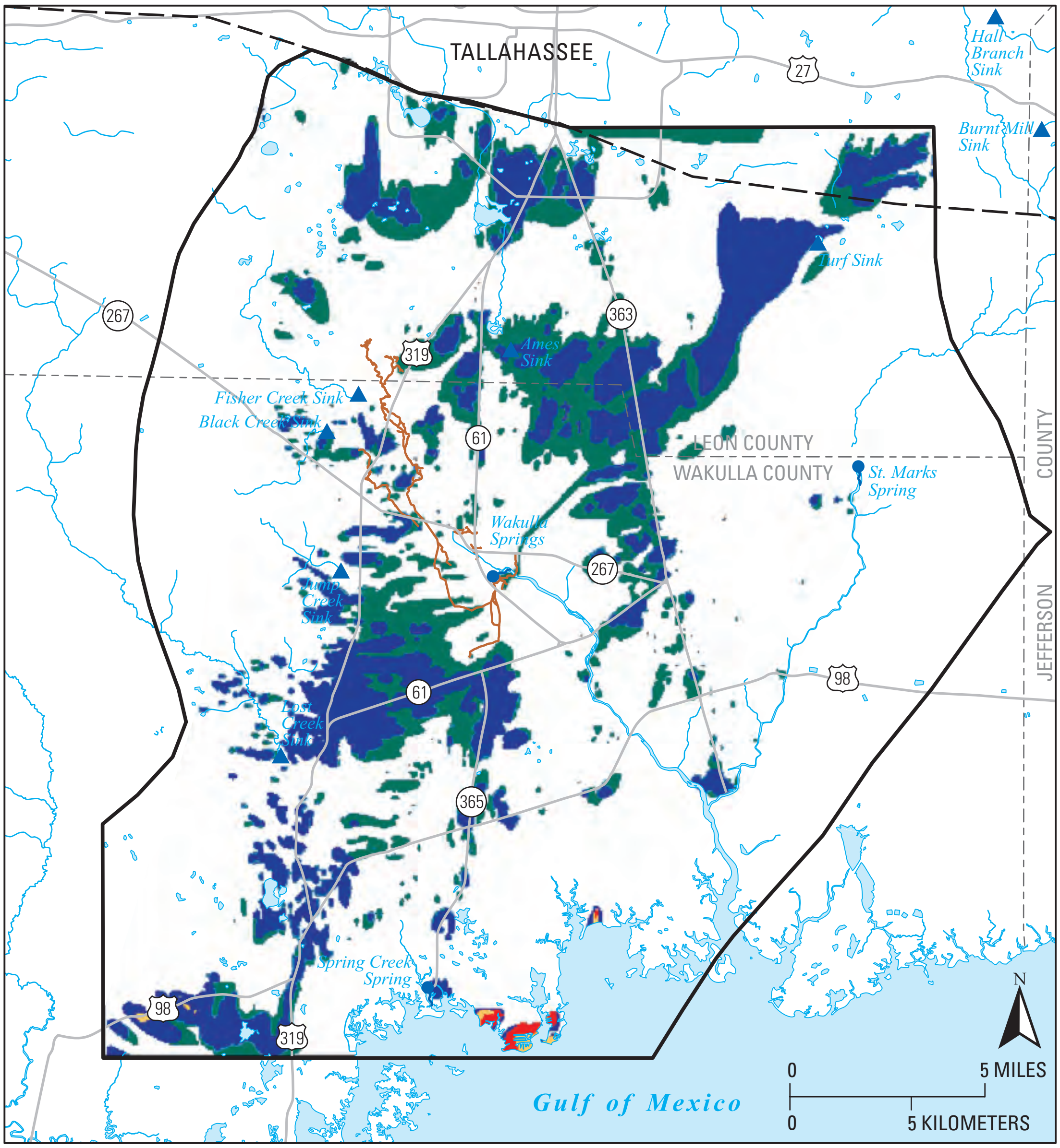


Figure 48. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 2 at the end of 2004.



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

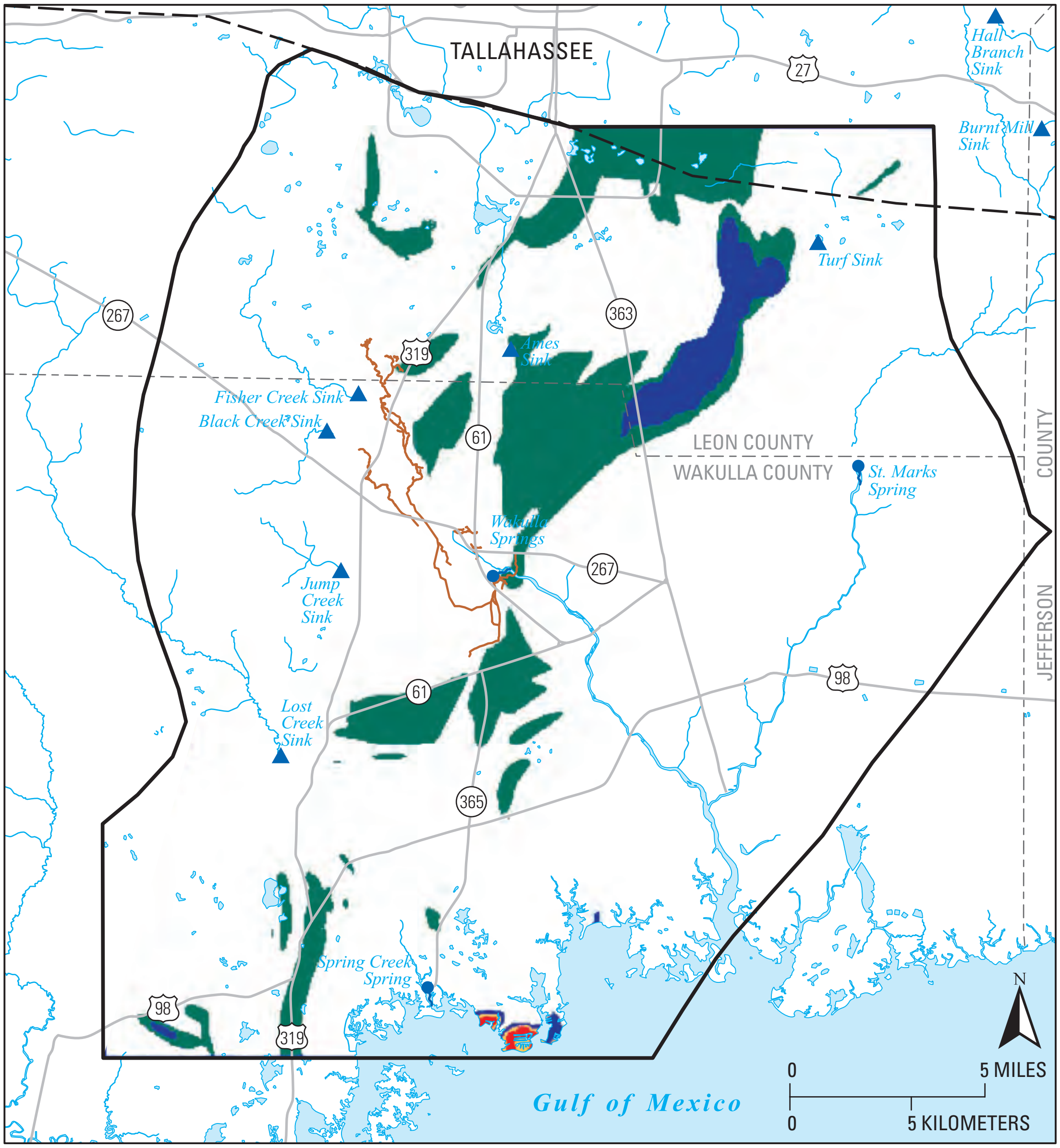
EXPLANATION

SIMULATED NITRATE CONCENTRATION—In milligrams per liter

- 0.5 to <1.0
- 1.0 to <5.0
- 5.0 to <10.0
- 10.0 and greater

- SUBREGIONAL MODEL BOUNDARY
- CODY SCARP
- MAPPED SUBMERGED CAVES
- SINK—With creek inflow
- SPRING LOCATION

Figure 49. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 1 at the end of 2006, assuming that Wakulla Springs is fully capturing the flow in the A-, K-, and R-tunnels.



Base from U.S. Geological Survey digital data, 1:24,000, datum nad83
Albers Equal-Area Conic Projection,
Standard parallels 29°30′ and 45°30′, central meridian -83°00′

EXPLANATION

SIMULATED NITRATE CONCENTRATION—In milligrams per liter

- 0.5 to <1.0
- 1.0 to <5.0
- 5.0 to <10.0
- 10.0 and greater

- SUBREGIONAL MODEL BOUNDARY
- CODY SCARP
- MAPPED SUBMERGED CAVES
- SINK—With creek inflow
- SPRING LOCATION

Figure 50. Simulated nitrate-N concentration in the Upper Floridan aquifer in model layer 2 at the end of 2006, assuming that Wakulla Springs is fully capturing the flow in the A-, K-, and R-tunnels.

End of 2007

The simulated nitrate-N concentrations discussed so far were from scenario 1; the starting year for scenario 2 is 2007 and both scenarios 1 and 2 will be discussed from hereafter. The scenario 1 nitrate-N distributions for the end of 2007 are shown on figures 51 and 52; the scenario 2 distributions are shown on figures 53 and 54. For both scenarios, the nitrate-N concentrations below the SEF sprayfield are less than 5 mg/L in layer 1, thus reflecting the elimination of fertilizer usage. Below the airport biosolids disposal site, the concentration is generally less than 0.5 mg/L, thus reflecting the elimination of disposal operations at this site in 2005. The widespread, relatively low concentrations related to residential OSDSs are slightly more widespread than in 2006. The nitrate-N concentrations below the SEF sprayfield are less than 5 mg/L (figs. 52 and 54) for both scenarios in layer 2. The predominant difference in the simulated nitrate-N distributions between scenario 1 and 2 occurs west and southwest of Wakulla Springs and is most apparent in layer 2 (figs. 52 and 54). The pattern of nitrate-N distribution west and southwest of Wakulla Springs in scenario 1, layer 2, is oriented toward the Spring Creek Springs Group because these springs are flowing. The nitrate-N concentrations are oriented toward Wakulla Springs in scenario 2, layer 2, because this spring is simulated to be capturing all the flow in the A-, K-, and R-tunnels and the Spring Creek Springs Group has essentially stopped flowing.

End of 2018

The scenario 1 nitrate-N distribution for layers 1 and 2 at the end of 2018 are shown on figures 55 and 56, respectively, and the scenario 2 distribution for layers 1 and 2 are shown on figures 57 and 58, respectively. For both scenarios, in layer 1, the nitrate-N concentrations below the SEF sprayfield are less than 5 mg/L, and downgradient, they fall below 1 mg/L due to dilution. The widespread, relatively low concentrations related to OSDSs are more widespread than in 2007. For both scenarios, in layer 2, the nitrate-N concentrations below the SEF sprayfield are less than 1 mg/L (figs. 56 and 58). The nitrate-N distribution west and southwest of Wakulla Springs for scenario 1, layer 2, is oriented toward the Spring Creek Springs Group because these springs are flowing. The nitrate-N concentrations are oriented toward Wakulla Springs for scenario 2, layer 2, because this is simulated to be capturing all of the flow in the A-, K-, and R-tunnels, and the Spring Creek Springs Group have essentially stopped flowing.

Simulated Nitrate-N Loading to the Upper Floridan Aquifer

The nitrate-N load to the UFA for each source was calculated using the calibrated model; this is the load that makes it through the unsaturated zone to reach this aquifer. This load was calculated for each model stress period by multiplying the nitrate-N concentration for each source by the volume of recharge for each source. The results of these calculations are shown on figures 13, 17, and 59, and table 8. The simulated nitrate-N load from the SWF sprayfield was about 4,800 kg/yr in 1967 (its first full year of operation), peaking at about 83,000 kg/yr in 1979, then abruptly declining to less than 2,000 kg/yr as wastewater effluent was diverted to the newly operational SEF sprayfield (fig. 59). The simulated nitrate-N load at SEF sprayfield was about 74,000 kg/yr in 1981 (its first full year of operation), peaking at about 241,000 kg/yr in 1986 when fertilizer usage was highest, and declining to about 118,000 kg/yr in 2004 due to the reduction in fertilizer usage. It is anticipated that the load will further decline to about 44,000 kg/yr in 2014 because of the City's plan to decrease the nitrate-N concentration in the wastewater effluent to 3 mg/L by 2013.

The nitrate-N load to the UFA from biosolids disposal was about 20,000 kg/yr in 1967, peaking at about 102,000 kg/yr in 1995, and then decreasing to essentially zero by the end of 2006 because biosolids disposal operations ceased in 2005. The simulated nitrate-N load to the UFA from OSDSs was about 21,000 kg/yr in 1967 and has increased ever since, reaching about 92,000 kg/yr in 2004. It is simulated to reach about 160,000 kg/yr by the year 2018. The loads from atmospheric deposition and creek inflows were simulated as constant at about 9,300 and 41,000 kg/yr, respectively, for the entire simulation period.

The simulated nitrate-N load to the UFA from fertilizer was about 8,400 kg/yr in 1967, increasing gradually to about 27,000 kg/yr in 2004. It is simulated to reach about 42,000 kg/yr by 2018. The load from livestock waste was about 5,000 kg/yr in 1967, increasing to about 19,000 kg/yr in 2004. It is simulated to reach about 32,000 kg/yr by 2018. The load from groundwater inflows along the lateral model boundaries was about 93,000 kg/yr in 1967, increasing to about 110,000 kg/yr in 2004. It is simulated to reach about 118,000 kg/yr by 2018.

Simulated Nitrate-N Loading to Wakulla Springs from All Sources

The calibrated model was used to simulate the effect of each nitrate-N source on Wakulla Springs. This was accomplished by running the model 16 separate times (8 times for each of the two scenarios). Only one nitrate-N source was simulated in each of the model runs to isolate its effect. The following discussion includes only the results from scenario 1, unless scenario 2 is specifically referenced.

Southeast and Southwest Farm Sprayfields

The nitrate-N load to Wakulla Springs from the SWF sprayfield was about 4,500 kg/yr in 1967, thus representing 6 percent of the total load to Wakulla Springs (fig. 59; table 8). It peaked at about 72,000 kg/yr (42 percent) in 1979 and then abruptly declined to less than 2,000 kg/yr (1 percent or less) as wastewater effluent was diverted to the newly operational SEF sprayfield. The nitrate-N load has been under 2,000 kg/yr ever since.

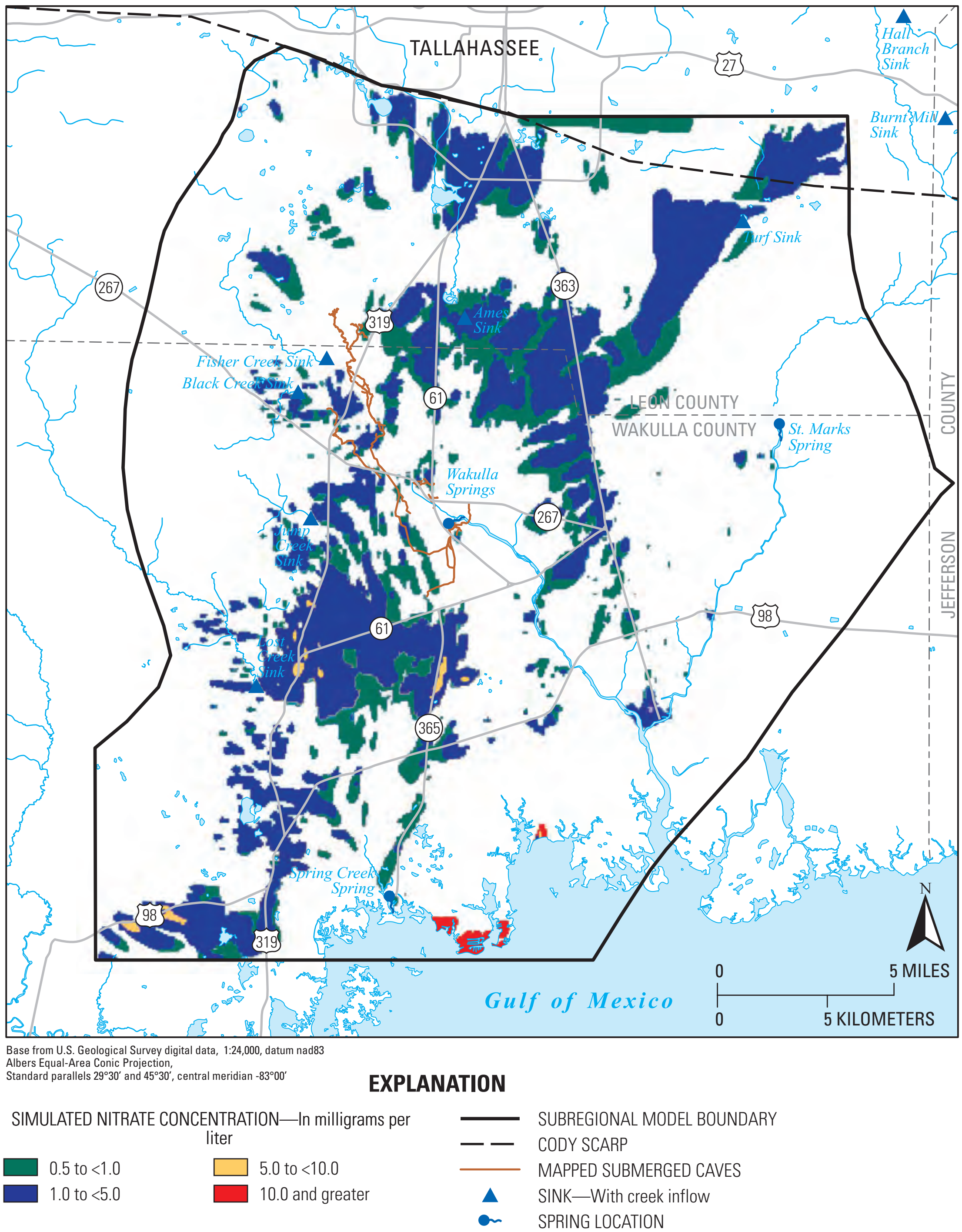


Figure 51. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 1 in model layer 1 at the end of 2007, assuming the flow in the R-tunnel is going to both Wakulla Springs and Spring Creek Springs Group.

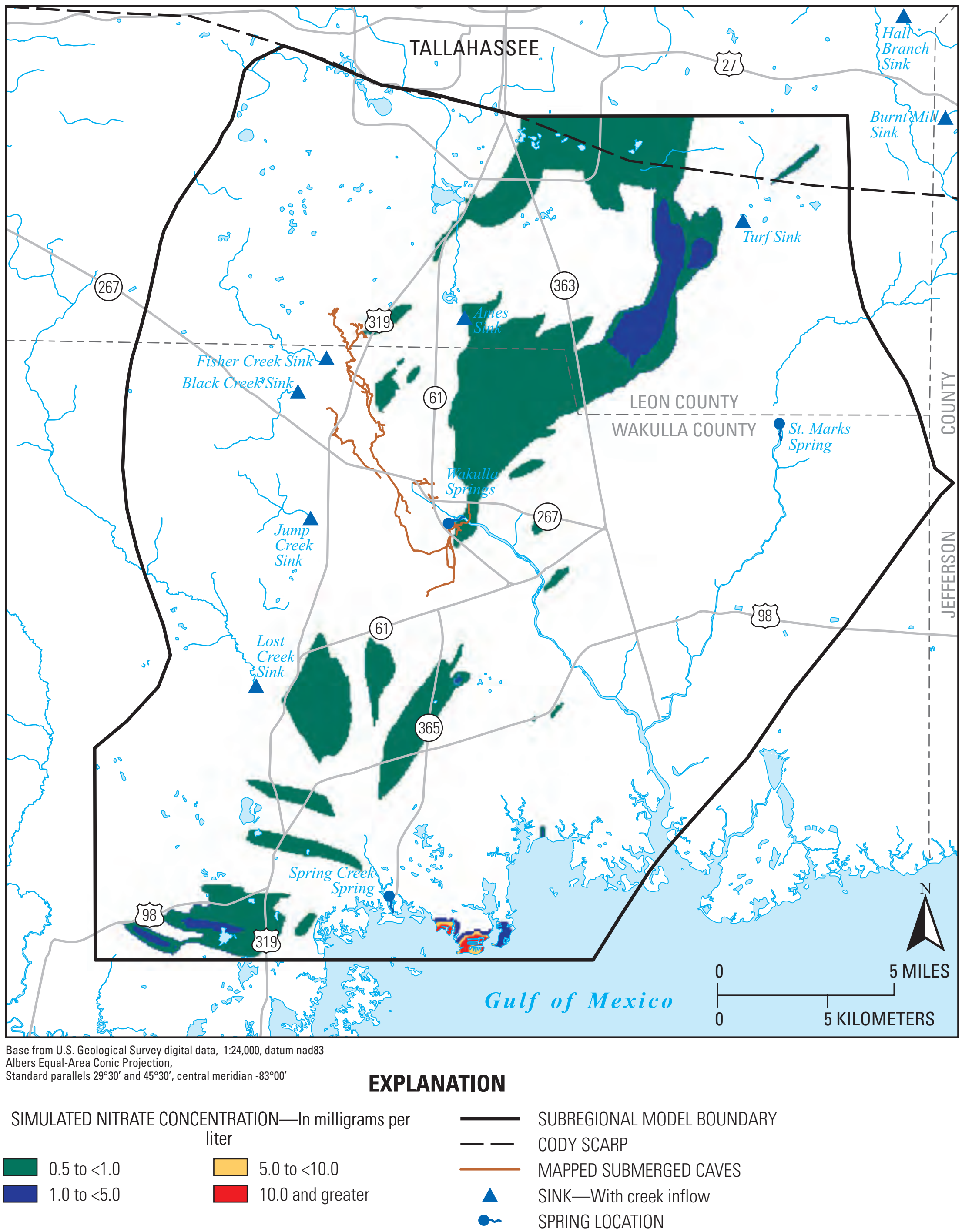


Figure 52. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 1 in model layer 2 at the end of 2007, assuming the flow in the R-tunnel is going to both Wakulla Springs and Spring Creek Springs Group.

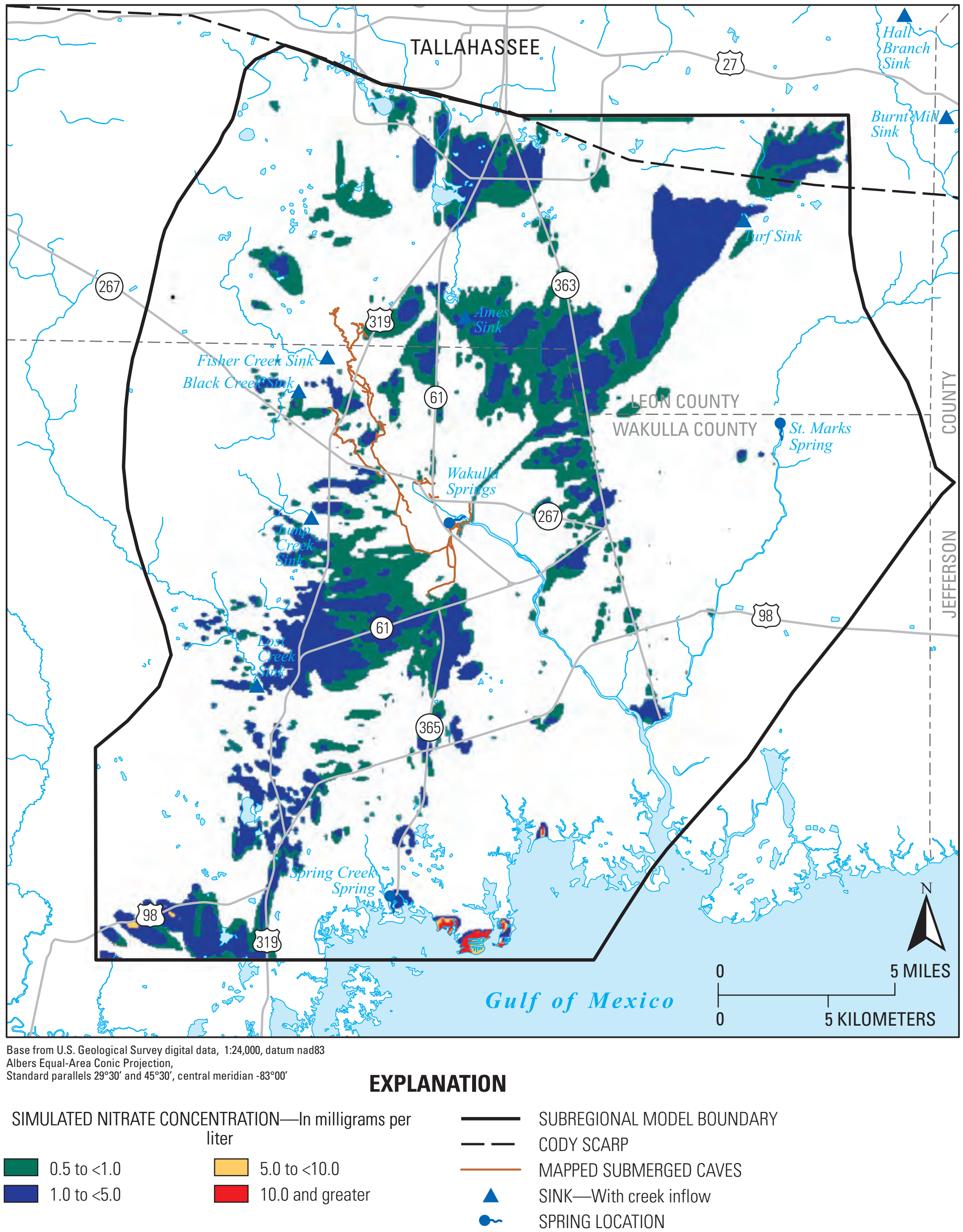


Figure 53. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 2 in model layer 1 at the end of 2007, assuming Wakulla Springs is fully capturing the flow in the A-, K-, and R-tunnels.

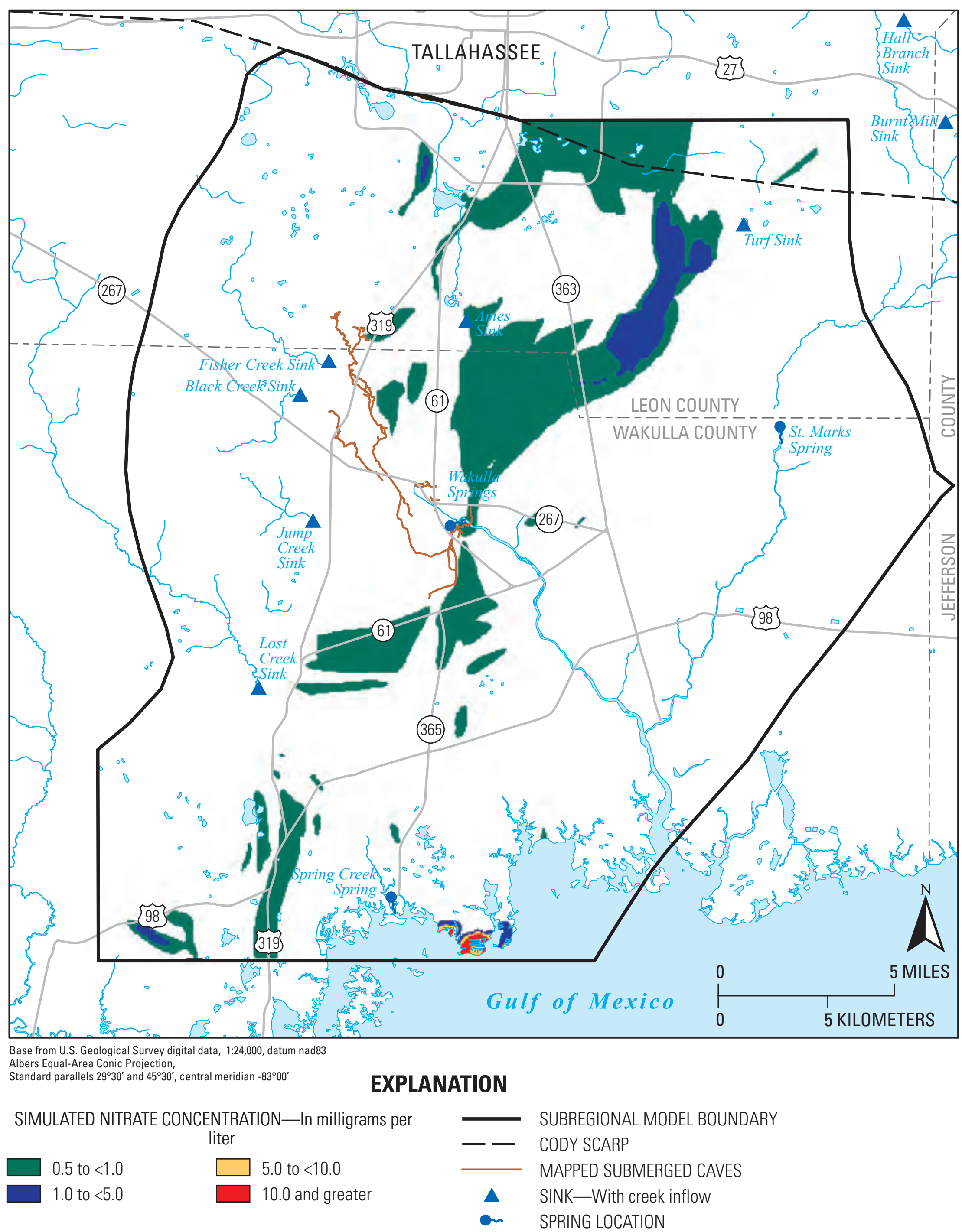


Figure 54. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 2 in model layer 2 at the end of 2007, assuming Wakulla Springs is fully capturing the flow in the A-, K-, and R-tunnels.

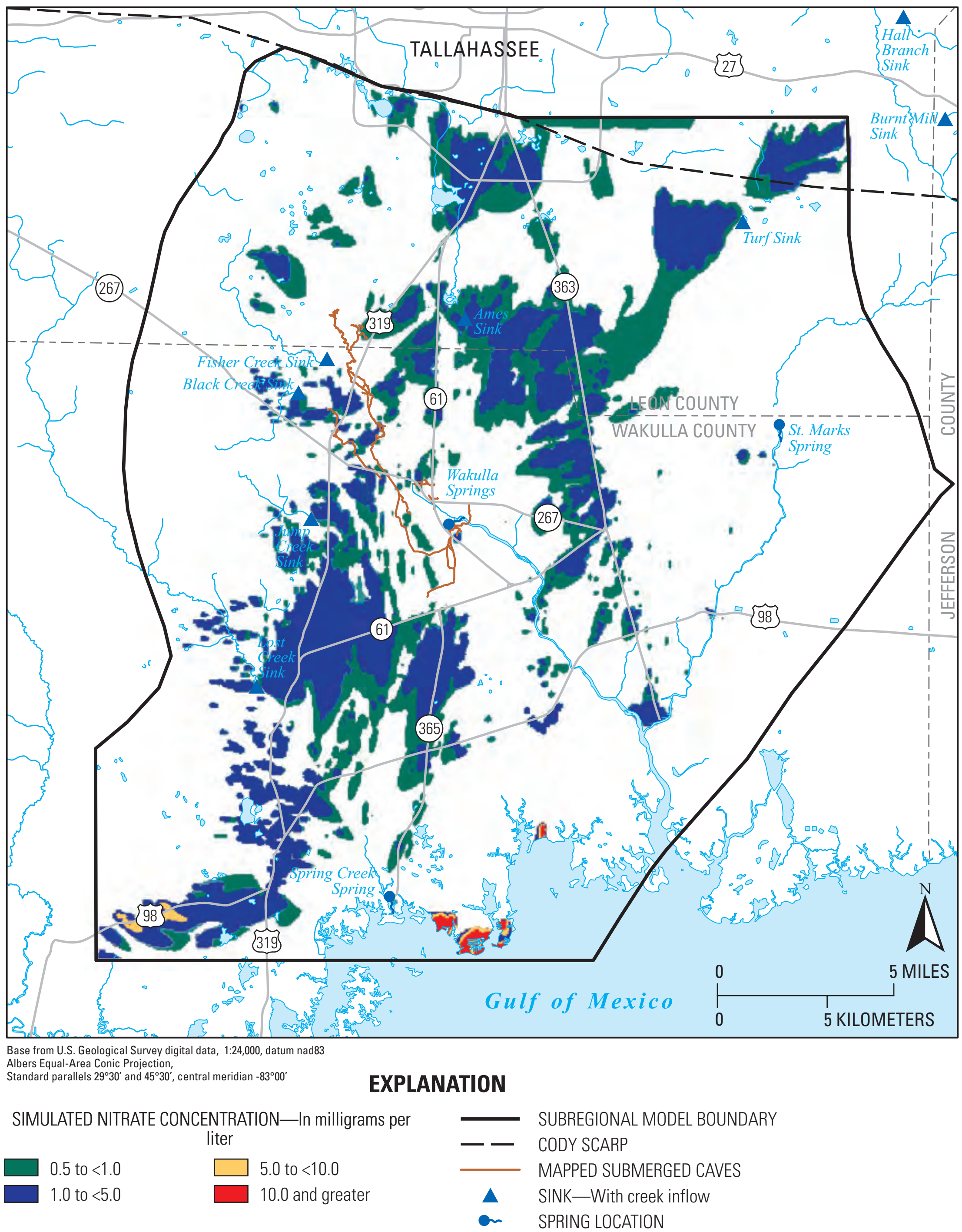


Figure 55. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 1 in model layer 1 at the end of 2018, assuming that the flow in the R-tunnel is going to both Wakulla Springs and the Spring Creek Springs Group.

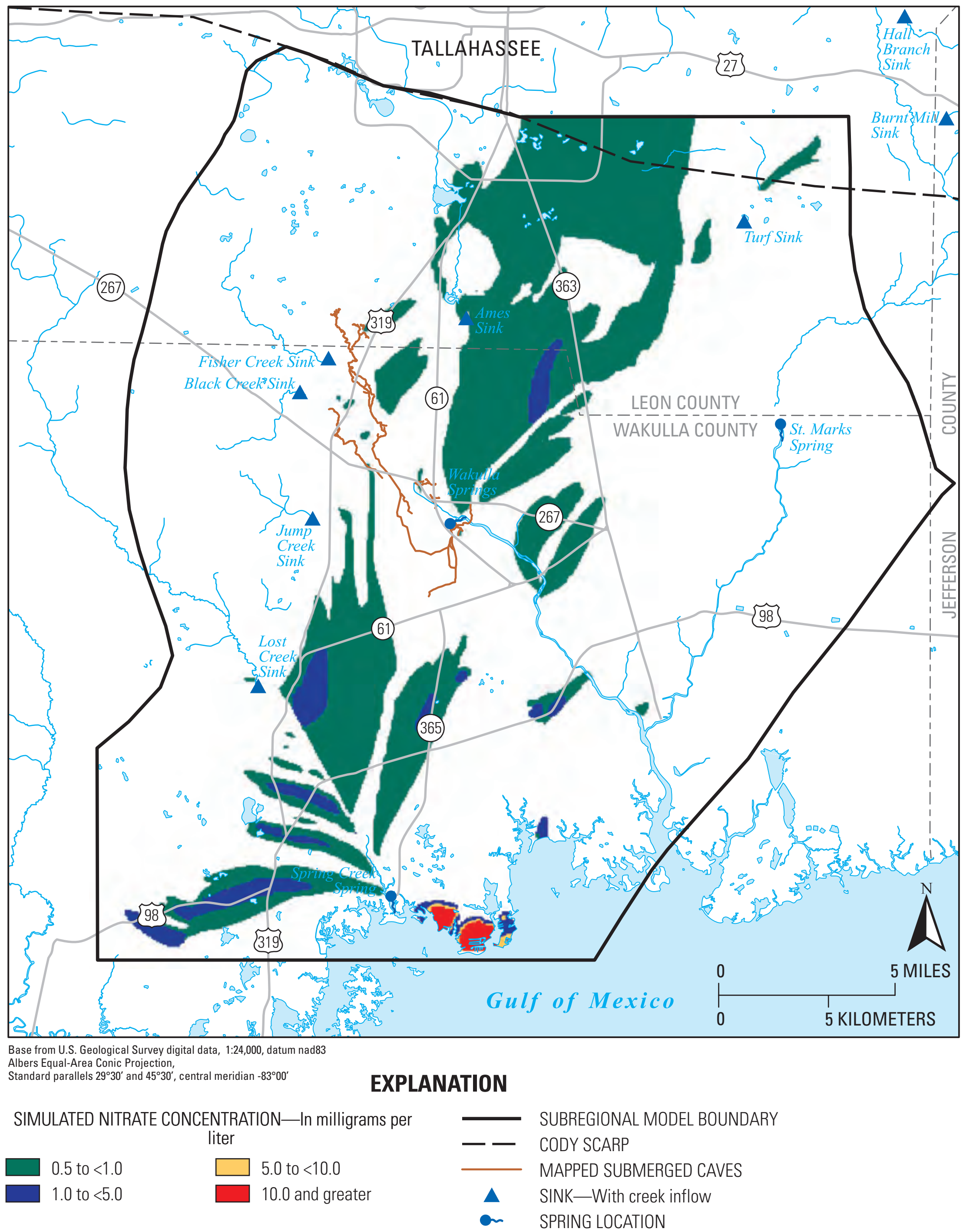


Figure 56. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 1 in model layer 2 at the end of 2018, assuming that the flow in the R-tunnel is going to both Wakulla Springs and the Spring Creek Springs Group.

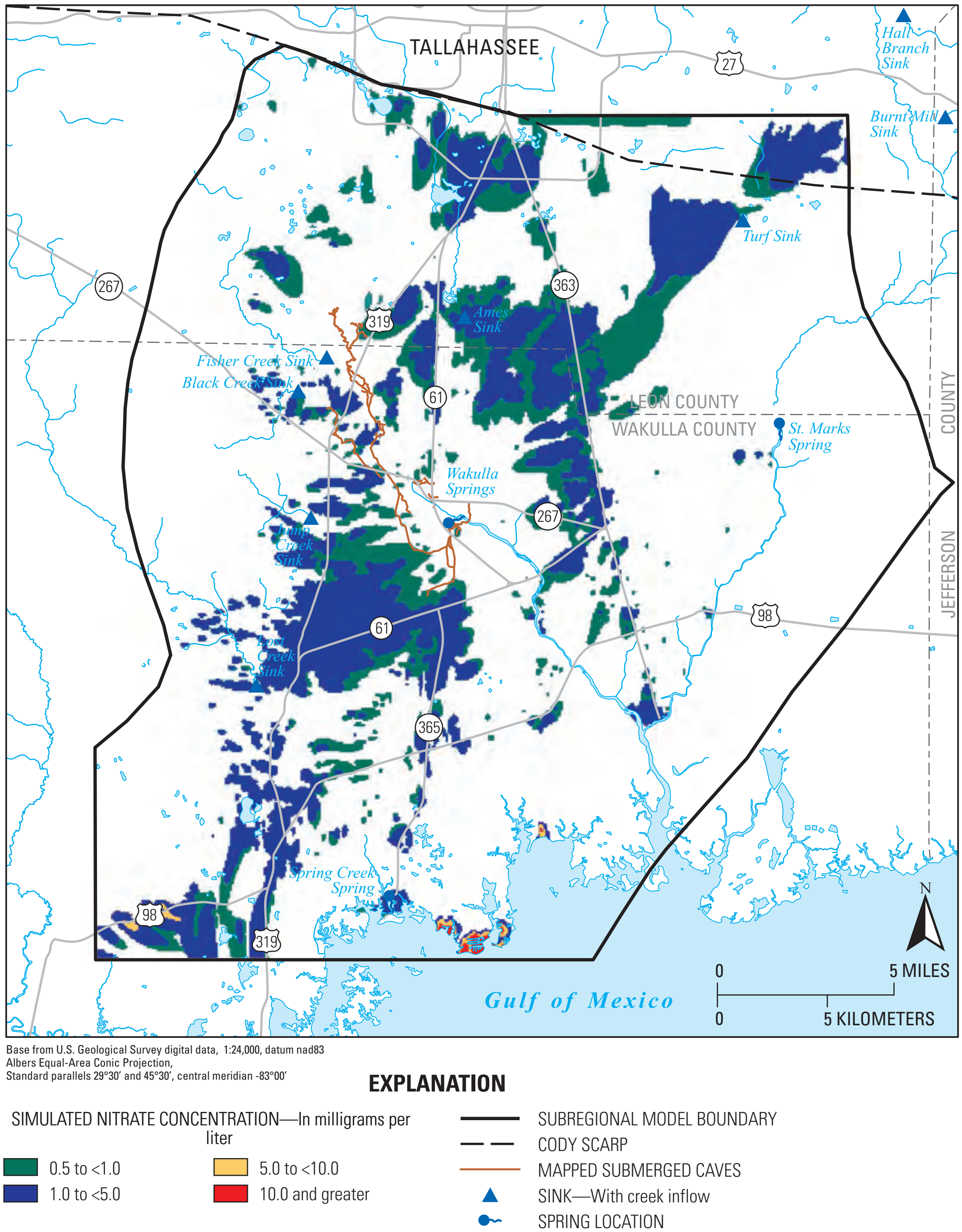


Figure 57. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 2 in model layer 1 at the end of 2018, assuming that Wakulla Springs is fully capturing the flow in the A, K and R-tunnels.

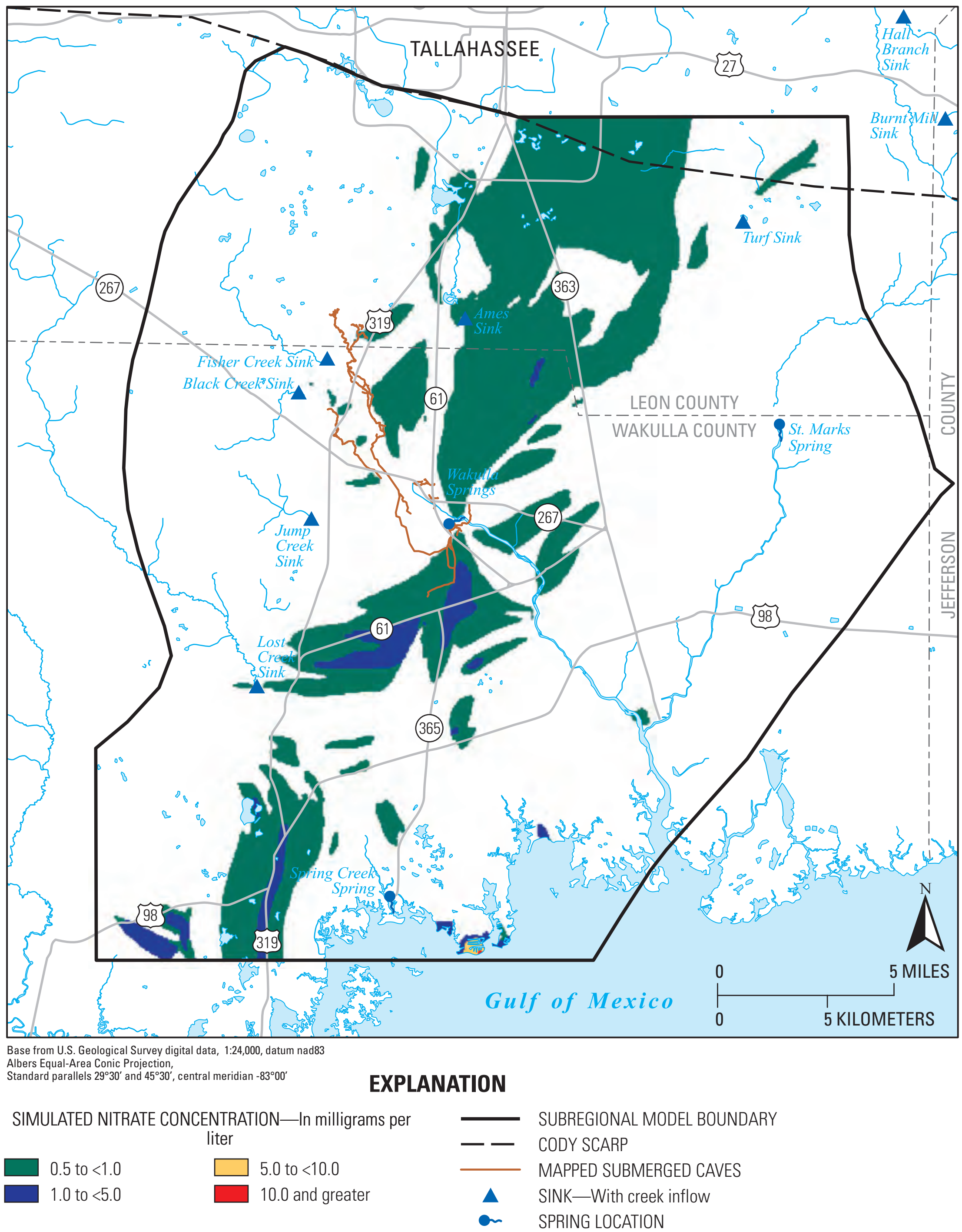


Figure 58. Simulated nitrate-N concentration in the Upper Floridan aquifer for scenario 2 in model layer 2 at the end of 2018, assuming that Wakulla Springs is fully capturing the flow in the A-, K-, and R-tunnels.

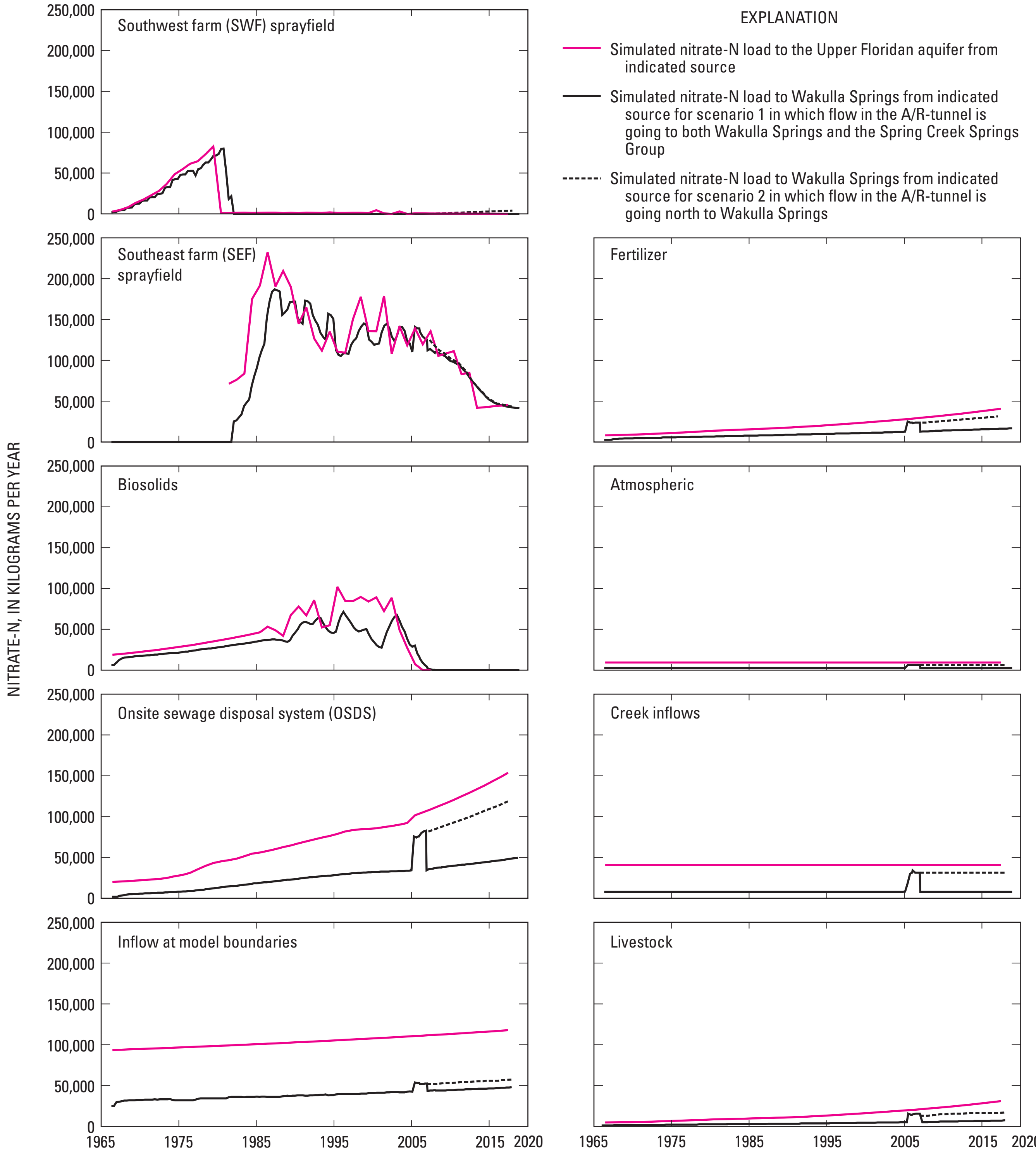


Figure 59. Simulated nitrate-N loads to the Upper Floridan aquifer and Wakulla Springs from all sources.

Table 8. Simulated nitrate-N loading to the Upper Floridan aquifer and Wakulla Springs in selected years.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; Nitrate-N, nitrate-nitrogen; OSDS, onsite sewage disposal systems; UFA, Upper Floridan aquifer; kg-N/yr, kg-N/yr, kilograms nitrate as nitrogen per year]

Year	SWF			SEF		
	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Spings from the SWF, in percent	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Spings from the SEF, in percent
Scenario 1: From 1/1/1966 to 4/1/2005 the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/1966[1]	2.8	2.2	4	0	0	0
12/31/1967	4.8	4.5	6	0	0	0
12/31/1979	83	72	42	0	0	0
12/31/1981[2]	1.1	0.8	0	74	22	17
12/31/1982	1.3	0.9	0	81	30	22
12/31/1983	1.5	1.1	0	89	48	31
12/31/1984	1.3	0.9	0	180	81	42
12/31/1986	1.6	1.1	0	241	172	59
12/31/1987	1.5	1.1	0	198	186	61
12/31/1995	1.1	0.8	0	116	107	39
12/31/1996	1.2	0.8	0	115	109	41
12/31/2001	0.7	0.5	0	187	145	49
12/31/2004	0.7	0.5	0	118	121	47
From 5/1/2005 to 1/1/2007, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2006	0.6	0.4	0	127	127	37
From 1/1/2007 to 12/31/2018, the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/2007	0.5	0.4	0	112	111	50
12/31/2013	0.2	0.1	0	54	65	33
12/31/2014	0.1	0.1	0	44	55	29
12/31/2018	0.1	0.1	0	47	42	24
Scenario 2. From 1/1/2007 to 12/31/2018, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2007	0.5	0.4	0	112	111	35
12/31/2013	0.2	0.1	0	54	66	21
12/31/2014	0.1	0.1	0	44	56	19
12/31/2018	0.1	0.1	0	47	43	14

[1]Southwest Farm sprayfield began operations in 1966.

[2]Southeast Farm sprayfield began operation in November 1980.

Table 8. Simulated nitrate-N loading to the Upper Floridan aquifer and Wakulla Springs in selected years—Continued.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; Nitrate-N, nitrate-nitrogen; OSDS, onsite sewage disposal systems; UFA, Upper Floridan aquifer; kg-N/yr, kg-N/yr, kilograms nitrate as nitrogen per year]

Year	Biosolids			Atmospheric Deposition		
	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Spings from biosolids, in percent	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs atmospheric deposition, in percent
Scenario 1: From 1/1/1966 to 4/1/2005 the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/1966[1]	19	6.1	15	9.3	2.6	4
12/31/1967	20	14	21	9.3	2.6	4
12/31/1979	35	28	16	9.3	2.6	2
12/31/1981[2]	39	31	24	9.3	2.6	2
12/31/1982	40	32	23	9.3	2.6	2
12/31/1983	42	33	21	9.3	2.6	2
12/31/1984	44	35	18	9.3	2.6	1
12/31/1986	53	37	13	9.3	2.6	1
12/31/1987	49	37	12	9.3	2.6	1
12/31/1995	102	58	25	9.3	2.6	1
12/31/1996	85	67	23	9.3	2.6	1
12/31/2001	72	57	16	9.3	2.6	1
12/31/2004	27	31	12	9.3	2.6	1
From 5/1/2005 to 1/1/2007, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2006	0	6.1	2	9.3	6.1	2
From 1/1/2007 to 12/31/2018, the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/2007	0	0	0	9.3	2.6	1
12/31/2013	0	0	0	9.3	2.6	1
12/31/2014	0	0	0	9.3	2.6	1
12/31/2018	0	0	0	9.3	2.6	1
Scenario 2. From 1/1/2007 to 12/31/2018, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2007	0	0	0	9.3	6.1	2
12/31/2013	0	0	0	9.3	6.1	2
12/31/2014	0	0	0	9.3	6.1	2
12/31/2018	0	0	0	9.3	6.1	2

[1]Southwest Farm sprayfield began operations in 1966.

[2]Southeast Farm sprayfield began operation in November 1980.

Table 8. Simulated nitrate-N loading to the Upper Floridan aquifer and Wakulla Springs in selected years—Continued.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; Nitrate-N, nitrate-nitrogen; OSDS, onsite sewage disposal systems; UFA, Upper Floridan aquifer; kg-N/yr, kg-N/yr, kilograms nitrate as nitrogen per year]

Year	Creeks Inflow to Sinks			OSDS		
	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs from creek inflows, in percent	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs from OSDS, in percent
Scenario 1: From 1/1/1966 to 4/1/2005 the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/1966[1]	41	7.8	13	20	4.8	8
12/31/1967	41	7.8	11	21	7.1	10
12/31/1979	41	7.8	5	43	15	9
12/31/1981[2]	41	7.8	6	47	18	14
12/31/1982	41	7.8	6	49	18	13
12/31/1983	41	7.8	5	52	19	12
12/31/1984	41	7.8	4	55	21	11
12/31/1986	41	7.8	3	58	22	8
12/31/1987	41	7.8	3	60	23	8
12/31/1995	41	7.8	3	79	31	12
12/31/1996	41	7.8	3	82	32	12
12/31/2001	41	7.8	3	87	35	12
12/31/2004	41	7.8	3	92	36	14
From 5/1/2005 to 1/1/2007, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2006	41	31	9	106	83	24
From 1/1/2007 to 12/31/2018, the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/2007	41	7.8	4	109	38	17
12/31/2013	41	7.8	4	134	45	24
12/31/2014	41	7.8	4	139	46	26
12/31/2018	41	7.8	4	160	51	29
Scenario 2. From 1/1/2007 to 12/31/2018, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2007	41	31	10	109	83	26
12/31/2013	41	31	10	134	104	34
12/31/2014	41	31	10	139	107	35
12/31/2018	41	31	10	160	119	39

[1]Southwest Farm sprayfield began operations in 1966.

[2]Southeast Farm sprayfield began operation in November 1980.

Table 8. Simulated nitrate-N loading to the Upper Floridan aquifer and Wakulla Springs in selected years—Continued.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; Nitrate-N, nitrate-nitrogen; OSDS, onsite sewage disposal systems; UFA, Upper Floridan aquifer; kg-N/yr, kg-N/yr, kilograms nitrate as nitrogen per year]

Year	Fertilizer			Livestock		
	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N Load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N Load to Wakulla Springs from fertilizer, in percent	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs from livestock, in percent
Scenario 1: From 1/1/1966 to 4/1/2005 the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/1966[1]	8.1	2.6	4	4.9	0.7	1
12/31/1967	8.4	3.7	5	5	1.5	2
12/31/1979	13	6.7	4	8.2	2.6	2
12/31/1981[2]	14	7.4	6	8.8	2.6	2
12/31/1982	15	7.4	5	9.1	2.6	2
12/31/1983	15	7.8	5	9.3	2.6	2
12/31/1984	15	7.8	4	9.6	3	2
12/31/1986	16	8.2	3	10	3	1
12/31/1987	17	8.6	3	10	3	1
12/31/1995	21	10	4	13	3.7	1
12/31/1996	22	10	4	14	3.7	1
12/31/2001	25	12	4	17	4.5	2
12/31/2004	27	13	5	19	4.8	2
From 5/1/2005 to 1/1/2007, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2006	29	26	8	21	14	4
From 1/1/2007 to 12/31/2018, the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.						
12/31/2007	29	13	6	22	5.2	2
12/31/2013	36	16	8	27	6	3
12/31/2014	37	16	9	28	6	3
12/31/2018	42	18	10	32	6.3	4
Scenario 2. From 1/1/2007 to 12/31/2018, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.						
12/31/2007	29	24	7	22	13	4
12/31/2013	36	29	9	27	16	5
12/31/2014	37	29	10	28	16	5
12/31/2018	42	32	10	32	17	6

[1]Southwest Farm sprayfield began operations in 1966.

[2]Southeast Farm sprayfield began operation in November 1980.

Table 8. Simulated nitrate-N loading to the Upper Floridan aquifer and Wakulla Springs in selected years—Continued.

[SWF, Southwest Farm sprayfield; SEF, Southeast Farm sprayfield; Nitrate-N, nitrate-nitrogen; OSDS, onsite sewage disposal systems; UFA, Upper Floridan aquifer; kg-N/yr, kg-N/yr, kilograms nitrate as nitrogen per year]

Year	Inflow at Model Boundaries			Totals	
	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs from the model boundaries, in percent	Nitrate-N load to the UFA, in 1000's of kg-N/yr	Nitrate-N load to Wakulla Springs, in 1000's of kg-N/yr
Scenario 1: From 1/1/1966 to 4/1/2005 the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.					
12/31/1966[1]	93	25	49	198	52
12/31/1967	94	31	43	204	72
12/31/1979	98	34	20	331	169
12/31/1981[2]	99	36	29	333	128
12/31/1982	99	36	26	345	138
12/31/1983	100	36	23	359	158
12/31/1984	100	36	19	455	195
12/31/1986	101	36	13	531	290
12/31/1987	101	36	12	487	306
12/31/1995	105	39	15	487	261
12/31/1996	106	40	15	476	273
12/31/2001	108	42	14	547	306
12/31/2004	110	43	17	444	259
From 5/1/2005 to 1/1/2007, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.					
12/31/2006	111	53	15	445	346
From 1/1/2007 to 12/31/2018, the simulated discharge from Wakulla Springs and Spring Creek Springs Group is approximately equal.					
12/31/2007	111	44	20	434	222
12/31/2013	115	46	25	416	188
12/31/2014	116	46	26	414	180
12/31/2018	118	48	28	449	175
Scenario 2. From 1/1/2007 to 12/31/2018, the simulated discharge at Wakulla Springs approximately doubled and Spring Creek Springs Group is not flowing significantly.					
12/31/2007	111	52	16	434	320
12/31/2013	115	55	18	416	307
12/31/2014	116	56	19	414	302
12/31/2018	118	57	19	449	305

[1]Southwest Farm sprayfield began operations in 1966.

[2]Southeast Farm sprayfield began operation in November 1980.

The simulated nitrate-N load to Wakulla Springs from the SEF sprayfield peaked in 1987 at about 186,000 kg/yr, or 61 percent (fig. 59; table 8). This peak was the result of the simulated application rate of 241,000 kg/yr, which occurred during 1986. The nitrate-N load trended downward irregularly after 1987, reaching 121,000 kg/yr (47 percent) in 2004. When Wakulla Springs was fully capturing the flow in the A-, K-, and R-tunnels in 2006, the load reached 127 kg/yr. However, this represented only 37 percent of the load; a percentage reduction occurred because the additional water brought in additional nitrate-N from other sources. The nitrate-N load to Wakulla Springs in 2007 was 111,000 kg/yr (50 percent). It is anticipated to decrease to 55,000 kg/yr (29 percent) in 2014 because of planned reductions in the nitrate-N wastewater effluent concentrations, and it is simulated to further decline to 42,000 kg/yr (24 percent) by 2018 due to these same reductions. The nitrate-N load to Wakulla Springs was 111,000 kg/yr (35 percent) for scenario 2 in 2007, and it is anticipated to decrease to 56,000 kg/yr (19 percent) in 2014. The nitrate-N load is simulated to further decline to 43,000 kg/yr (14 percent) by 2018. Total loads were similar for both scenarios, but the percentages that these loads represented were lower for scenario 2 because the additional water going to Wakulla Springs carried nitrate-N from other sources.

Atmospheric Deposition

The nitrate-N concentration in precipitation was simulated as a constant and the recharge rates were also a constant, thus indicating that the load to the UFA was constant during the entire simulation period. Therefore, the load to Wakulla Springs only varied when the flow to Wakulla Springs varied, increasing when the spring captured all of the flow in the A-, K-, and R-tunnels and falling when the spring did not capture all of the flow. When Wakulla Springs was simulated as not fully capturing the flow in these A-, K-, and R tunnels, the load was a constant 2,600 kg/yr. When Wakulla Springs was capturing this flow, the load was a constant 6,100 kg/yr. Atmospheric deposition accounted for 4 percent of the nitrate-N load to Wakulla Springs in 1967, decreasing to about 1 percent by 1984. The nitrate-N load from atmospheric deposition after 1984 remained between 1 and 2 percent for both the scenario 1 and 2 simulations.

Effluent Discharges from Onsite Sewage Disposal Systems

The simulated nitrate-N load to Wakulla Springs from OSDSs was about 7,100 kg/yr in 1967 (10 percent), and reached about 36,000 kg/yr in 2004 (14 percent) (fig. 59; table 8). When Wakulla Springs was fully capturing the flow in the A-, K-, and R-tunnels in 2006, the load from OSDSs increased dramatically to 83,000 kg/yr (24 percent). This substantial increase occurred because the additional flow going to Wakulla Springs came from an area with a high nitrate-N concentrations (figs. 49 and 50); these high concentrations were caused by a high density of OSDSs. Ironically, this influx of water increased the nitrate-N load to Wakulla Springs but decreased the concentration. This decrease occurred because the additional flow, almost doubling the discharge from Wakulla Springs, had a lower concentration of nitrate-N than the B-, C-, and D-tunnels. The simulated nitrate-N load to Wakulla Springs in 2007 decreased to 38,000 kg/yr (17 percent) as the Wakulla Springs stopped fully capturing the flow in the A-, K-, and R-tunnels and is anticipated to increase to 46,000 kg/yr (26 percent) in 2014 and to 51,000 kg/yr (29 percent) by 2018. For scenario 2, the nitrate-N load to Wakulla Springs in 2007 was 83,000 kg/yr (26 percent) and is anticipated to increase to 107,000 kg/yr (35 percent) in 2014 and to 119,000 kg/yr (39 percent) by 2018.

Inflow at Model Boundaries

The simulated nitrate-N load to Wakulla Springs across the model boundaries was about 31,000 kg/yr (43 percent) in 1967, reaching about 43,000 kg/yr (17 percent) in 2004, and increasing to 53,000 (15 percent) after May 1, 2005, when Wakulla Springs was fully capturing the flow in the A-, K-, and R-tunnels. The simulated nitrate-N load then decreased to about 44,000 kg/yr (20 percent) after January 1, 2007, when Wakulla Springs was no longer fully capturing the flow in the A-, K-, and R-tunnels. The load across the model boundaries is anticipated to be 48,000 kg/yr (28 percent) in 2018. The load reached about 52,000 kg/yr (16 percent) in 2007 in scenario 2, and is anticipated to reach about 57,000 kg/yr (19 percent) in 2018, thus reflecting the full capture of the flow in the A-, K-, and R-tunnels.

Disposal of Biosolids by Land Spreading

The simulated nitrate-N load to Wakulla Springs from biosolids was about 14,000 kg/yr in 1967 (21 percent) and peaked at about 67,000 kg/yr in 1996 (23 percent). The load decreased to zero in 2007, because biosolids disposal operations ceased in 2005.

Creeks Discharging into Sinks

The nitrate-N concentration and creek inflows were simulated as a constant; therefore, the load to the UFA was constant during the entire simulation period. The load to Wakulla Springs only varied when the flow to Wakulla Springs varied, increasing when the spring captured all of the flow in the A-, K-, and R-tunnels and decreasing when it did not capture all of the flow. When Wakulla Springs was simulated as not fully capturing the flow in these tunnels, the load was a constant 7,800 kg/yr. When Wakulla Springs was capturing this flow, the load was a constant 31,000 kg/yr (fig. 59 and table 8). Creek inflow accounted for 11 percent of the nitrate-N load to Wakulla Springs in 1967, decreasing to about 3 percent. Creek inflow increased to 9 percent after May 1, 2005, when Wakulla Springs was fully capturing the flow in the A-, K-, and R-tunnels. For scenario 1, the creek inflow load decreased to between 4 and 5 percent after January 1, 2007, when Wakulla Springs stopped fully capturing the flow in the A-, K-, and R-tunnels. The nitrate-N load was 10 percent from January 1, 2007, through 2018 in scenario 2, thus reflecting the full capture of the flow in the A-, K-, and R-tunnels.

Fertilizer Application

The simulated nitrate-N load to Wakulla Springs from fertilizer was about 3,700 kg/yr in 1967 (5 percent), increasing to about 13,000 kg/yr in 2004 (5 percent), and increasing to 26,000 kg/yr (8 percent) after May 1, 2005, when Wakulla Springs was fully capturing the flow in the A-, K-, and R-tunnels. Then, nitrate-N load from fertilizer decreased to about 13,000 kg/yr (6 percent) after January 1, 2007, when Wakulla Springs was no longer fully capturing the flow in the A-, K-, and R-tunnels. The nitrate-N load from fertilizer is anticipated to increase again to about 18,000 kg/yr (10 percent). The load reached about 24,000 kg/yr in 2007 (7 percent) in scenario 2, and about 32,000 kg/yr in 2018 (10 percent), thus reflecting the full capture of the flow in the A-, K-, and R-tunnels.

Livestock Wastes

The simulated nitrate-N load to Wakulla Springs from livestock in 1967 was about 1,500 kg/yr (2 percent), increasing to about 4,800 kg/yr (2 percent) in 2004, and increasing to 14,000 kg/yr (4 percent) after May 1, 2005, when Wakulla Springs was fully capturing the flow in the A-, K-, and R-tunnels. Then, nitrate-N load decreased to about 5,200 kg/yr (2 percent) after January 1, 2007, when Wakulla Springs was no longer fully capturing the flow in the A-, K-, and R-tunnels. The load is anticipated to reach 6,300 kg/yr (4 percent) by 2018. The nitrate-N load reached about 13,000 kg/yr (4 percent) in 2007 in scenario 2 and reached about 17,000 kg/yr (6 percent) in 2018, thus reflecting the full capture of the flow in the A-, K-, and R-tunnels.

Model Sensitivity Analysis

Model sensitivity tests were conducted to assess the response of the calibrated model to a change in one input parameter while the other parameters were unchanged. The subregional groundwater flow model will be discussed first, and the fate and transport model will be discussed next. A sensitivity analysis was conducted on the original regional groundwater flow model for the parameters transmissivity, vertical conductance, and recharge (Davis, 1996) and will not be repeated in these discussions.

Groundwater Flow Model Sensitivity Analysis

The input parameters tested for the subregional groundwater flow model were hydraulic conductivities for layers 1 and 2, vertical conductance between layers 1 and 2, and net recharge. The sensitivity tests were conducted by:

1. Changing an input parameter by plus or minus 50 percent from the calibrated value,
2. Calculating the number of simulated heads exceeding the error criterion, and
3. Comparing the simulated rate of groundwater discharge to rivers with the measured values.

The greater the number of heads that exceeds the error criterion (not being within 5 ft of the measured values), and the larger the difference between simulated river discharges and measured discharges, the greater the sensitivity of the model to that particular parameter.

The model sensitivity test for 1991 was selected because both water levels and flow measurements for all three major spring groups were available. Generally, the number of heads that exceeded the error criterion changed little for each parameter tested because the model boundary consisted of constant head cells that suppressed water-level fluctuations. However, the simulated discharges did change across a broad range. The model was most sensitive to changes in horizontal hydraulic conductivities, especially in layer 2 (table 9). A decrease in horizontal hydraulic conductivities of 50 percent caused the number of simulated heads exceeding the error criterion to increase slightly from 1 to 2. However, the simulated groundwater discharges to Wakulla Springs, the Spring Creek Springs Group, and St. Marks River springs decreased 25, 50, and 39 percent, respectively (table 9). The lower horizontal hydraulic conductivities restricted inflow of water to the model from the constant head cells along the model boundaries, thus reducing the spring and river discharges. In contrast, an increase in horizontal hydraulic conductivities of 50 percent caused the simulated groundwater discharges to Wakulla Springs, the Spring Creek Springs Group, and the St. Marks River springs to increase by 24, 32, and 78 percent, respectively (table 9). The higher horizontal hydraulic conductivities allowed more inflow of water to the model along the model boundaries, thus increasing the spring and river discharges. Raising and lowering the horizontal hydraulic conductivities in layer 1 had a similar effect (except to a lower degree), because the hydraulic conductivities overall were lower in layer 1.

In the calibrated model, neither a decrease nor an increase of 50 percent in the vertical hydraulic conductivities caused a change in the number of heads within the calibration criterion, or in the simulated groundwater discharges in Wakulla Springs, the Spring Creek Springs Group, and St. Marks River springs. The vertical hydraulic conductivities were set equal to the horizontal hydraulic conductivities in layer 1 because the aquifer consists of very permeable limestone with no known clay or other horizontal low-permeability layers. Since they were relatively high to begin with, lowering them 50 percent did not substantially restrict vertical flow; likewise, raising them by 50 percent did not increase vertical flow.

A decrease in the recharge rate of 50 percent caused the simulated groundwater discharges in Wakulla Springs, the Spring Creek Springs Group, and St. Marks River springs to decrease 23, 5, and 6 percent, respectively (table 9). In contrast, an increase in recharge of 50 percent caused the simulated groundwater discharges to Wakulla Springs, the Spring Creek Springs Group, and St. Marks River springs to increase by 23, 16, and 6 percent, respectively (table 9). The simulated discharges in the St. Marks River were relatively insensitive to recharge rates because the river is located near the model boundaries and received a relatively small volume of water from recharge and a larger volume from the model boundaries.

The sensitivity of discharge in the simulated springs to a change in stage at the Spring Creek Springs Group was tested. The sensitivity analysis was conducted by raising the simulated stage in the Spring Creek Springs Group by 2, 4, and 6 ft (table 10). When the simulated stage in the Spring Creek Springs Group was raised to 2 ft (it was 0 ft in the calibrated model), the flow in the Spring Creek Spring Group decreased from 328 ft^3/s in the calibrated model to 189 ft^3/s; meanwhile, the flow in Wakulla Springs increased from 368 ft^3/s in the calibrated model to 533 ft^3/s (table 10). When the simulated stage in the Spring Creek Springs Group was raised to 4 ft, the flow in the Spring Creek Springs Group decreased to 90 ft^3/s and the flow at Wakulla Springs increased to 613 ft^3/s (table 10). When the simulated stage in the Spring Creek Springs Group was raised to 6 ft, the Spring Creek Springs Group ceased to flow and the flow at Wakulla Springs increased to 685 ft^3/s (table 10). Effects of these changes on St. Marks River discharge was relatively minor, because the St. Marks River springs are farthest away from the Spring Creek Springs Group.

Fate and Transport Model Sensitivity Analysis

Model sensitivity tests for the fate and transport model were conducted to determine the effect of changes in effective porosity and dispersion. Effective porosity is the most important of the fate and transport parameters because it determines how fast groundwater moves through the UFA, and thus, how rapidly nitrate-N reaches Wakulla Springs. To determine the impact of changing the effective porosity in layer 1, the calibrated value of 0.01 was changed to 0.001, thus increasing the velocity of groundwater flow; and the calibrated value was increased to 0.3, thus decreasing the velocity of groundwater. Decreasing the layer 1 effective porosity from 0.01 to 0.001 resulted in the model predicting about the same nitrate-N concentrations as the calibrated model predicted (fig. 60*A*). This result indicates that the effective porosity in the calibrated model is sufficiently low, and the traveltime through layer 1 is sufficiently short. Therefore, reducing effective porosity further does not affect the simulated concentrations at Wakulla Springs (the flow in this layer is largely vertical so the distance traveled is relatively short). However, increasing the layer 1 effective porosity from 0.01 to 0.3 resulted in the model predicting much lower nitrate-N concentrations than the concentrations in the calibrated model (fig. 60*B*). The higher effective porosity resulted in

Table 9. Results of the subregional groundwater flow model sensitivity analysis.

Parameter changed	Number of cells in which the difference between the simulated head and measured head exceeded 5 feet for 1991	Difference between measured river gain and simulated river gain, in percent		
		Wakulla Springs	Spring Creek Springs Group	St. Marks River springs
Calibrated model	1	+5	+7	-3
Horizontal hydraulic conductivity for layer 1 is -50 percent	1	-5	-6	-19
Horizontal hydraulic conductivity for layer 1 is +50 percent	1	+9	+8	+10
Horizontal hydraulic conductivity for layer 2 is -50 percent	2	-25	-50	-39
Horizontal hydraulic conductivity for layer 2 is +50 percent	1	24	32	78
Vertical hydraulic conductivity for layer 1 is -50 percent	1			
	+5	+7	-3	
Vertical hydraulic conductivity for layer 1 is +50 percent	1	+5	+7	-3
Recharge is -50 percent	1	-23	-5	-6
Recharge is +50 percent	2	23	16	6

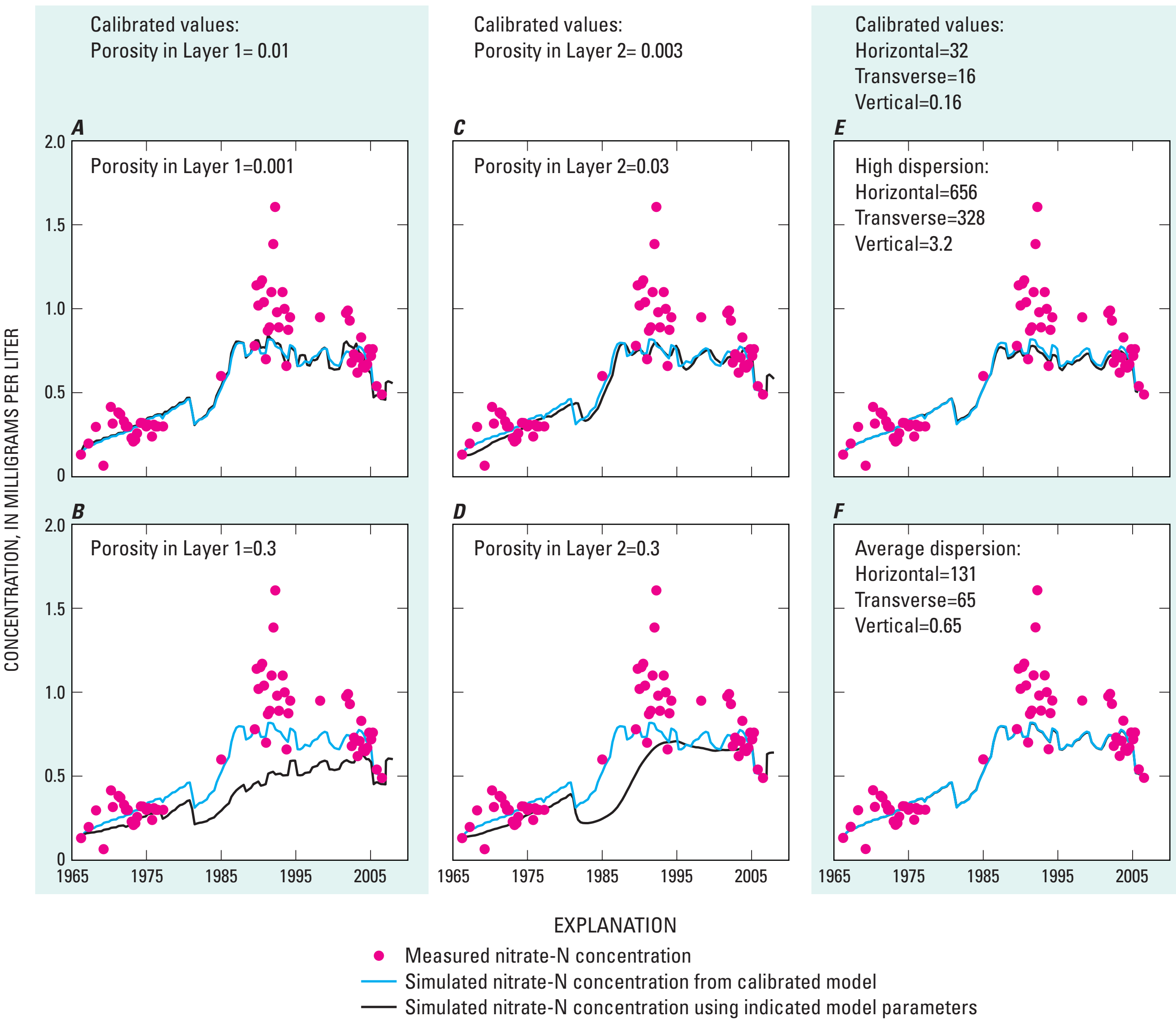


Figure 60. Results of the subregional fate and transport model sensitivity analysis.

Table 10. Results of the subregional groundwater flow sensitivity analysis for stage in Spring Creek Springs Group.

[ft, feet; ft³/s, cubic feet per second]

Parameter changed	Number of cells in which the difference between the simulated head and measured head exceeded 5 feet for 1991	Difference between measured river gain and simulated river gain, in percent		
		Wakulla Springs, in ft³/s	Spring Creek Springs Group, in ft³/s	St. Marks River springs, in ft³/s
Stage in Spring Creek Springs Group at 0 ft (calibrated model)	1	368	328	589
Stage in Spring Creek Springs Group raised 2 ft	1	533	189	592
Stage in Spring Creek Springs Group raised 4 ft	1	613	90	596
Stage in Spring Creek Springs Group raised 6 ft	1	685	0	599

groundwater and nitrate-N moving much slower through layer 1. Therefore, nitrate-N loading took much longer to reach layer 2 and much longer to arrive at Wakulla Springs, thus resulting in lower simulated concentrations.

The sensitivity analysis for porosity in layer 2 was more complicated because all of the simulated caves were in this layer. Traveltimes through some of the most important caves were determined by tracer tests determined directly. Dye injected into Fisher Sink was detected in Wakulla Springs in about 10 days; dye injected into Ames Sink was detected in Wakulla Springs in about 20 days (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006). Dye was injected into Turf Sink, located at the SEF, and was detected in Wakulla Springs in about 40 days (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006). Porosities in the calibrated model were adjusted to match the measured traveltimes (because these were known, they were not tested in the sensitivity analysis). However, most of the model domain was in areas away from the caves and the effective porosity in these areas is not well known. The only measurement of traveltime away from known caves was made at the SEF where dye was injected into wells SE-06, SE-40, and SE-11S (Todd Kincaid, Hazlett-Kincaid, Inc., written commun., 2006) particle tracking techniques indicated that an effective porosity of 0.003 in layer 2 best matched this test. Therefore, this value was used for all of layer 2 (not including the simulated caves). To determine the impact of changes in this value, effective porosity was lowered to 0.001 in one test, thus increasing the velocity of groundwater flow; the calibrated was increased to 0.3 in another test, thus decreasing the velocity of groundwater flow. Lowering the effective porosity to 0.001 resulted in the model predicting about the same nitrate-N concentrations as the calibrated model (fig. 60*C*). This indicates that the effective porosity in the calibrated model is sufficiently low and the traveltime through layer 2 sufficiently short. Reducing effective porosity further would not affect the simulated concentrations at Wakulla Springs. Increasing the effective porosity to 0.3 in layer 2 resulted in the model predicting much lower nitrate-N concentrations than in the calibrated model (fig. 60*D*). Increased effective porosity resulted in groundwater moving much slower through layer 2, thus taking nitrate-N much longer to reach Wakulla Springs and resulting in lower simulated concentrations.

The dispersivity coefficient determines how rapidly the solutes spread as they move with the groundwater. For the calibrated model, the longitudinal dispersivity coefficient was 32 ft (in the direction of the flow axis), the transverse dispersivity coefficient was 16 (perpendicular to the flow axis), and the vertical dispersivity coefficient was 0.16. To determine the effect of a change in dispersivity, one model run was conducted where the values were raised by a factor of 4 to 131, 65, and 0.65 for longitudinal, transverse, and vertical dispersivities, respectively. Another model run was conducted where the values were raised by a factor of 20 to 656, 328, and 3.2 for longitudinal, transverse, and vertical dispersivities, respectively. The effects of the changes were determined by comparing the new simulated nitrate-N concentrations at Wakulla Springs to those in the calibrated model run. Increasing dispersivity by a factor of 4 resulted in a simulated nitrate-N concentration that was similar to the calibrated model (fig. 60*E*); increasing dispersivity by a factor of 20 had a similar result (fig. 60*F*). The insensitivity to dispersivity is because the groundwater is converging toward the springs, and this convergence can override the spreading effect of dispersivity. The dispersivity values used in the calibrated model were taken from Gelhar and others (1992) and were on the low end of the range for the values that Gelhar and others considered reasonable. Therefore, it is unlikely that the values used in the modeling should have been any lower, because lower values would have produced less dispersion and, even the higher values did not result in substantial dispersion.

Model Limitations

The simulation of nitrate-N concentrations and the traveltimes to Wakulla Springs are subject to three major sources of error:

1. The simulated groundwater flow velocities might not accurately reflect the actual flow velocities,
2. The measured nitrate-N concentrations used to calibrate the model might not fully characterize the contaminant concentrations in the aquifer, and
3. The model input parameters might not accurately characterize the transport mechanisms.

Groundwater velocity is the most important factor when predicting the traveltime from the source areas to the springs. If the actual groundwater velocities are greater than the simulated velocities, then the nitrate-N will move toward and into the springs faster than predicted. If the simulated velocities are slower, then nitrate-N will remain in the aquifer longer and arrive at the springs later than predicted. Simulated nitrate-N concentrations discharging to the springs are related to initial concentrations at the sources. If the simulated concentrations in the source areas are substantially higher than the actual concentrations, then the model-predicted concentrations discharging to the springs will be too high. However, the nitrate-N concentrations at the SEF sprayfield were characterized by multiple monitoring wells, thus making it less likely that substantially higher concentrations existed at this important source.

Model parameters, such as hydrodynamic dispersion and porosity, can have a strong influence on the simulated movement and concentrations of nitrate-N. Variations in either of these parameters can affect the model-simulated fate and transport of contaminants. As discussed earlier, the effect of hydrodynamic dispersion on these simulations was minimal. In contrast, the effect of porosity can be substantial. If the porosity is doubled, then the traveltime of the nitrate-N is halved. Conversely, if the porosity factor is halved, then the traveltime is doubled.

Summary

Increasing concentrations of nitrate-N in rivers, lakes, and springs in many parts of Florida have resulted in detrimental effects to aquatic ecosystems, including a proliferation of nuisance aquatic vegetation and accelerated algal growth. In particular, public concern has grown over the last few years about the increased nitrate-N levels in Wakulla Springs, which, in combination with the generally clear spring water and abundant sunshine, may be encouraging invasive plant species growth.

Prior to 1966, the City of Tallahassee discharged treated wastewater to a local lake, causing algal blooms. To reduce the impact on the lake, the City began using wastewater in 1966 to irrigate crops, using center pivot irrigation techniques in a pilot project at the Southwest Farm (SWF) sprayfield. Based on the success of this project, the City opened the new larger Southeast Farm (SEF) sprayfield in November 1980. However, recent studies indicate that nitrate-N from these operations may be moving through the UFA to impact Wakulla Springs. Determining the link between nitrate-N application at the sprayfields and rising levels in Wakulla Springs was complicated because there are other sources of nitrate-N in the springshed, including atmospheric deposition, onsite sewage disposal systems, disposal of biosolids by land spreading, sinking streams, domestic fertilizer application, and livestock wastes.

Groundwater flows to Wakulla Springs through one of the most extensive submerged cave systems in the United States, with approximately 37 mi of mapped, submerged cave passages. The discharge from Wakulla Springs shows a long-term increase between 1900 and 2008. This spring is located upgradient from the Spring Creek Springs Group, so it is possible that the flow in Wakulla Springs has increased at the expense of the downgradient spring. In addition to the long-term increase in flow, rapid short-term changes have occurred that are not associated with rainfall, but were caused by groundwater flow shifting from the Spring Creek Springs Group to Wakulla Springs.

Groundwater flow modeling and fate and transport modeling were conducted to determine the effect of each nitrate-N source on Wakulla Springs. MODFLOW was used for the groundwater flow modeling and MT3D was used for the fate and transport modeling. First, a regional groundwater model was calibrated that covered the entire springshed for Wakulla Springs, St. Marks River springs, and the Spring Creek Springs Group; these springs are regional groundwater discharge points for the UFA of northern Florida and southern Georgia. The regional model was used to set the boundary conditions for a subregional model, where both groundwater flow and nitrate-N movement were simulated. The subregional study area included just southern portions of the Wakulla Springs, St. Marks River springs, and the Spring Creek Springs Group springsheds. Model simulations in the subregional study area began in the year 1966, when the SWF sprayfield began operation, and ended in 2018, when the planned reductions in nitrate-N applied at the sprayfields will have worked their way through the groundwater flow system.

Two groundwater flow scenarios were simulated to cover the range of spring flow conditions observed. Sometimes the flow in Wakulla Springs and the Spring Creek Springs Group was approximately equal; at other times, the flow in Wakulla Springs would double while the Spring Creek Springs Group essentially ceased flowing. For scenario 1, the starting date was January 1, 1966, and the ending date was December 31, 2018; in the simulation, groundwater discharge from Wakulla Springs and from the Spring Creek Springs Group was approximately equal, except in the interval from May 1, 2005 to January 1, 2007, when Wakulla Springs captured the flow going to the Spring Creek Springs Group. In scenario 2, the simulation starting date was from January 1, 2007 to December 31, 2018; in this simulation, the capture of Spring Creek Springs Group flow by Wakulla Springs (that began in May 1, 2007 in scenario 1) was maintained through the year 2018.

At the end of 1967, the total simulated nitrate-N load to Wakulla Springs was a relatively modest 72,000 kilograms per year (kg/yr). The sources were inflow to the study area across the lateral model boundaries at 31,000 kg/yr (43 percent), biosolids disposal by land spreading at 14,000 kg/yr (21 percent), sinking streams at 7,800 kg/yr (11 percent), the SWF sprayfield, which peaked at 4,500 kg/yr (6 percent), onsite sewage disposal system at 7,100 kg/yr (10 percent), fertilizer at 3,700 kg/yr (5 percent), atmospheric deposition at 2,600 kg/yr (4 percent), and livestock wastes at 1,500 kg/yr (2 percent).

By the end of 1987, the total simulated nitrate-N load to Wakulla Springs had risen dramatically to 306,000 kg/yr. The sources were the SEF sprayfield at 186,000 kg/yr (61 percent), biosolids at 37,000 kg/yr (12 percent), inflow to the study area across the lateral model boundaries at 36,000 kg/yr (12 percent), onsite sewage disposal system at 23,000 kg/yr (8 percent), fertilizer at 8,600 kg/yr (3 percent), sinking streams at 7,800 kg/yr (3 percent), livestock wastes at 3,000 kg/yr (1 percent), and atmospheric deposition at 2,600 kg/yr (1 percent). The nitrate-N load to Wakulla Springs from the SEF sprayfield peaked in 1987. This was a period of heavy fertilizer usage; the nitrate-N load at the sprayfield comes from both wastewater and fertilizer used for crops. After 1987, the City began reducing the amount of fertilizer that was applied, thus reducing the nitrate-N load.

By the end of 2007, under the assumptions of scenario 1, the total simulated nitrate-N load to Wakulla Springs was down to 222,000 kg/yr; under the assumptions of scenario 2, the total simulated nitrate-N load to Wakulla Springs was 320,000 kg/yr. The load increased in

scenario 2 because Wakulla Springs had captured additional ground-water with its own nitrate-N load. The nitrate-N sources for scenario 1 (at the end of 2007) were the SEF sprayfield at 111,000 kg/yr (50 percent), inflow to the study area across the lateral model boundaries at 44,000 kg/yr (20 percent), onsite sewage disposal system at 38,000 kg/yr (17 percent), fertilizer at 13,000 kg/yr (6 percent), sinking streams at 7,800 kg/yr (4 percent), livestock wastes at 5,200 kg/yr (2 percent), and atmospheric deposition at 2,600 kg/yr (1 percent). The nitrate-N sources for scenario 2 were the SEF sprayfield at 111,000 kg/yr (35 percent), onsite sewage disposal system at 83,000 kg/yr (26 percent), inflow to the study area across the lateral model boundaries at 52,000 kg/yr (16 percent), sinking streams at 31,000 kg/yr (10 percent), fertilizer at 24,000 kg/yr (7 percent), livestock wastes at 13,000 kg/yr (4 percent), and atmospheric deposition at 6,100 kg/yr (2 percent). The nitrate-N load to Wakulla Springs from the SEF sprayfield for scenarios 1 and 2 were both 111,000 kg/yr; these loads were identical because, in both simulations, almost all the water from the SEF sprayfield went to Wakulla Springs. In contrast, the nitrate-N load from onsite sewage disposal system in scenarios 1 and 2 were 38,000 kg/yr and 83,000 kg/yr, respectively; the higher value in scenario 2 occurred because the additional water captured by Wakulla Springs came from an area that had a high density of home sites using onsite sewage disposal systems.

By the end of 2018, under the assumptions of scenario 1, the total simulated nitrate-N load to Wakulla Springs will be down to 175,000 kg/yr; but under the assumptions of scenario 2, the load will be 305,000 kg/yr. As in 2007, the additional nitrate-N in scenario 2 is due to Wakulla Springs capturing nitrate-N containing groundwater that had been going to the Spring Creek Springs Group. The nitrate-N sources for scenario 1 were the SEF sprayfield at 42,000 kg/yr (24 percent), inflow to the study area across the lateral model boundaries at 48,000 kg/yr (28 percent), onsite sewage disposal system at 51,000 kg/yr (29 percent), fertilizer at 18,000 kg/yr (10 percent), sinking streams at 7,800 kg/yr (4 percent), livestock wastes at 6,300 kg/yr (4 percent), and atmospheric deposition at 2,600 kg/yr (1 percent). For scenario 2, the nitrate-N sources were the SEF sprayfield at 43,000 kg/yr (14 percent), onsite sewage disposal system at 119,000 kg/yr (39 percent), inflow to the study area across the lateral model boundaries at 57,000 at kg/yr (19 percent), sinking streams at 31,000 kg/yr (10 percent), fertilizer at 32,000 kg/yr (10 percent), livestock wastes at 17,000 kg/yr (6 percent), and atmospheric deposition at 6,100 kg/yr (2 percent).

From 2007 to 2018, the simulated nitrate-N load from the SEF sprayfield to Wakulla Springs dropped from 111,000 kg/yr to 42,000 kg/yr in scenario 1, and from 111,000 kg/yr to 43,000 kg/yr in scenario 2. Both scenarios indicate a dramatic decline in the nitrate-N load due to the planned reduction in nitrate-N in the wastewater from approximately 12 mg/L in 2007 to 3 mg/L in 2018. In contrast, from 2007 to 2018 the simulated nitrate-N load from onsite sewage disposal systems to Wakulla Springs rose from 38,000 kg/yr to 51,000 kg/yr in scenario 1 and from 83,000 kg/yr to 119,000 kg/yr in scenario 2. Both scenarios show a dramatic increase in nitrate-N to Wakulla Springs due to the rising population and increase in onsite sewage disposal systems. From 2007 to 2018, the simulated nitrate-N load to Wakulla Springs from inflow across the model boundaries rose from 44,000 kg/yr to 48,000 kg/yr in scenario 1, and from 52,000 kg/yr to 57,000 kg/yr in scenario 2. Both scenarios show an increase due to rising nitrate-N levels in central Leon County, which is upgradient of the study area. The nitrate-N sources of fertilizer and livestock wastes also showed an increase from 2007 to 2018; however, these are smaller sources overall. The nitrate-N from streams that flow into sinks and atmospheric deposition were simulated as constants, so they did not change from 2007 to 2018.

References

Brooks, H.K., 1981, Physiographic divisions of Florida: Florida Cooperative Extension Service Institute of Food and Agricultural Sciences, University of Florida, 12 p.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p.

Chelette, A.R., Pratt, T.R., and Katz, B.G., 2002, Nitrate loading as an indicator of nonpoint source pollution in the lower St. Marks-Wakulla Rivers watershed: Northwest Florida Water Management District Water Resources Special Report 02-1, 138 p.

Davis, J.H., 1996, Hydraulic investigation and simulation of ground-water flow in the Upper Floridan aquifer of north-central Florida and southwestern Georgia and delineation of contributing areas for selected City of Tallahassee, Florida, water-supply wells: U.S. Geological Survey Water-Resources Investigations Report 95-4296, 55 p.

Davis, J.H., and Katz, B.G., 2007, Hydrogeologic investigation, water chemistry analysis, and model delineation of contributing areas for City of Tallahassee public-supply wells, Tallahassee, Florida: U.S. Geological Survey Scientific Investigations Report 2007-5070, 67 p.

Florida Springs Task Force, 2000, Florida's springs—strategies for protection and restoration: Florida Springs Task Force Report to the Florida Department of Environmental Protection, 59 p.

Gelhar, L.W., Welty, C., and Rehfeldt, K.R., 1992, A critical review of data on field-scale dispersion in aquifers: Water Resources Research, v. 28, no. 7, 19 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model — user guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hendry, C.W., and Sproul, C.R., 1966, Geology and ground-water resources of Leon County, Florida: Florida Geological Survey Bulletin 47, 174 p.

Horsley and Witten, Inc., 2000, Onsite sewage disposal systems pollutant loading evaluation — Test and validation of Indian River Lagoon nitrogen model: Melbourne, Florida.

Huddlestun, P.F., 1988, A revision of the lithostratigraphic units of the coastal plain of Georgia, the Miocene through Holocene: Georgia Geological Survey Bulletin 104, 162 p.

Katz, B.G., Griffin, D.W., and Davis, J.H., 2009, Ground-water quality impacts from the land application of treated municipal wastewater in a large karstic spring basin—Chemical and microbiological indicators: Elsevier, Science of the Total Environment 407, p. 2872-2,886.

Katz, B.G., Griffin, D.W., McMahon, P.B., Harden, H.S., Wade, E., Hicks, R.W., and Chanton, J.P, 2010, Fate of effluent-borne contaminants beneath septic tank drainfields overlying a karst aquifer: Journal of Environmental Quality, doi:10.2134/jeq2009.0244.

Kincaid, T.R., 1999, Morphologic and fractal characterization of saturated karstic caves: University of Wyoming, Ph.D. dissertation, 174 p.

Loper, D.E., Werner, C.L., Chicken, E., Davies, G., and Kincaid, T., 2005, Coastal carbonate aquifer sensitivity to tides: EOS Transactions, American Geophysical Union, v. 86, no. 39, 2 p.

Miller, J.A., 1986, Hydrologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.

Otis, R.J., Anderson, D.L., and Apfel, R.A., 1993, Onsite sewage disposal system research in Florida: An evaluation of current OSDS practices in Florida: Tampa, Florida, Ayres Associates, 176 p.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open File Report 89-381, 188 p.

Rosenau, J.C., Faulkner, G.L., Hendry, C.W., Jr., and Hull, R.W., 1977, Springs of Florida: Florida Department of Natural Resources, Bureau of Geology Bulletin No. 31, 461 p.

Science and Technology Committee, 2007, Statement on sea level in the coming century: Miami, Florida, Miami-Dade County Climate Change Task Force, 4 p.

Smajstrla, A.G., Clark, G.A., Shih, S.F., Zazueta, F.S., and Harrison, D.S., 1984, Characteristics of potential evapotranspiration in Florida: Soil and Crop Science Society of Florida, Proceedings, v. 43, 7 p.

Todd, K.D., 1980, Groundwater Hydrology: New York, John Wiley & Sons, 535 p.

U.S. Census Bureau, 2005, accessed December, 2005, at *http://www.census.gov/*.

U.S. Environmental Protection Agency, 1980, Design Manual — Onsite wastewater treatment and disposal systems: Report No. EPA-625/ 1-80-012, 390 p.

Zheng, C., and Wang, P., 1998, MT3DMS Documentation and user’s guide: Tuscaloosa, University of Alabama, Departments of Geology and Mathematics, 185 p.

Appendix

Appendix. Monitoring well details used for this study.

[USGS, U.S. Geological Survey, NGVD 29, National Geodetic Vertical Datum of 2929; NWF, Northwest; WW, water-supply well; FSU: Florida State University; SJ, St. Joe; SE, Southeast Farm; PK, park; Plant., Plantaion; REC, recreation area; na, not applicable; unk, unknown]

USGS identifier number	Site identifier	Measuring point elevation, in feet above NGVD 29	Well depth, in feet	Casing depth, in feet	Diameter, in inches	Water altitude in late May to early June, 2006, in feet
301118084014001	Fanlew 79	13	7	7	unk	4.38
301126084050601	Game Well	13	36	14	unk	6.38
301831084365601	NWF Forest Well	110	255	218	unk	83.6
301855084145001	City WW 1	35	199	117	unk	12.94
302315084192801	na	58	248	166	unk	17.91
302424084211301	na	67	194	-999	unk	17.18
302628084062701	St. Peter Church	53	-999	-999	4	34.98
302640084170001	FSU Well	101	310	-999	unk	19.85
302655084175502	City Well 5	141	390	222	unk	19.75
302721084162401	Laffayette Deep Well	212	602	487	6	21.79
302801084163401	City Well 8	189	466	223	unk	33.7
303109084275401	NWF Office Well	202	360	237	unk	49.92
303126084141302	City Well 18	185	388	267	unk	31.58
303142084214601	Lake Jackson Deep	125	225	100	unk	30.67
302006084120201	SJ-1	31	240	190	2	12.08
302007084120201	SJ-2	31	126	75	2	12.07
302013084130901	SJ-3	29	150	65	2	11.87
302013084131001	SJ-4	30	210	160	2	11.86
301950084110301	SJ-5	23	230	180	2	12.37
301950084110201	SJ-6	23	149	100	2	12.37
301901084115701	SJ-7[1]		264	200	2	na
301901084115600	SJ-8[1]		150	100	2	na
301909084131801	SJ-9[1]		250	190	2	na
301910084131801	SJ-10[1]		150	100	2	na
302116084123701	SE-1	22	71	57	4	11.95
302049084120901	SE-2	28	46	42	4	12.03
302116084120701	SE-3	44	62	54	4	10.86
302045084120901	SE-4	29	47	42	4	9.64
302157084115101	SE-6	51	102	101	8	12.92
302157084115102	SE-7	52	242	214	4	13.21
302053084115101	SE-9	39	52	51	4	11.49
302053084115102	SE-10	40	133	124	4	11.52
302146084110301	SE-11N	58	70	0	4	19.68
302146084110302	SE-11S	58	88	0	4	19.67
302208084123801	SE-12	48	55	51	4	12.82
302141084123601	SE-14	38	51	47	4	12.23
302141084123602	SE-15	37	102	96	4	13.02
302051084123502	SE-16	33	70	60	4	11.55
302051084123501	SE-17	34	122	112	4	12.34

Appendix. Monitoring well details used for this study—Continued.

[USGS, U.S. Geological Survey, NGVD 29, National Geodetic Vertical Datum of 2929; NWF, Northwest; WW, water-supply well; FSU: Florida State University; SJ, St. Joe; SE, Southeast Farm; PK, park; Plant., Plantaion; REC, recreation area; na, not applicable; unk, unknown]

USGS identifier number	Site identifier	Measuring point elevation, in feet above NGVD 29	Well depth, in feet	Casing depth, in feet	Diameter, in inches	Water altitude in late May to early June, 2006, in feet
302141084114001	SE-18	61	62	52	4	13.26
302117084113801	SE-19	48	74	52	4	12.01
302051084113802	SE-20	32	53	50	4	12.23
302051084113801	SE-21	32	139	125	4	11.74
302051084120901	SE-22	29	127	102	4	11.47
302051084120501	SE-22A	31	121	96	4	12.28
302045084123701	SE-23	32	57	48	4	10.85
302046084113801	SE-24	27	58	56	4	10.35
302114084105201	SE-37	32	240	191	4	12.87
302114084105202	SE-38	33	115	101	4	11.58
302114084105203	SE-39	34	73	63	4	14.13
302151084111901	SE-40	49	194	164	4	14.54
302151084111902	SE-41	49	134	120	4	13.91
302151084111903	SE-42	49	65	43	4	15.06
302110084110601	SE-43	40	183	174	4	11.49
302110084110602	SE-44	43	120	109	4	13.12
302110084110603	SE-45	44	72	55	4	13.02
302058084105101	SE-46	29	174	171	4	12.92
302058084105102	SE-47	28	45	31	4	10.76
302203084110001	SE-48	57	95	89	4	16.34
302150084103801	SE-49	33	55	47	4	14.26
302045084123702	SE-50	34	129	125	4	11.38
302046084113802	SE-51	27	170	146	4	10.3
302050084110501	SE-52	30	53	0	4	12.93
302050084110502	SE-53	31	100	93	4	12.93
302157084115104	SE-54	53	43	0	4	17.54
302045084120902	SE-55	31	34	0	2	14.09
302150084103802	SE-59	35	30	0	2	14.14
302129084091701	SE-75	37	32	22	4	22.31
302129084091801	SE-76	36	57	47	4	22.64
302053084100401	SE-77	32	57	47	4	16.4
302153084100402	SE-78	33	127	105	4	17.65
302104084094801	SE-79	45	43	34	4	18.7
302102084094801	SE-80	45	57	47	4	18.67
302149084094201	SE-81	34	37	27	4	21.19
302148084094101	SE-82	33	50	40	4	21.31
302202084091901	SE-83	37	27	17	4	26.82
302204084091901	SE-84	36	45	35	4	23.32
302100084092401	SE-85	29	17	7	4	20.75

Appendix. Monitoring well details used for this study—Continued.

[USGS, U.S. Geological Survey, NGVD 29, National Geodetic Vertical Datum of 2929; NWF, Northwest; WW, water-supply well; FSU: Florida State University; SJ, St. Joe; SE, Southeast Farm; PK, park; Plant., Plantaion; REC, recreation area; na, not applicable; unk, unknown]

USGS identifier number	Site identifier	Measuring point elevation, in feet above NGVD 29	Well depth, in feet	Casing depth, in feet	Diameter, in inches	Water altitude in late May to early June, 2006, in feet
302100084092001	SE-86	30	127	105	4	20.02
300655084223701	WAKULLA PK WELL	33	120	35	unk	4.15
300905084172801	WELCH WELL	21	185	26	unk	4.84
300931084210601	R. BREG	22	100	28	unk	5.92
301104084204001	D. BRAZIER	15	35	0	unk	5.99
301114084241201	USGS ARRAN WORK	32	129	75	unk	25.45
301126084215601	R. WARREN	29	70	60	unk	6
301156084103601	NEWPORT REC.	10	69	12	unk	4.87
301258084152401	GODARD PLANT.	22	48	21	unk	7.78
301426084144001	PENNINGTON	20	65	37	unk	7.69
301504084201701	C WELCH	16	57	25	unk	6.33
301655084245401	na	67	-999	-999	unk	48.34
301701084205201	MARSHALL WELL	20	70	42	unk	6.62
301726084122701	WALTER GERREL	30	70	40	unk	10.12
301839084173801	C DONAHUE DEEP	27	157	11	unk	6.58
301910084174901	J. LEWIS	24	50	35	unk	7.03
302110084154301	BIKE TRAIL WELL	39	90	80	unk	12.85
302521084223901	na	48	-999	-999	unk	18.86
301325084204001	DENHARDT	21	140	32	unk	5.93
301743084195101	J.J. FLORES	18	60	20	unk	6.62
301714084211601	A. SCOTT	25	28	22	unk	6.47
301820084134001	DISC VILLAGE	45	140	40	unk	11.03
301050084150101	CHRIS RACKLEY	13	80	60	unk	2.51
301423084183701	WAKULLA SPRINGS	17	65	57	unk	6.18
301618084154201	ROBERT SMITH	36	100	30	unk	7.39
301159084135601	MARTHA DINGLER	15	100	21	unk	6.73
300915084162501	NITRATE #2	19	120	10	unk	4.32
301447084184701	NITRATE #3	15	270	25	unk	6.32
302038084082701	NITRATE #5	31	270	25	unk	19.88
301703084090901	Natural Bridge well	27	70	42	4	10.07
301634084085601	St. Marks Rise	11	na	na	na	9.9
302022084124001	Hideaway Sink	20	na	na	na	12.53
301407084180501	Wakulla Dock	8	na	na	na	5.24
301833084213601	Sullivan Sink	16	na	na	na	8.17

[1]Well was not installed in time for areawide water-level measurements but was used for water-quality sampling.

Manuscript approved on May 6, 2010 by:
Sandra C. Cooper, USGS Bureau Approving Official

This project on which this publication is based was funded in part by:
The City of Tallahassee

Publishing support was provided by the:
USGS Publishing Service Center, Ft. Lauderdale, Florida

For more information concerning this publication contact:
J. Hal Davis, Hydrologist
U.S. Geological Survey
2639 North Monroe Street, Suite A-200
Tallahassee, FL 32303
(850) 553-3673

Davis, J.H., Katz, B.G., and Griffin, D.W.—**Nitrate-N Movement in Groundwater from the Land Application of Treated Municipal Wastewater and Other Sources in the Wakulla Springs Springshed, Leon and Wakulla Counties, Florida, 1966-2018**—USGS/SIR 2010-5099

ISBN 978-1-4113-2857-0

Printed on recycled paper