

**Ground Water Chemistry
and
Origin of Water Discharging
from**

MANATEE and FANNING SPRING

Levy and Gilchrist County, Florida

TROY SPRING

Lafayette County, Florida

MADISON BLUE SPRING

Madison County, Florida

Prepared for the
SUWANNEE RIVER WATER MANAGEMENT DISTRICT
Live Oak, Florida

By
SDII Global Corporation
4509 George Road
Tampa, Florida 33634

March 30, 2005



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Endorsement

This report, entitled “Ground Water Chemistry and Origin of Water Discharging from Manatee and Fanning Springs, Levy and Gilchrist Counties, Florida,” was prepared for the Suwannee River Water Management District by the undersigned individuals under Contract No. 03/04-058. Opinions and conclusions expressed in this report are those of the authors only. The data and conclusions presented herein do not necessarily reflect opinions or policy of the District.

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INTRODUCTION

Manatee and Fanning Springs are two of north Florida's most valuable natural resources. The springs represent two of the State's many first-magnitude springs, as well as two of the most popular state parks in the region. The springs are important to the natural and scenic beauty of the area, and to the region's rich historical heritage. However, protecting Manatee and Fanning Springs, and others like it, require a thorough understanding of the geology and hydrology of the regions surrounding the springs and adjacent Suwannee River.

Since the 1970's, much information has been gathered concerning large spring systems in north Florida and the importance of karst to water quality in the Floridan aquifer. Lawrence and Upchurch (1976), for example, determined that karst features could be used to deduce the vulnerability of ground water to ground-water contamination, and determine the extent to which ground-water recharge affects water quality in the Floridan aquifer. Similar results were obtained by Ceryak and others (1983) and Crane (1986) in two regional studies of the upper and lower Suwannee River Basin, respectively. More recently, nitrogen-isotope data collected by Katz and others (1999) suggested that Manatee and Fanning Springs discharge nitrate that is derived from a mixture of artificial fertilizers and wastewater. It has also been discovered that flow through large spring systems, such as Manatee and Fanning Springs, can be rapid. For example, a dye trace in Columbia County from Rose Creek Sink to the Ichetucknee Springs resulted in a transport rate of approximately one mile per day (Karst Environmental Services, 1997).

An important step in understanding the hydrology of Manatee and Fanning Springs (Figure 1) is to define their spring recharge basins, or springsheds (Copeland, 2003). A springshed is defined as the areas within ground-water and surface-water basins that contribute to the discharge of a spring. The inclusion of surface-water drainage basins in the definition may be important to the Manatee-Fanning Springs system because the eastern boundary of the springshed lies adjacent to the Waccasassa Flats and the Devils Hammock (Figure 1). Both of these regions are generally wetlands areas that reflect rejected recharge or low recharge to the Floridan aquifer. The high water table in the Flats and Hammock reflects the relative inability of ground water to percolate downward through clay-rich soils of the underlying Pleistocene and Miocene sediments (Puri and others, 1967).

Given the low topographic gradients of the area within the Waccasassa Flats and the lack of interconnected flow paths through the swamp into the upper reach of the Waccasassa River, it is assumed that only a very small portion of the surface water in the Waccasassa Flats actually leaves the region as surface flow. Instead, a large portion of the surface water in the Flats eventually flows laterally to large sinkholes and closed depressions that line the edges of the Flats and the eastern boundary of the springshed. At these locations, the sheet flow and shallow ground water flows off the Flats and is directed into the subsurface. It then recharges the underlying Floridan aquifer. Only during very heavy rainfall events or prolonged periods of heavy rainfall (e.g. El Niño events) would significant amounts of surface water leave the area as surface flow. As in other springsheds (e.g., Ichetucknee springshed), contaminants transported to the ground-water system from surface-water basins that extend beyond the ground-water basin may constitute a

significant threat to a spring system. In this paper, statistical analysis of water-quality data in the study area is utilized to delineate the source areas of ground water in the Manatee-Fanning springshed.

Of interest is an understanding of the chemical composition and source areas for spring water in the study area. The chemistry of ground water in the study area is affected by a number of geologic, hydrologic, and anthropogenic factors. Principal components analysis (PCA) is a useful tool for sorting out hydrogeologic process-response relationships within a sample population of ground-water quality data (Lawrence and Upchurch, 1976, 1982). In this paper, a PCA of ground-water chemistry data was used to group chemical constituents into specific factors that reflect differences in the chemical composition of ground water and geochemical processes in the study area. A graphical analysis of these factors was then utilized to define specific source areas and processes for spring water in the study area.

DESCRIPTION OF STUDY AREA

The Manatee-Fanning Springs study area encompasses several hundred square miles of northwestern Levy County and southwestern Gilchrist County (Figure 1). This region contains both the southern extent of the Suwannee River watershed and the ground-water basins that contribute subsurface flow to the springs (Upchurch and Champion, 2004). Because of their close proximity and uncertainties as to the location of the divide between the individual spring basins for Manatee and Fanning Springs, these two basins are treated as one basin in this report. The Manatee-Fanning springshed lies to the east of the Suwannee River and encompasses approximately 450 square miles of northwestern Levy and southwestern Gilchrist counties. The ground-water basins were identified and described by Upchurch and Champion (2003a), who used geostatistical analysis to define the basin boundaries. The Suwannee River Water Management District (SRWMD) is currently monitoring the Manatee-Fanning springshed, which will greatly improve future basin delineation (Upchurch and others, 2001).

Note that most of the surface-water portion of the springshed appears to lie within the ground-water basin (Figure 2). However, surface-water basins extend outside of the ground-water basin to the east of the ground-water basin. For this reason, the study area was selected to include both surface- and ground-water basins and to extend somewhat outside of these basins.

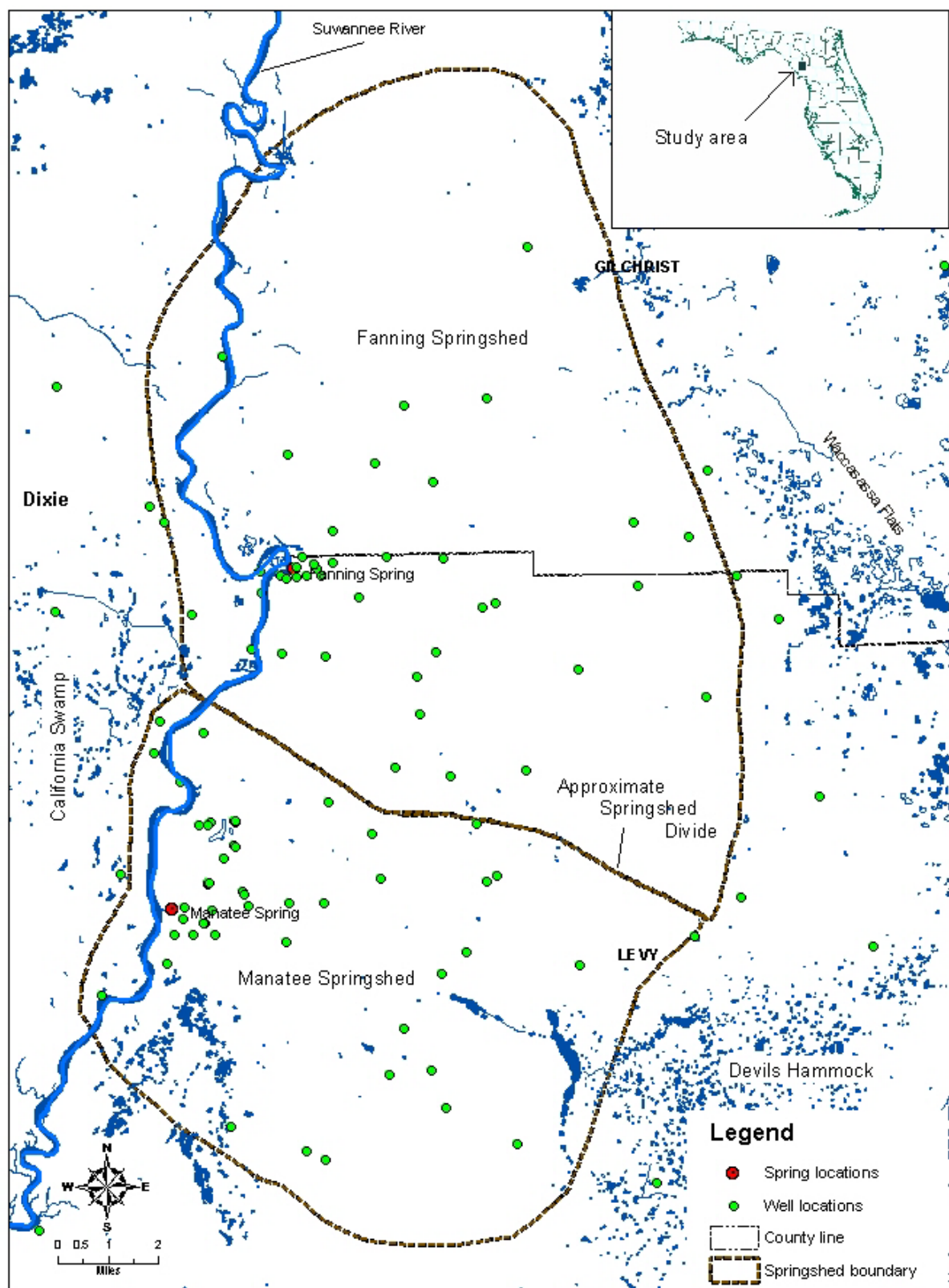


Figure 1. Location of the study area and the Manatee-Fanning springshed (modified from Upchurch and Champion, 2003a).

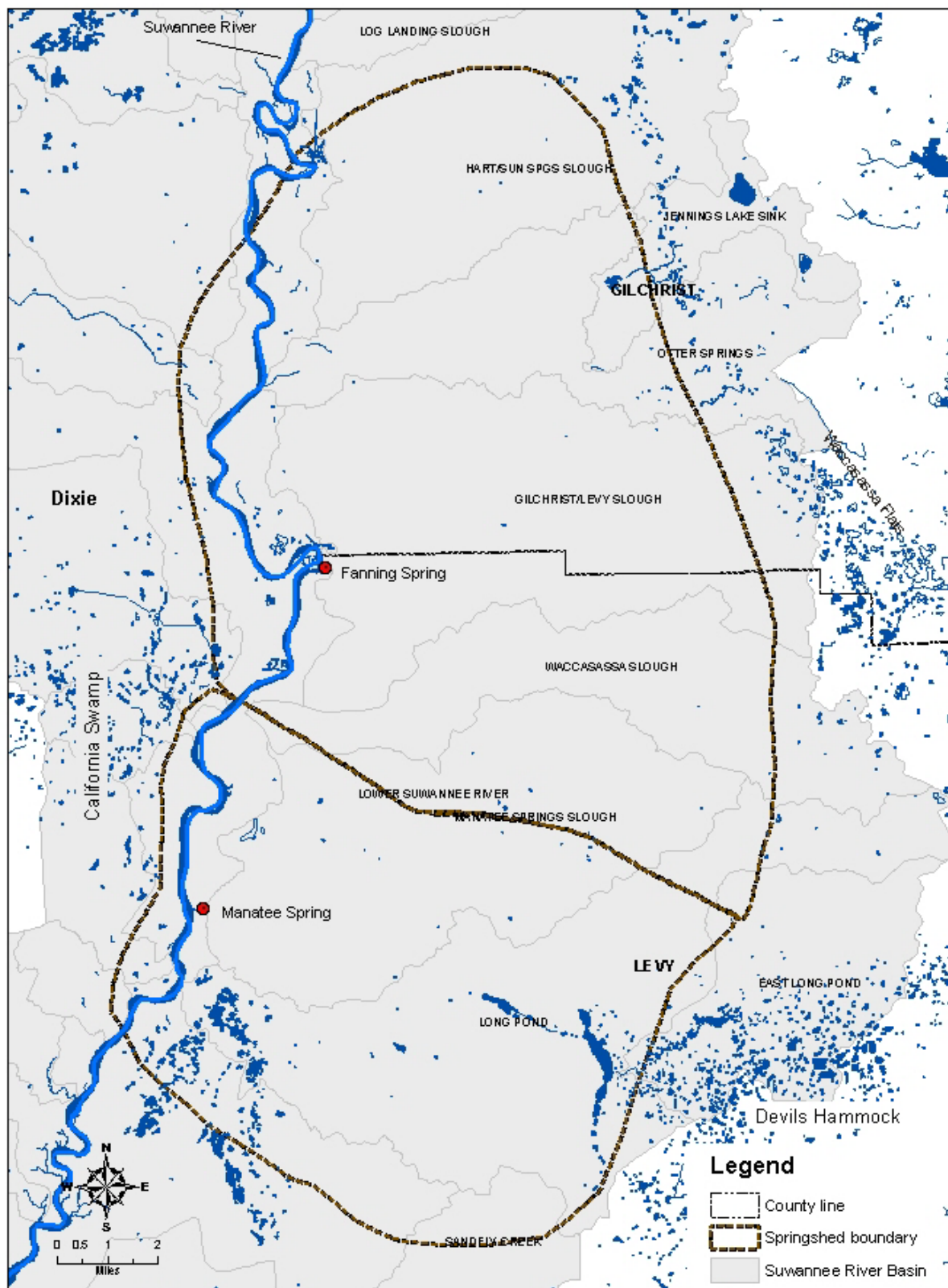


Figure 2. Surface-water basins in the study area and within the Manatee-Fanning springshed. Shaded basins are within the Suwannee River watershed.

Population and Water Use

Two centers of population lie within the Manatee-Fanning springshed (Figure 3). Chiefland, the largest population center in the study area, contains approximately 2,000 residents. Since 1960, the population of Levy County has increased 150 percent, from approximately 10,364 to 25,923 (U.S. Census Bureau, 2002). Even with this growth, the County retains a decidedly rural character, with a population density of approximately 31 persons per square mile.

The second center of population, Trenton, is a small community that contains approximately 1,617 residents. This town lies just north of the Gilchrist/Levy County line. Since 1960, the population of Gilchrist County has increased 237 percent, from approximately 2,868 to 9,667 (U.S. Census Bureau, 2002). Much like Levy County to the south, Gilchrist County is largely rural, with a population density of approximately 41 persons per square mile.

According to estimates by Marella (1999), ground water was withdrawn from the Floridan aquifer in Levy County at the rate of approximately 20.9 million gallons per day (mgd) in 1995. Agricultural withdrawals, rural self-supplied, and public water-supply systems accounted for approximately 72.7 percent (15.2 mgd), 17.7 percent (3.7 mgd) and 9.1 percent (1.9 mgd), respectively, of the total withdrawals in the County (Marella, 1999). Cumulatively, these withdrawals accounted for more than 99 percent of the water use in the County in 1995.

Marella (1999) also estimated that ground water was withdrawn from the Floridan aquifer in Gilchrist County at the rate of approximately 9.3 million gallons per day (mgd) in 1995. Agricultural withdrawals, rural self-supplied, and public water-supply systems accounted for approximately 81.7 percent (7.6 mgd), 14.0 percent (1.3 mgd) and 2.2 percent (0.2 mgd), respectively, of the total withdrawals in the County (Marella, 1999). Cumulatively, these withdrawals accounted for more than 97 percent of the water use in the County in 1995.

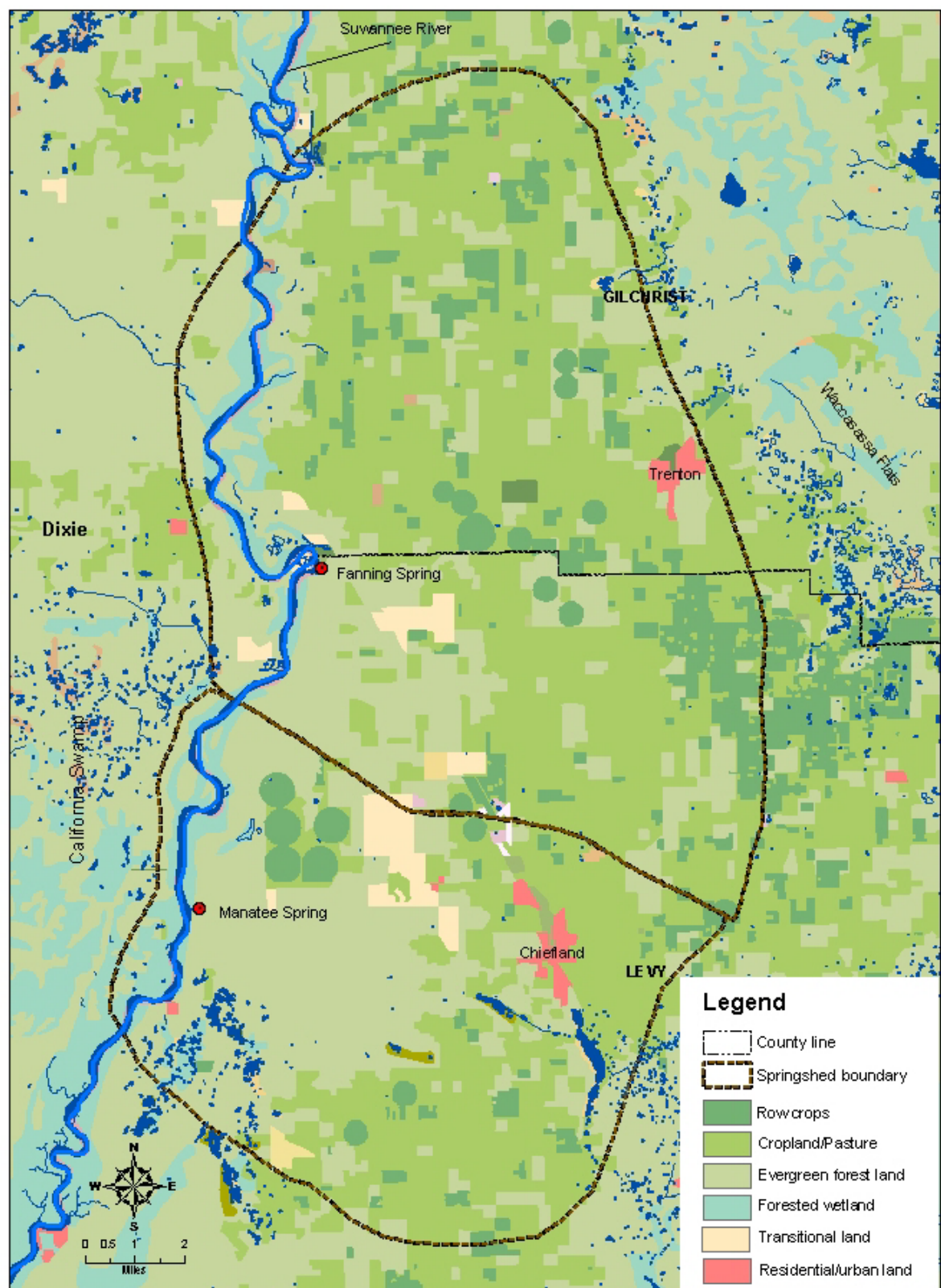


Figure 3. Major land uses in the study area (Florida Geographic Data Library, 2004).

Land Use

Land use in the study area was identified using the 1996 USGS Arcview™ land-use coverage (Florida Geographic Data Library, 2004). Except for areas in and near Trenton and Chiefland, the study area is a sparsely populated region. The major land uses in the Manatee-Fanning springshed include pine plantations, improved pasture, hardwood conifer forests, wetland-mixed forests, temperate hardwood forests, and areas of forest regeneration (Figure 3). Together, these six land uses cover approximately 75 percent of the springshed (Upchurch and Champion, 2004).

Topography, Physiography, and Drainage

The topography of the Manatee-Fanning study area is somewhat subdued. Land-surface elevations range from less than 25 feet above sea level along the Suwannee River on the southwestern boundary to areas in excess of 75 feet above sea level in higher regions to the northeast of the springshed (Figure 4). In the immediate vicinity of the springs, however, elevations are typically less than 25 feet above sea level.

White (1970) divided Levy County into two physiographic regions: the Gulf Coast Lowlands and Bell Ridge. Bell Ridge is a broad upland area that lies to the west of the Waccasassa Flats (Figure 5). In contrast, the Gulf Coast Lowlands (typically less than 100 feet above sea level) is a mature, karst plain characterized by rapid infiltration of runoff, and few, if any, lakes or wetlands (Figure 6). Sinkholes in the Coastal Lowlands are typically small in area, but they are numerous (Upchurch, 2002).

Between the Waccasassa Flats and the Manatee-Fanning springshed is a transitional region characterized by an abundance of large sinkholes (Figure 7). Hydraulically, this transitional area behaves very similarly to the Cody Scarp (White, 1970), where sinkholes and sinkhole-related karst features tend to be large and recharge is relatively high (Upchurch, 2002; Upchurch and Champion, 2003b, 2004).

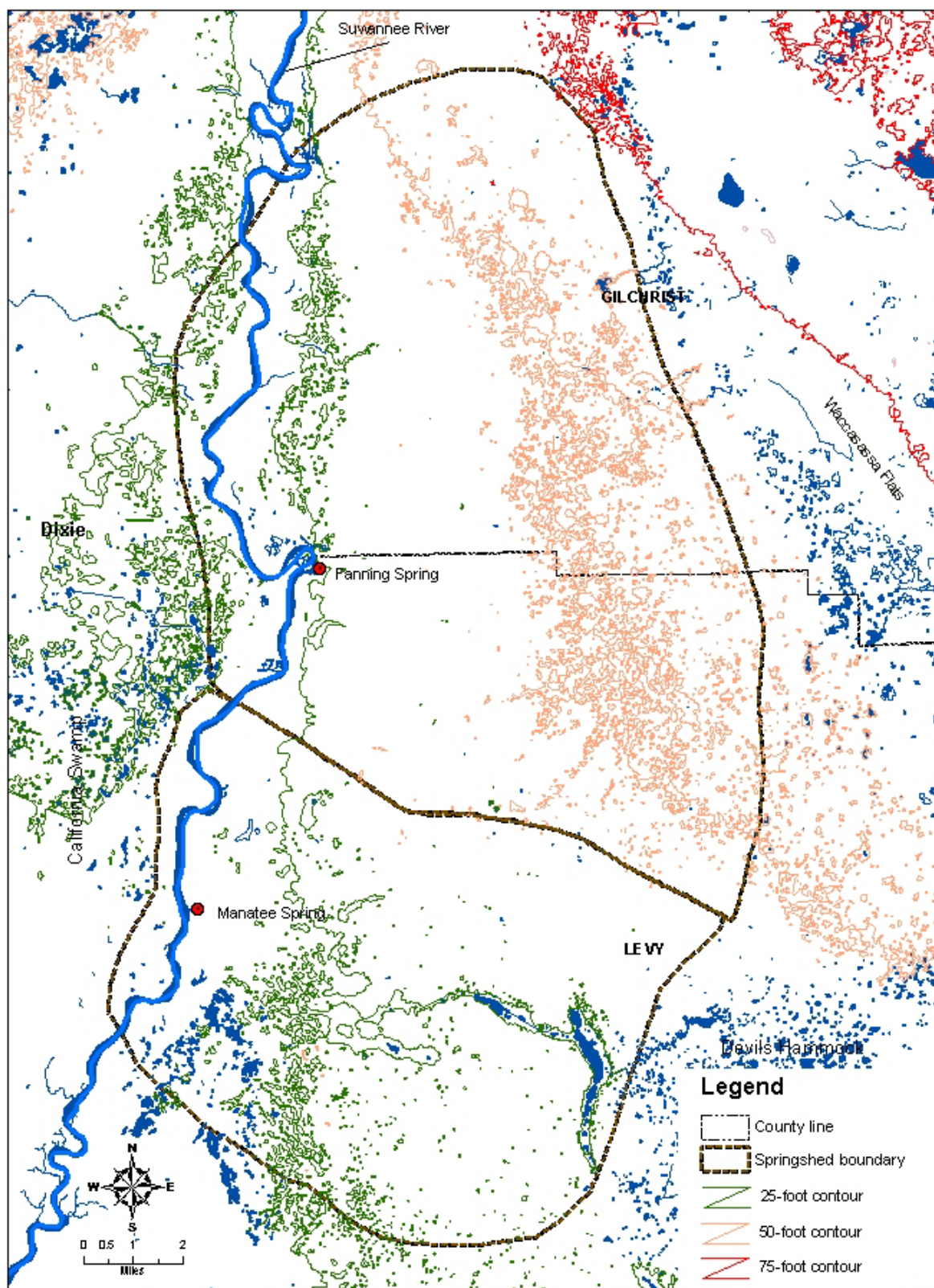


Figure 4. Land-surface elevations in the Manatee-Fanning study area (Florida Geographic Data Library, 2004).

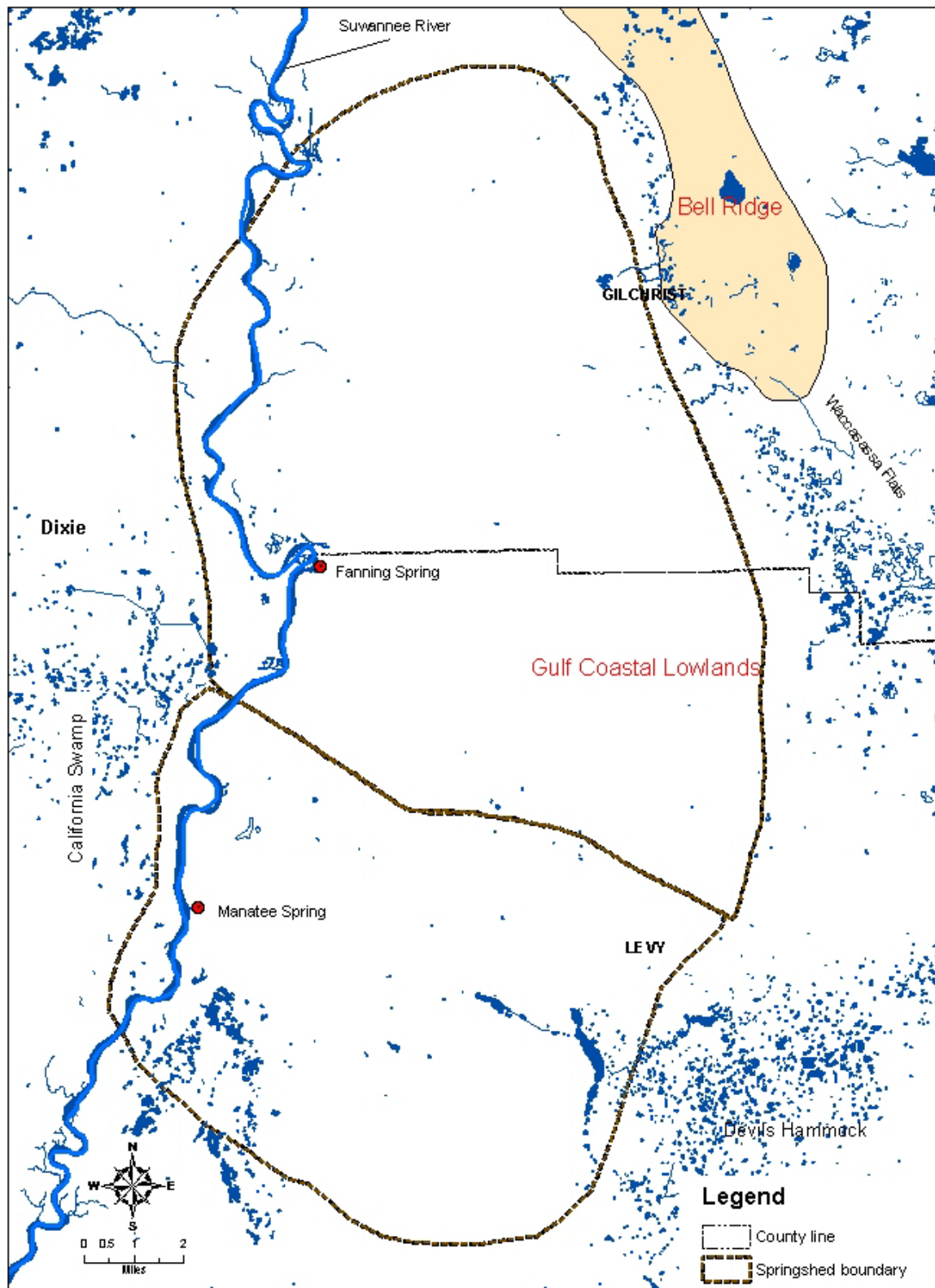


Figure 5. Physiographic provinces within the Manatee-Fanning study area (modified from White, 1970).

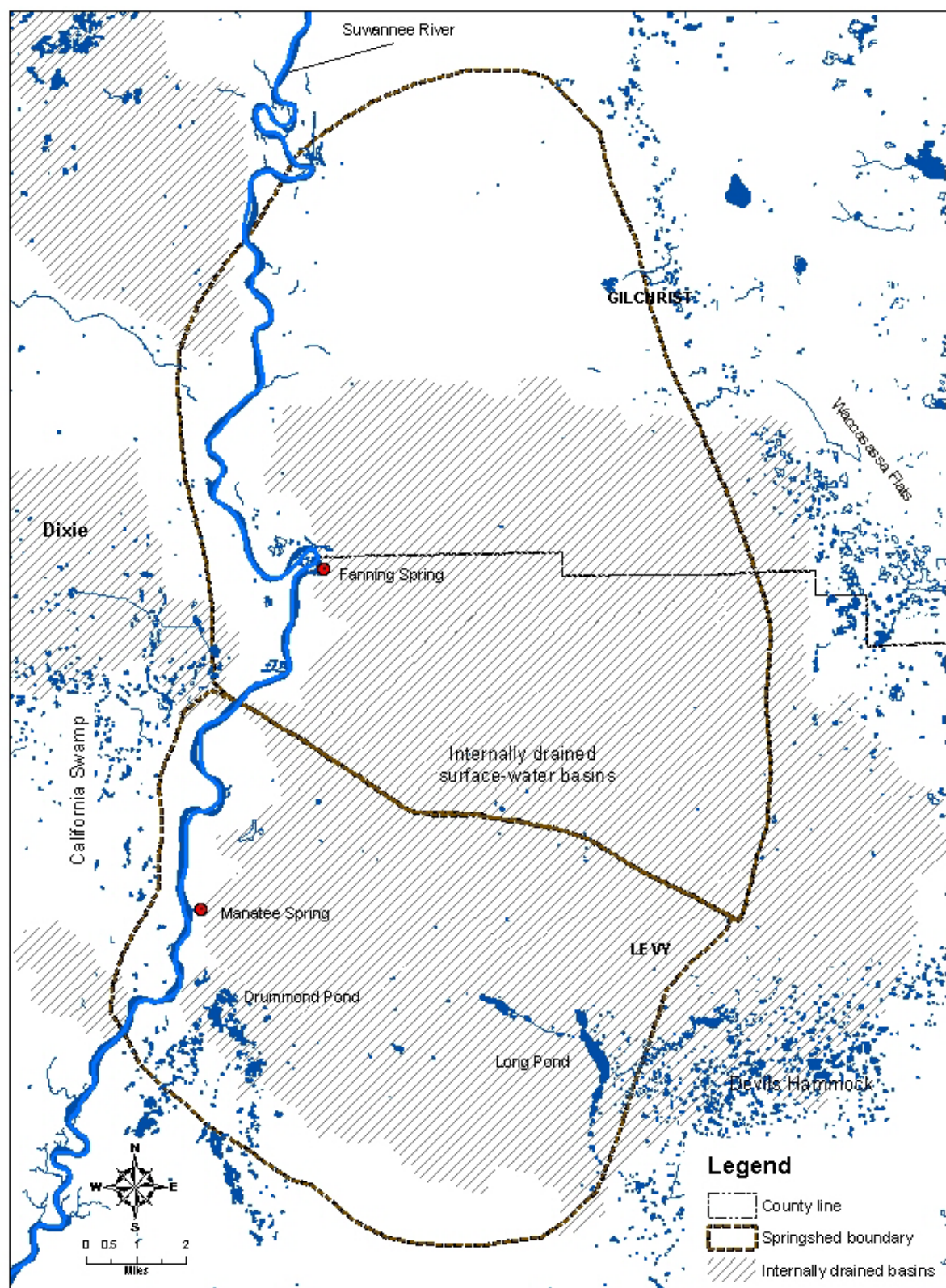


Figure 6. Significant hydrologic features within the Manatee-Fanning study area.

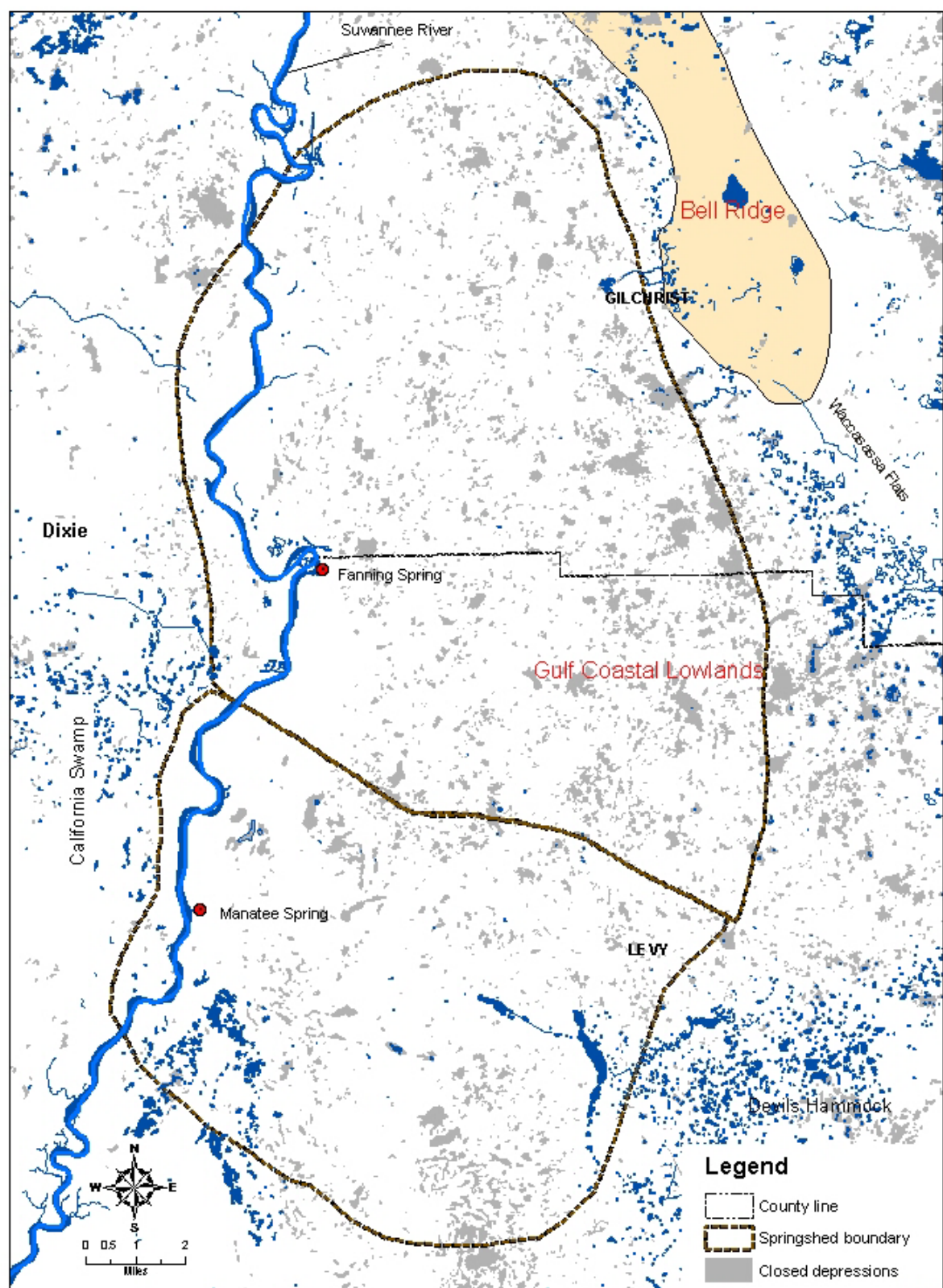


Figure 7. Sinkholes and closed depressions within the Manatee-Fanning study area.

Geology

Figure 8 is a geologic map showing the stratigraphic units at or near land surface in the study area. Thick sequences of limestone are exposed at or very near (10-20 feet) the land surface in many parts of the study area, especially along the Suwannee River. Where limestone is near land surface, the thin veneer of sediment that covers the limestone consists of Quaternary-age, unconsolidated to poorly indurated, siliciclastic deposits dominated by quartz sand. These sands are primarily marine terrace deposits.

The uppermost limestone units in the study area include the Ocala Limestone and Avon Park Formation, both of Eocene age. The major carbonate unit in the study area is the Ocala Limestone, which lies at or near land surface throughout much of the region (Figure 8). Based on well cuttings, Crane (1986) described the Ocala Limestone in the study area as consisting of several lithologies of marine origin. The deepest of these lithologies is a medium to well-indurated calcarenite composed almost entirely of Miliolid foraminifera. Above this unit lies a medium to well-indurated calcarenite composed of the foraminifera *Operculinoides* sp. and Miliolids. Capping these two lower lithologies is a unit that is described as a poorly to moderately indurated, calcarenite composed of the foraminifera *Lepidocyclina* sp. Much like the underlying Avon Park Formation, the upper surface of the Ocala Limestone is highly variable and karstic (Crane, 1986).

The Avon Park Formation is the oldest rock unit that crops out in the State of Florida. In the study area, the early Eocene age Avon Park Formation consists of moderate to well-indurated, sugary dolostone, and moderately to well-indurated calcilutite, calcarenite and calcirudite. Thin seams of peat are often associated with the more dolomitized sections of the Avon Park Formation. In deeper, more calcitic sections of the Avon Park, Miliolids and foraminifers, especially *Dictyoconus americanus*, are often present (Crane, 1986). Gypsum is also present in small amounts in the Avon Park Formation, though it typically occurs several hundred feet below sea level in the study area (Crane, 1986). The Ocala Limestone and the Avon Park Formation comprise the Floridan aquifer in the Manatee-Fanning Springs.

In Bell Ridge, the carbonate units of the Floridan aquifer are overlain by Pleistocene-Holocene, undifferentiated sand (Figure 8). This sand was apparently deposited as part of a barrier-island system during periods of higher sea level over the last several million years. Sand hills along the margin of the Bell Ridge originated as dune features (Puri and others, 1967).

While Miocene sediments have been eroded from the Manatee-Fanning springshed, the weathering of phosphorite in the Hawthorn Group sediments in the geologic past has resulted in dissolution of carbonate-fluorapatite and re-precipitation of carbonate-hydroxylapatite in localized crusts and nodules in the Ocala Limestone (Upchurch 1992, 2002). These deposits of re-precipitated phosphate, which were locally termed "hard-rock phosphate," were extensively mined throughout northern Florida from the late 1880's through the 1960's (Dinkins, 1969). None of the mines were large because the deposits were localized in karst features. Puri and others (1967) noted that phosphate-ore deposits were generally mined in eastern Gilchrist County near the Gilchrist-Alachua county line.

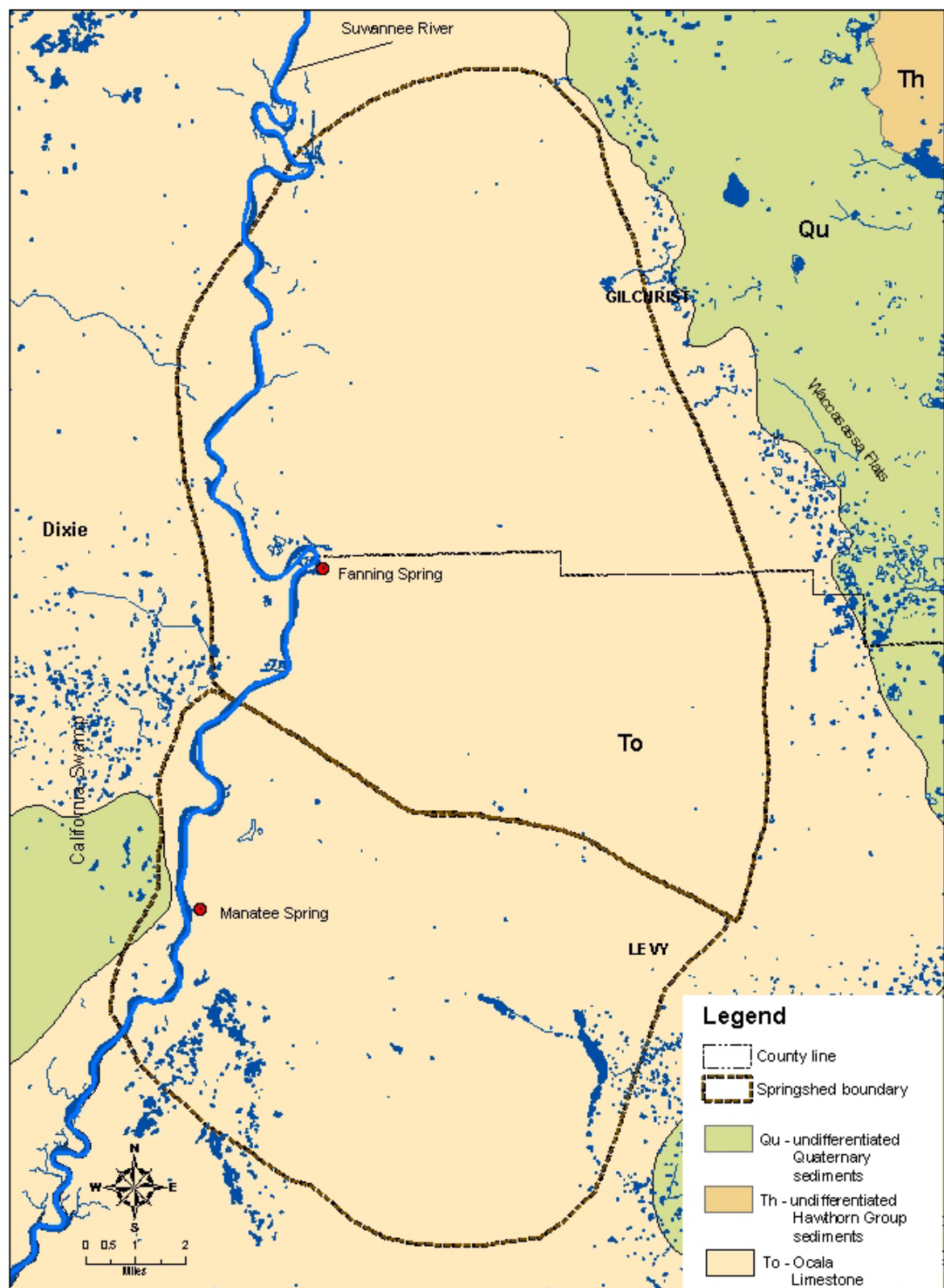


Figure 8. Geologic map of the Manatee-Fanning study area (modified from Scott and others, 2001).

Surface-Water Hydrology

Surface-water features are abundant in the eastern and southwestern portions of the Manatee-Fanning springshed (Figure 6). These areas correspond to the Waccasassa Flats and Devils Hammock, respectively. As noted earlier, these wetland areas are important hydrologic boundaries to the Manatee-Fanning springshed. To the west of the springshed in Dixie County lies the California Swamp. This wetland area covers a significant amount of eastern Dixie County and, as will be shown later in this report, has imparted subtle water-quality characteristics that differ from Floridan aquifer ground water in Levy-Gilchrist portions of the study area.

The lack of streams and rivers throughout the Manatee-Fanning springshed results from a well-developed underground drainage system in the Floridan aquifer. Recharge to the Floridan aquifer is relatively high in the springshed because Hawthorn Group sediments are generally absent and the limestone is at or near land surface. In addition, the sandy soils that mantle the limestone are generally well drained and porous.

Karst and Ground-Water Hydrology

Karst - A prerequisite to characterizing the ground-water hydrology of the study area is an understanding of the dominant role that karst processes play in moving ground water through the Floridan aquifer. The Manatee-Fanning springshed is an area of intensive karst development, characterized by numerous sinkholes, lack of surface drainage, and undulating topography (Figures 4, 6, and 7). In karst areas, the dissolution of limestone has created enlarged cavities along fractures in the limestone, which eventually collapse or reach the surface and form sinkholes. Sinkholes capture surface-water runoff and funnel it underground, which promotes further dissolution of limestone. This leads to progressive integration of voids beneath the surface over time and allows increasingly larger amounts of water to be transported through the ground-water system.

Dissolution is most active near the water table or zone of water-table fluctuation. In this zone, carbonic acid contained in atmospheric precipitation and generated by reaction with soil carbon dioxide reacts with limestone and dolostone (Carroll, 1970). Because the altitude of the water table has shifted in response to changes in sea level over the last 30 million years, many vertical and lateral paths have developed in the underlying carbonate strata in the study area. Many of these paths or conduits lie below the present water table (the Floridan aquifer is essentially unconfined in the Coastal Lowlands) and greatly facilitate ground-water flow.

Ground water may flow rapidly through conduits and passages with the limestone, or slowly through minute pore spaces within the rock matrix. Dye-trace studies in Columbia County show that ground water near Ichetucknee Springs may travel approximately one mile per day in active conduits in the Floridan aquifer (Karst Environmental Services, 1997). Similar velocities were recorded near Sulphur Springs in Hillsborough County (Stewart and Mills, 1984). Studies such as these clearly indicate that ground water has the potential to flow rapidly and traverse great distances in a short amount of time in karst environments near major springs.

Because the flow in these karst conduits is rapid and direct, dispersion, dilution, and retardation of contaminants is likely to be minimal and the springs are vulnerable to contamination. For example, when Lawrence and Upchurch (1976) sampled the Floridan in the vicinity of Lake City, they described a plume of surface water under Alligator Lake that extended to the southwest for several miles. Shortly after completion of the study, the lake drained and residents down gradient reported colored water, organic debris, and other indicators of lake water. We now know that Alligator Lake is part of the headwaters of the Ichetucknee Springs and that the plume of surface water was migrating in a karst conduit system to the springs.

In contrast, recent studies by the USGS and SRWMD have demonstrated that much of the spring water in northern Florida (and the study area) has been in the Floridan aquifer for an average of 10-25 years (Katz and others, 1999). This estimate is based on age-dating techniques using chlorofluorocarbons (CFC's) derived from the use of aerosol propellants and refrigerants. These CFC compounds, released into the atmosphere over the last 50 years, have dissolved in precipitation that recharges ground water (Katz and Hornsby, 1998). The occurrence of CFC's in spring water in the study area indicates that, while a portion of the ground water moves quickly through conduits in the Floridan aquifer, much of the water percolates slowly through the soil and into the aquifer. Once the ground water recharges the aquifer, it begins moving through the smaller pores and openings in the limestone before reaching an active conduit or spring vent. The slower movement of ground water through the aquifer is known as diffuse flow. Because of the diffuse flow and ability of the limestone matrix to improve ground water quality, the springs are typically clear and free of most contaminants.

It is important to understand the processes of rapid, conduit flow and slower, diffuse flow karst aquifers, such as the study area. Older ground water, traveling in small pore spaces as diffuse flow, mixes with younger ground water traveling through active conduits near the spring. Two recent studies by the St. Johns River Water Management District and the SRWMD demonstrate and support this mixing model of ground water at springs (Katz and Hornsby, 1998; Toth, 1999). Therefore, the mixing of ground waters must not be overlooked when assessing the origin, health, and history of spring waters in karst environments, such as that found in the study area.

Recharge - Recharge to the Floridan aquifer is directly related to the confinement of the aquifer system. The highest recharge rates occur where the Floridan is unconfined or poorly confined, as in those areas where the aquifer is at or near land surface. Such conditions occur throughout the study area. Recharge may also be high in areas where the confining layers are breached by karst features, such as sinkholes (Figure 7). Other factors affecting recharge rates include the development of surface-water drainage; variations in water-level gradients between surface water, the surficial aquifer and the Floridan aquifer; and aquifer permeability. Low recharge rates occur where confining materials overlying the aquifer retard downward vertical movement of water, or where an upward water-level gradient exists between the Floridan and surficial aquifers. Figure 9 shows the estimated recharge potential of the Floridan aquifer in the study area.

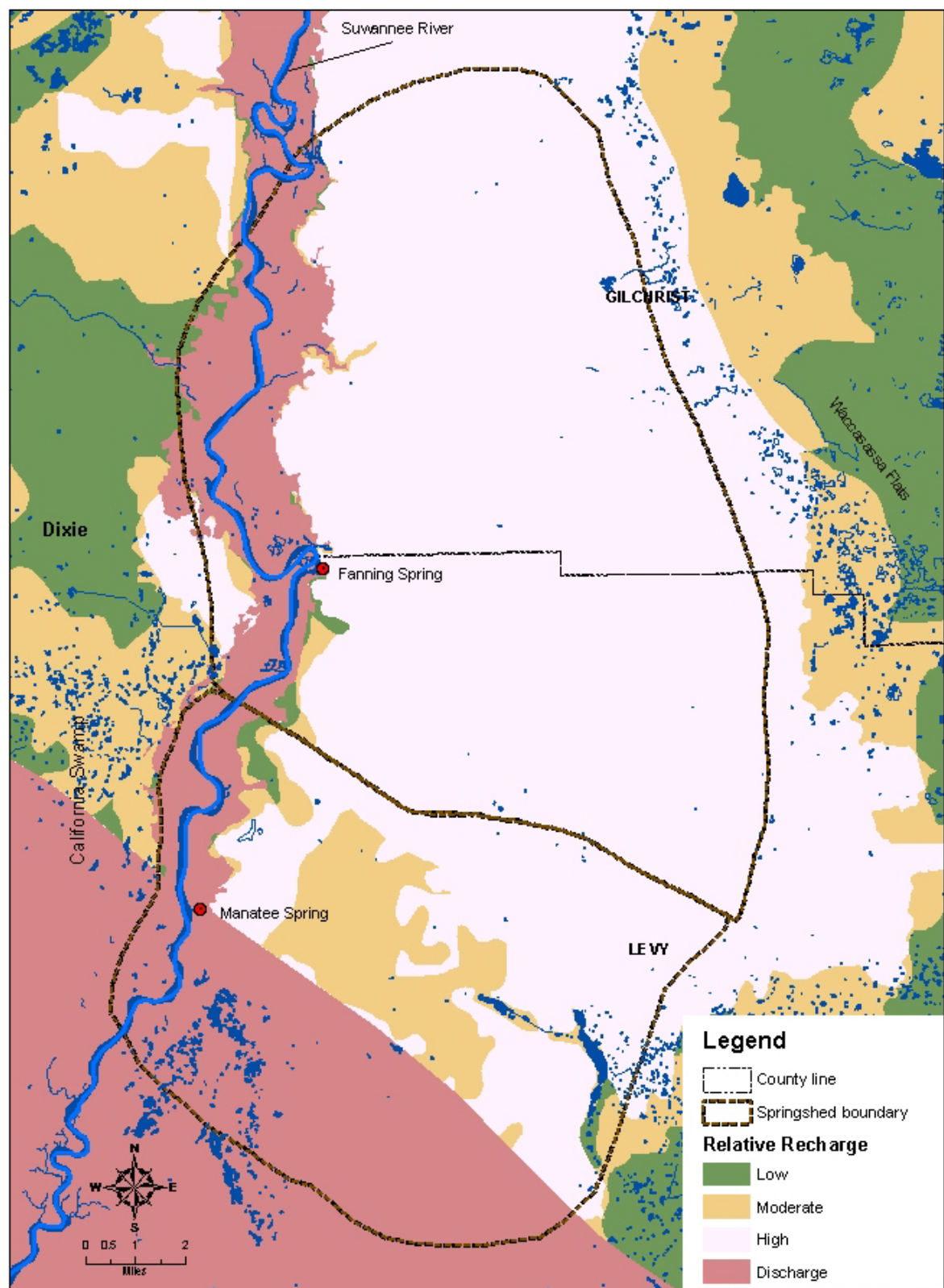


Figure 9. Relative recharge to the Floridan aquifer in the Manatee-Fanning study area (Florida Geographic Data Library, 2004)

Potentiometric Surface - The potentiometric surface of the Floridan aquifer in the study area is shown in Figure 10. This map was created by statistically analyzing water levels from approximately 100 monitor wells within the study area. This geostatistical analysis consisted of two steps. First, a structural analysis is performed to determine the pattern of variance with distance between sample pairs. Then, by kriging the data using these “rules” of uncertainty estimation, a traditional contour map and a map showing levels of uncertainty in the contour map are produced. The ground-water basin is then delineated from the contour map, and the uncertainty map is used to define areas that would benefit from additional monitoring locations. The geostatistical analysis conducted by Upchurch and Champion (2003a) provided an accurate picture of the basin’s shape.

Some distinctive features are visible on the potentiometric surface map. Most importantly, the areas where the contour lines are hachured (an artifact of the contouring software) delineate the area of drawdown as a result of spring discharge. Note that the contour interval in this area is 1 foot. If the contour interval were constant at 5 feet, this area of the potentiometric surface would appear to have a low slope, as depicted east of the hachured contours. This low potentiometric-surface relief area immediately east of the Suwannee River (including the hachured, 1-foot contours and the 5 foot contours east of the springs) represents a region of well-developed karst and high hydraulic conductivity. This karst region is several miles wide and extends from the Suwannee River eastward to Trenton and Chiefland. The slope of the potentiometric surface in this area is low and averages roughly 1 to 2 feet per mile. On the other hand, the steep isopleths that surround the central low-relief area indicate regions where the Floridan aquifer has lower permeabilities and flow is less dynamic. The variable contour interval in Figure 10 reflects this steepness. The slope of the potentiometric surface in this region is much steeper and averages 5 to nearly 10 feet per mile. Given the elevation of the potentiometric surface in the study area, an "average" ground-water basin boundary between the two springsheds, was drawn by Upchurch and Champion (2004).

The steep isopleths that lie to the west of the springshed also indicate a region where the Floridan aquifer has lower permeabilities and flow is less dynamic. As with areas to the east of the springshed, the slope of the potentiometric surface in this region is much steeper and averages 5 to nearly 10 feet per mile. The close proximity of the steep potentiometric-surface contours west of the Suwannee River suggests that there is minimal contribution of ground water from water west of the river to the springs.

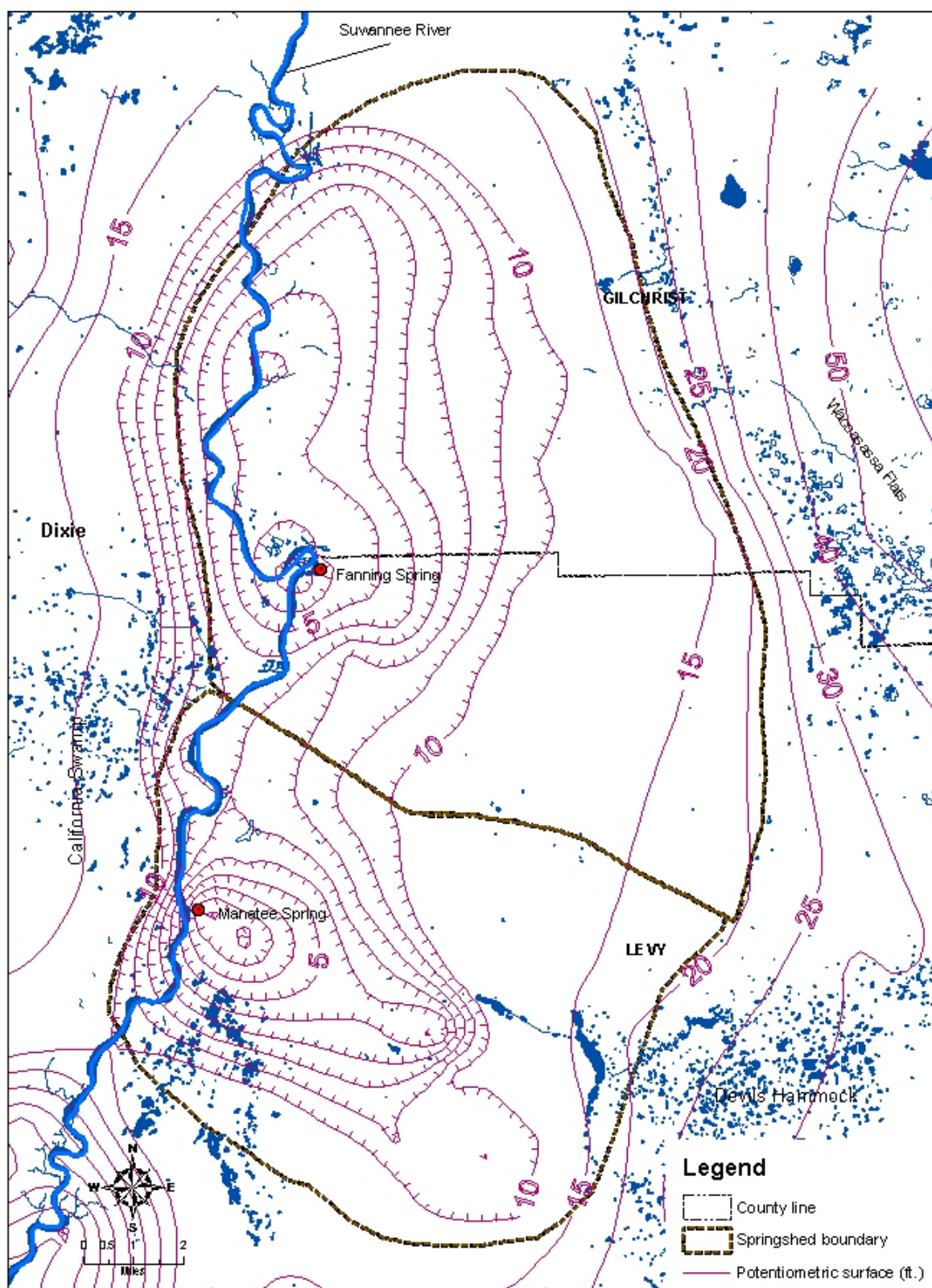


Figure 10. Potentiometric surface of the Floridan aquifer in the Manatee-Fanning study area (modified from Upchurch and Champion, 2003a). Note: variable contour interval.

GROUND-WATER CHEMISTRY

Previous ground-water investigations have indicated that the chemistry of ground water in north Florida is affected by a number of geologic, hydrologic, and anthropogenic (man-made) factors. These include 1) residence time in the aquifer, which affects the amount of dissolution of limestone, 2) the thickness and mineralogy of the Hawthorn Group sediments, 3) recharge rates (Lawrence and Upchurch, 1976; Crane, 1986; Upchurch, 1992), and 4) the presence of agricultural and other land uses in areas near the springs (Katz and others, 1999). In addition, data presented by Katz and others (1999) suggest that much of the water discharging from the springs has moved through a relatively short, shallow flow system and has been in the Floridan aquifer for only a few decades, at most.

Water quality discharging from springs in north Florida has been characterized in a number of studies, including Rosenau and others (1977), Hornsby (1998), Katz and others (1999), Scott and others (2002), and Upchurch and Champion (2003a, 2003b, 2004). In general, the water is of excellent quality, but there is concern for increasing nitrate concentrations in several of the springs within the District.

Ground-water quality within the study area has been characterized by Upchurch (1990, 1992). The SRWMD updates the results of nitrate monitoring in its Groundwater Quality Monitoring Reports on an annual basis (Hornsby and Ceryak, 1999), as well.

Several studies have examined the connectivity of surface and ground water in north Florida, including Skiles (1991), Hirth (1995), and Martin and Gordon (1998). These studies, and the well-known Rose Creek Sink dye trace (Karst Environmental Services, 1997), clearly demonstrate the sensitivity of the ground-water system to surface-water events.

Floridan aquifer ground water is characterized as a calcium-bicarbonate water type because of interactions with the limestone of the aquifer. Because of the preponderance of karst in the Manatee-Fanning springshed, Floridan aquifer water contains numerous indicators of interaction with surface water, including color, high organic carbon, and high dissolved oxygen (Upchurch, 1990). These surface-water indicators demonstrate that the aquifer is highly vulnerable to human activities.

DELINEATION OF GROUND-WATER QUALITY DOMAINS

Study Area Monitor-Well Network

The water-quality data used to determine the chemical composition and source areas for spring water in the study area were obtained from a regional monitor-well network designed and sampled by staff at SRWMD. The monitor-well network totaled 102 wells, consisting of dedicated monitor wells and wells used for domestic and public supply.

Factor Analysis

Factor analysis is used to sort out hydrogeologic, process-response relationships from commonly collected ground-water data. It has been applied to the Floridan aquifer system by Lawrence and Upchurch (1976; 1982), Ceryak (1977), Dalton (1978), and Dalton and Upchurch (1978). Factor analysis combines variables that are correlated into analyte clusters in order of the amount of variance explained. Using the SYSTAT[®] software, principal components analysis (PCA), a form of factor analysis using Varimax rotation, was performed for data on 20 chemical analytes from the 102 well samples (Figure 1).

The PCA combines chemical variables into groups, or factors, each representing a statistically independent chemical process (Lawrence and Upchurch, 1976, 1982). Factor loadings are calculated for each chemical variable. The loadings show how well each analyte is associated with each factor. Most chemical variables are specific to a single process, or factor, though a chemical variable may load heavily on more than one factor if it is important in more than one process. The PCA also calculates a factor score for each sample, which reflects the importance of a given factor at that sample site. Extreme negative scores (<-1) reflect water essentially unaffected by a given process (as represented by the factor), positive scores ($>+1$) reflect water most affected, and near zero scores reflect water affected to an “average degree” by the chemical process or factor. The factor scores can be contoured on maps to evaluate the spatial importance of the chemical process represented by each factor.

The final PCA revealed six chemically distinct, but not mutually exclusive, hydrochemical processes. These six factors accounted for 74.7 percent of the total variability present in the water sample data. Table 1 shows the factor loadings for the 20 chemical variables. Figures 11 through 16 show contour maps of factor scores for each factor identified.

Note in Table 1 that many groupings of analytes reflect intuitive relationships of analytes. For example, sodium and chloride group in Factor IV is interpreted to represent a “sea water” aerosol component in rainfall (Upchurch, 1992). These groups are discussed below.

Factor I includes the variables potassium, nitrate, specific conductance, total dissolved solids (TDS), sulfate, and calcium. These are constituents that result from several processes, including the upwelling of sulfate-rich ground water near springs and along the salt-water transition zone, and the use of nitrogen fertilizers. Therefore, Factor I appears to represent two separate processes: deep ground-water flow paths in the Floridan aquifer and land use. Figure 11 shows the spatial distribution of factor scores for Factor I. Low Factor I scores indicate areas where ground-water flow paths are shallow and where land uses are not causing leaching of nutrients into the aquifer. On the other hand, high Factor I scores indicate areas where 1) deep, sulfate-rich ground water is upwelling, such as in isolated locations along the Suwannee River, 2) areas are impacted by the use of nitrogen fertilizers, or 3) there is irrigation by agricultural land uses may be causing up-coning of deep sulfate-rich ground water and the irrigation water is affected by concomitant use of nitrogen fertilizers in upland regions away from the Suwannee River. Several isolated areas of elevated and high Factor I scores can be seen on Figure 11, including areas to the northeast of Manatee Springs, to the southeast of Chiefland, and to the east of Fanning Springs.

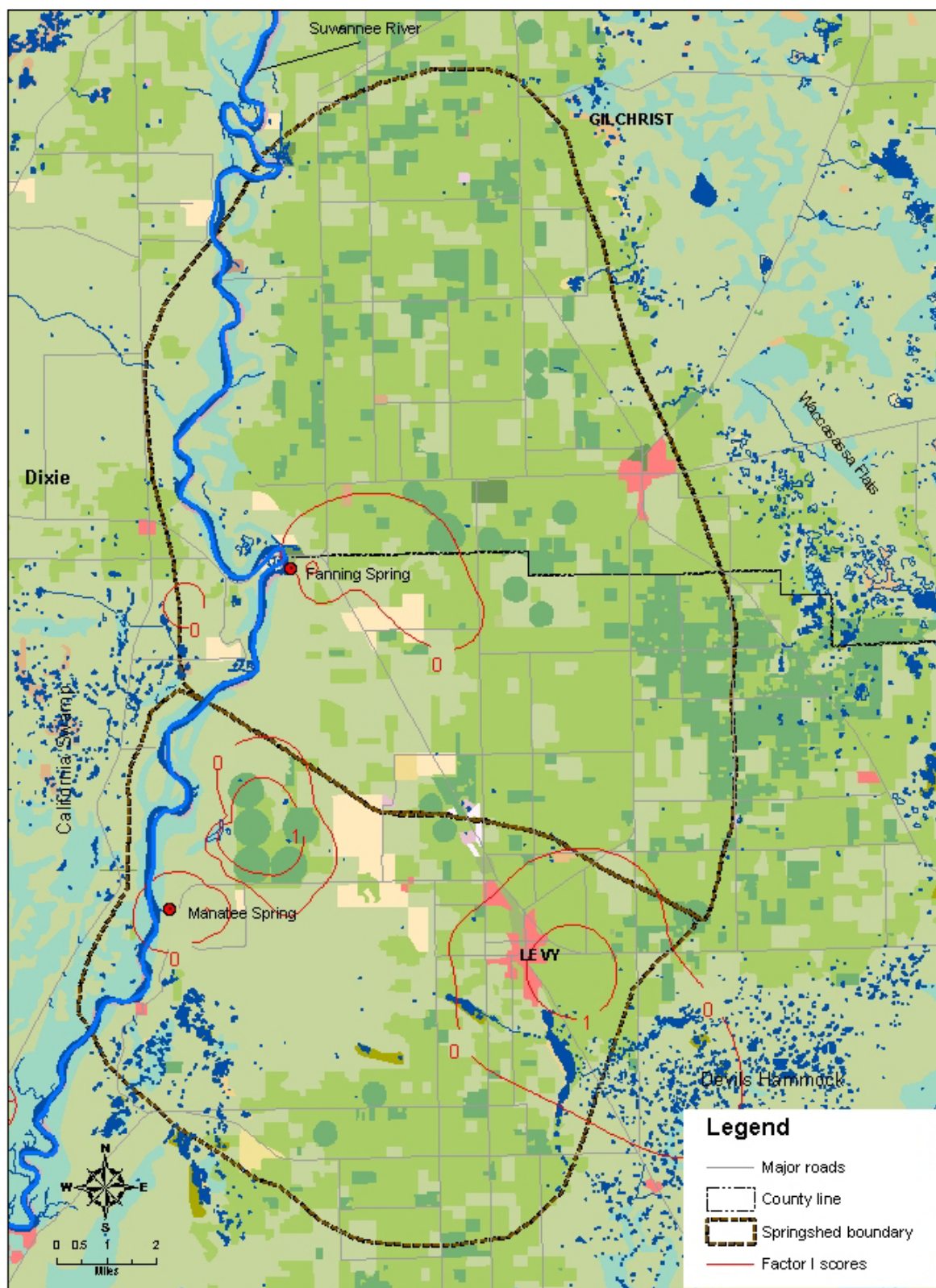


Figure 11. Factor 1 (potassium, nitrate, sp. conductance, TDS, sulfate, and calcium) scores in the Manatee-Fanning study area. Land-use color scheme can be found on Figure 3.

Factor II includes total organic carbon (TOC), ammonia (NH_3), total kjeldahl nitrogen (TKN), and dissolved organic carbon (DOC). These constituents result from the recharge of chemically-reduced, organic-rich ground water to the Floridan aquifer in the lowland, swampy areas encompassed by the Waccasassa Flats, Devils Hammock, and California Swamp in Dixie County. Therefore, Factor II is recharge controlled. The spatial distribution of Factor II scores is shown in Figure 12.

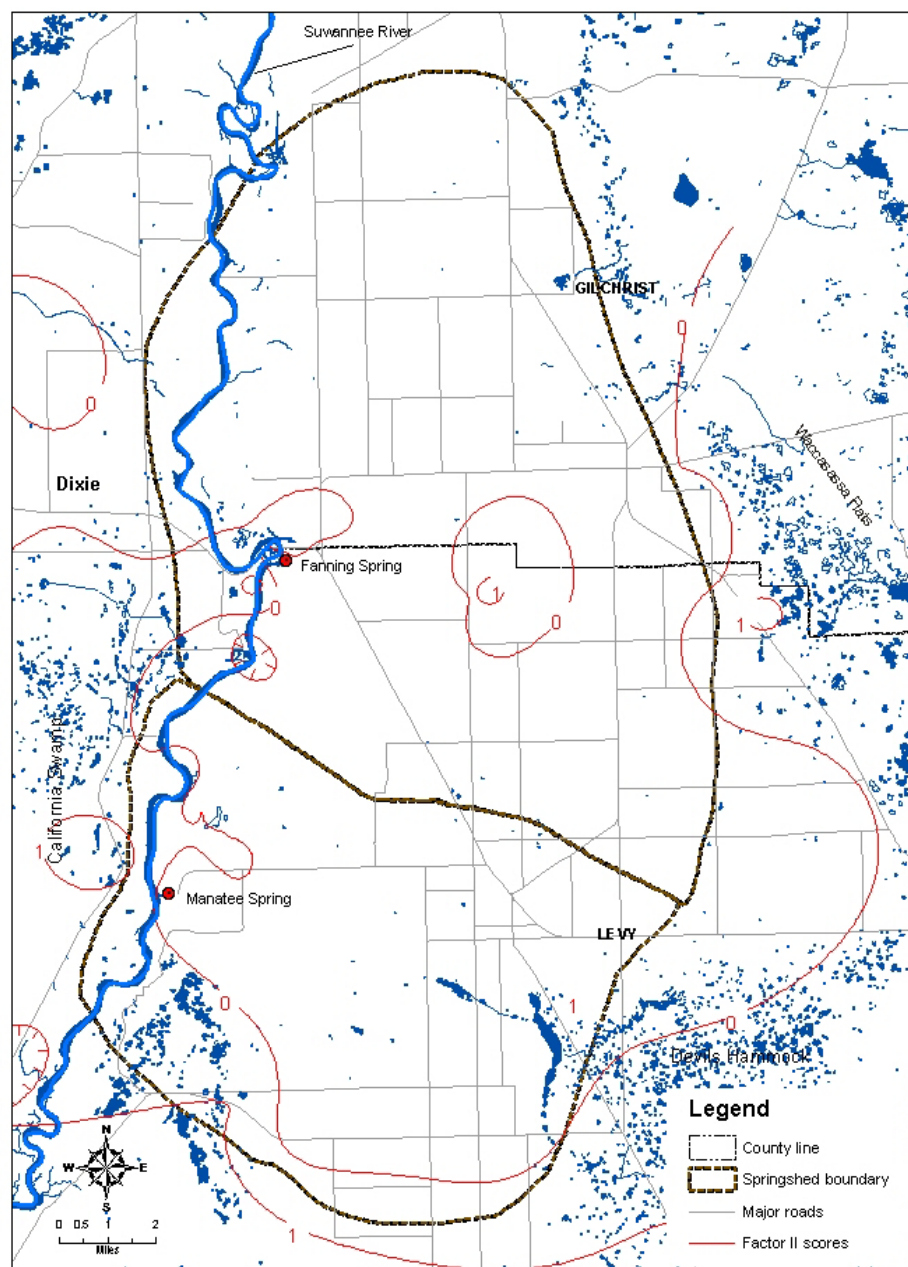


Figure 12. Factor II (TOC, ammonia, TKN, and DOC) scores in the study area.

An isolated area of elevated Factor II scores in the interior of the springshed (Figure 12) suggests recharge of organic-rich ground water to the Floridan aquifer. One monitor well (#85), which contains sulfate-rich ground water with elevated levels of ammonia, TOC, and DOC, appears to cause this isolated area of high Factor II scores. This well is open to the Floridan aquifer from 124 to 225 feet below land surface, and its chemical composition suggests mixing of organic- and sulfate-rich ground water in flow zones in the Avon Park Formation.

Factor III includes magnesium, silica, fluoride, sulfate, and TDS. These constituents result from the leaching of phosphatic sands and clays of Hawthorn Group sediments and residua. Therefore, Factor III is lithologically controlled. In the Manatee-Fanning springshed, however, the Hawthorn Group has been largely removed by erosion and may only be found in isolated outliers in deep karst features or numerous sinkhole features (Figure 7). Several large areas of high Factor III scores are found in the springshed (Figure 13). Two of these areas are found along the course of the Suwannee River, suggesting discharge to the River. This discharge zone contains a mixture of water types, as reflected in the influence of sulfate in Factors I and III.

The large region in the interior of the springshed represents two major processes. First, the highest scores are again found in the sample from well # 85 and a second well, # 37 (Figure 13). Well completion depth and raw chemical data indicate that these wells tap the Avon Park Formation or lower portions of the Ocala Limestone. The eastern side of this high Factor III score region is likely due to the interaction of ground water with Hawthorn Group sediments in the Waccasassa Flats region. The proximity of a number of wells to the eastern boundary of the springshed, which corresponds closely to the western limits of the Flats, suggests that the adjacent strata likely influence ground-water chemistry in this region. A potentiometric surface map of the Manatee-Fanning springshed (Figure 10) suggests that this area is characterized by sluggish flow in the Floridan aquifer (Upchurch and Champion, 2004). Therefore, the exchange of ground water from the Flats into the springshed and the chemical evolution of Floridan aquifer ground water will be relatively slow in this portion of the springshed.

Factor IV includes chloride and sodium. In areas with the highest Factor IV scores (Figure 14), these chemical variables represent low concentrations of sea water near the salt-water transition zone and, possibly, septic tank leachate, derived from onsite sewage disposal. The wells showing the highest Factor IV scores are generally found in the western half of the springshed along the Suwannee River (Figure 14). A review of well completion data indicates that the wells associated with high Factor IV scores are completed in the upper 50 to 60 feet of the Floridan aquifer. Factor IV scores in the 0 to 1 range occur in a number of wells along the western margin of the springshed along the Suwannee River (Figure 14). These moderately high Factor scores likely reflect water derived from the uppermost portions of the sea-water transition zone near the River.

Factor V includes phosphorus, silica, DOC, and -pH. The negative sign associated with pH reflects a negative correlation of pH with the other analyte data. The inverse relationship between phosphorus, silica, and DOC with pH suggests a process by which lower pH (relatively acidic) waters have relatively higher amounts of phosphorus, silica,

and DOC. Such a process suggests that recharge is controlling Factor V. While the highest Factor V scores (>1) are concentrated in the western half of the basin (Figure 15), numerous wells throughout the springshed contain positive Factor V scores. This regional characteristic suggests a lithologic and/or a flow path control.

Factor VI includes calcium and bicarbonate. Factor VI is a lithologically controlled factor reflecting the dissolution of carbonate minerals in the Floridan aquifer. Figure 16 shows the areal distribution of factor scores for Factor VI. High Factor VI scores may indicate relatively stagnant areas of the aquifer where longer residence times have resulted in more dissolution of the formation. The largest area of high Factor VI scores can be seen to the west of the Manatee-Fanning springshed in Dixie County in the California Swamp (Figure 16). Low Factor VI scores indicate areas where dissolution of limestone has not reached a maximum. Areas containing low Factor VI scores include isolated locations in the springshed, as well as regions near the main springs that suggest short flow paths through the aquifer.

			Factor Loadings					
Variable	Units	Range	I	II	III	IV	V	VI
FACTOR I								
Potassium	mg/l	0.16-8.70	0.92	-0.02	0.06	-0.04	0.03	-0.02
Nitrate+Nitrite	mg/l	0.01-14.2	0.90	-0.13	-0.06	-0.01	0.03	-0.02
Sp. Conductance	µS/cm	24.0-1815	0.72	0.06	0.27	0.28	0.16	0.34
TDS	mg/l	30.0-788	0.68	0.12	0.48	0.35	-0.06	0.34
Sulfate	mg/l	0.80-349	0.63	-0.10	0.70	0.06	-0.08	0.00
Calcium	mg/l	1.15-218	0.54	0.14	0.25	0.11	0.16	0.69
FACTOR II								
TOC	mg/l	0.38-15.0	-0.04	0.93	-0.05	0.15	0.02	0.09
Ammonia	mg/l	0.02-0.29	-0.07	0.85	0.04	0.17	-0.08	-0.01
TKN	mg/l	0.04-1.70	0.05	0.81	0.01	-0.01	0.12	0.22
DOC	mg/l	0.38-16.2	-0.04	0.70	-0.04	0.08	0.5	0.23
FACTOR III								
Magnesium	mg/l	0.41-34.7	0.36	-0.08	0.86	-0.02	-0.06	0.13
Silica	mg/l	0.11-16.1	-0.21	0.20	0.62	-0.11	0.48	0.14
Fluoride	mg/l	0.02-1.14	-0.05	-0.02	0.61	0.14	-0.11	-0.16
Sulfate	mg/l	0.80-349	0.63	-0.10	0.70	0.06	-0.08	0.00
TDS	mg/l	30.0-788	0.68	0.12	0.48	0.35	-0.06	0.34
FACTOR IV								
Sodium	mg/l	1.88-74.4	0.03	0.17	0.04	0.97	0.10	0.12
Chloride	mg/l	1.99-141	0.12	0.11	0.01	0.92	-0.04	0.02
FACTOR V								
Phosphate	mg/l	0.01-2.78	-0.00	-0.04	0.06	-0.04	0.80	0.29
pH	s.u.	4.98-7.51	-0.19	-0.16	0.12	-0.12	-0.74	0.20
DOC	mg/l	0.38-16.2	0.05	0.70	-0.04	0.08	0.50	0.23
Silica	mg/l	0.11-16.1	-0.21	0.20	0.62	-0.11	0.48	0.14
FACTOR VI								
Alkalinity	mg/l	1.50-372	0.04	0.33	-0.03	0.10	0.05	0.89
Calcium	mg/l	1.15-218	0.54	0.14	0.25	0.11	0.16	0.69
PERCENT OF TOTAL VARIANCE EXPLAINED			18.0	15.6	12.0	10.7	9.3	9.1

Table 1. Factor loadings for the 20 chemical variables used in the factor analysis. Bold factor loadings reflect the variables most closely associated within each factor. Negative factor loadings suggest an inverse relationship between a particular variable and other variables within the factor.

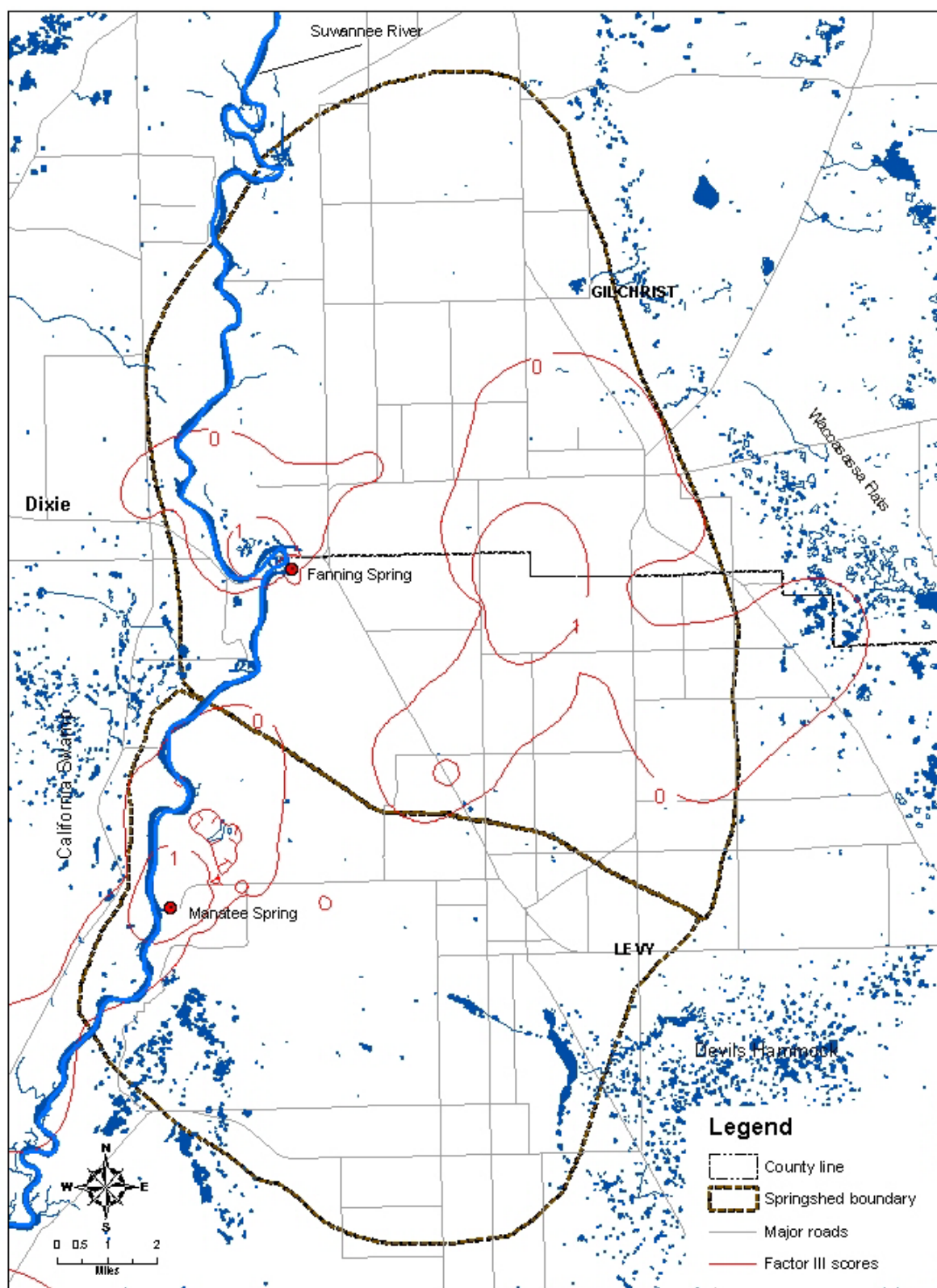
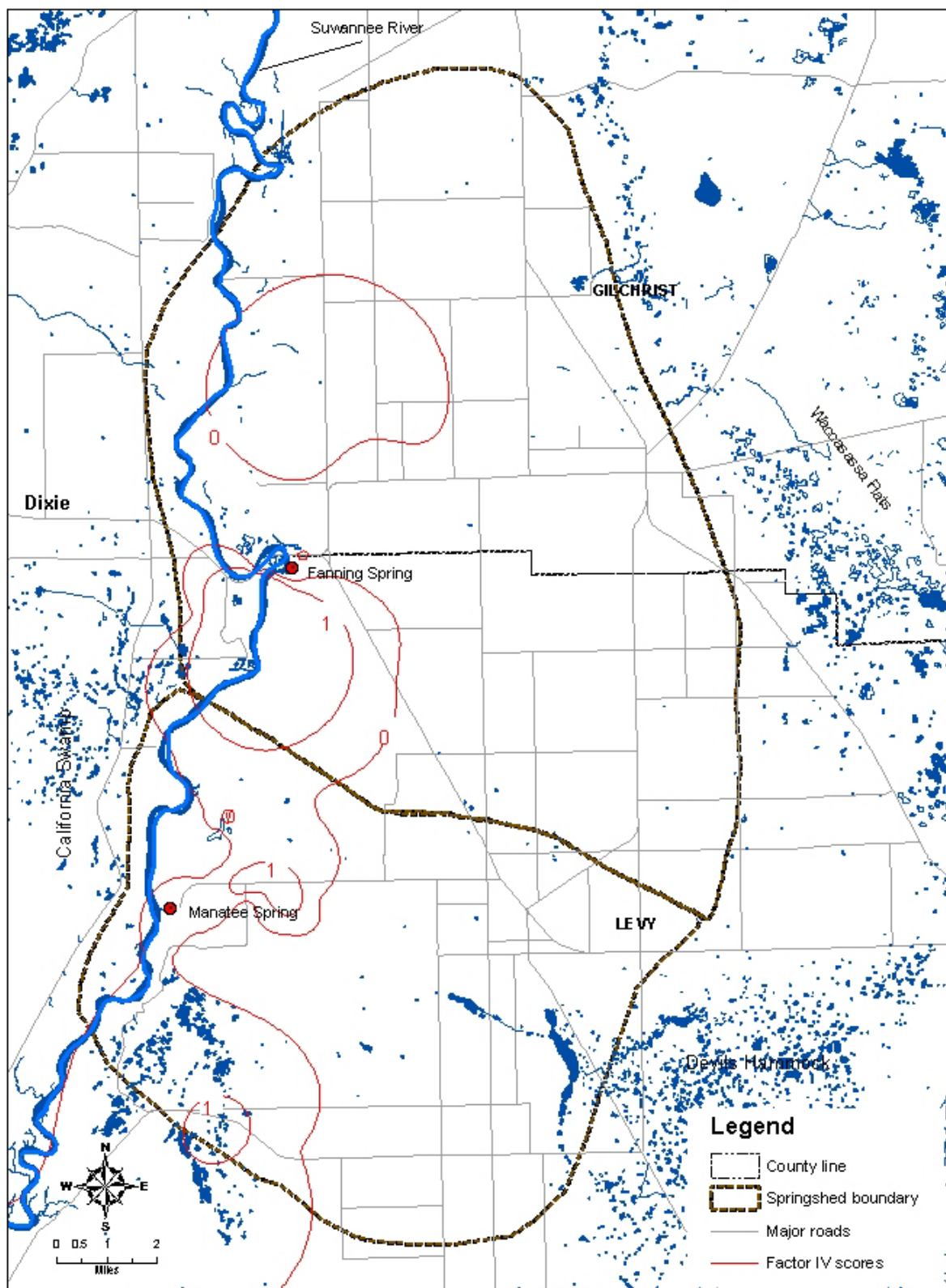


Figure 13. Factor III (magnesium, silica, fluoride, sulfate, and TDS) scores in the study area.



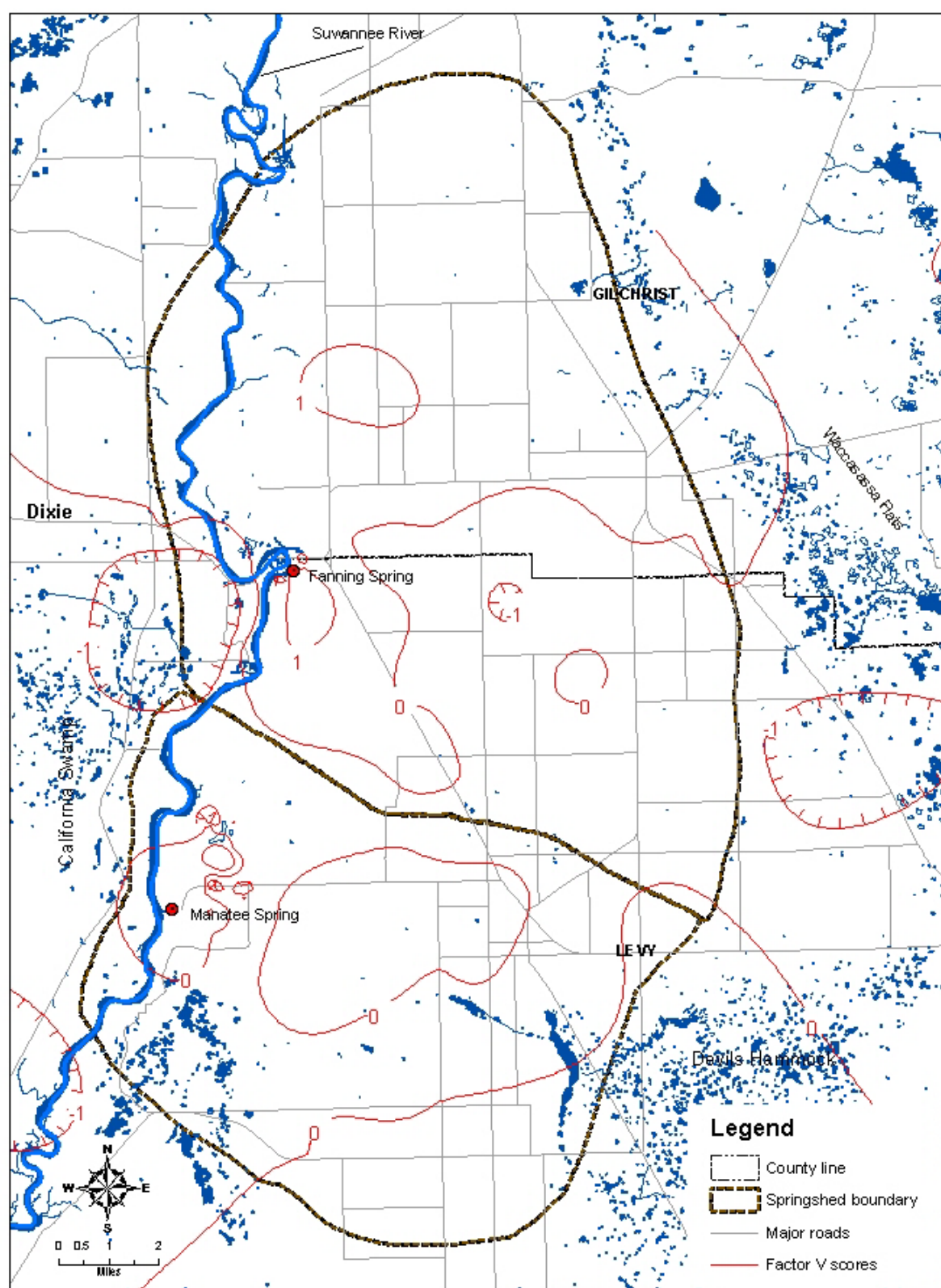


Figure 15. Factor V (phosphorus, -pH, DOC, and silica) scores in the study area.

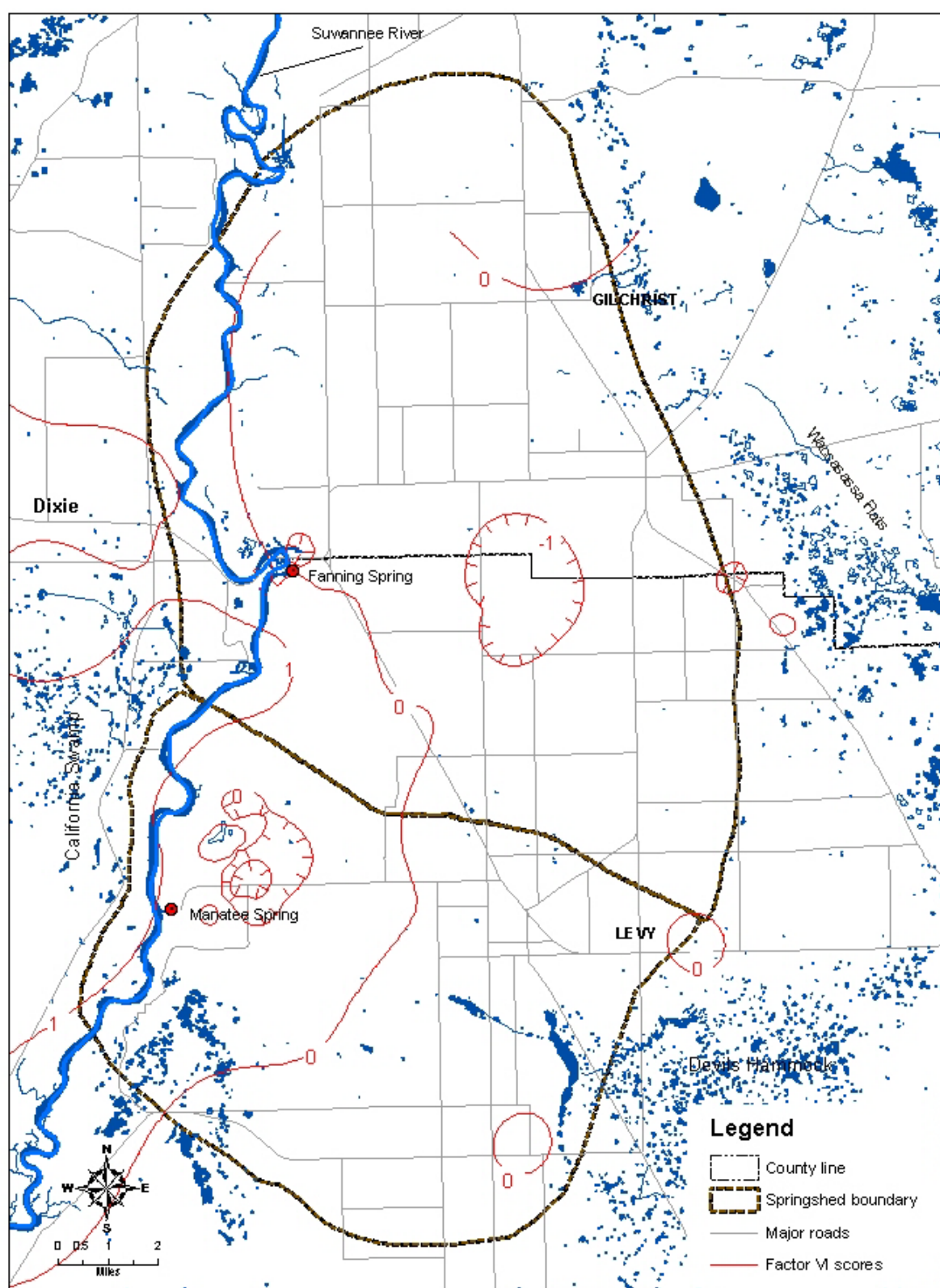


Figure 16. Factor VI (bicarbonate and calcium) scores in the study area.

Hydrochemical Facies Analysis

Hydrochemical facies analysis (Upchurch, 1992) is an excellent way to place a series of water-quality analyses into a spatial context. The analysis depends on pattern recognition techniques. In order to place the patterns into groups and identify the spatial patterns of chemical variables, a hierarchical analysis was performed using the SYSTAT[®] software. This type of analysis produces a tree of clusters that represent distinct groups of samples. The initial hierarchical analysis produced six clusters. However, this grouping was then modified to that shown in Figure 17.

Using Stanford Graphics[®] software, individual samples are plotted on “star” diagrams, which show the relative proportions of ions in the sample. Star diagrams were used in preference to other pattern-recognition methods (i.e., Stiff diagrams), because star diagrams allow use of non-standard combinations of chemicals and minor constituents can be emphasized. The analytes were selected for use in the star diagrams based on the PCA; one analyte was chosen to represent each of the six identified factors.

Figure 17 displays the star diagrams for each of the water-quality groups in the study area. When looking at the star diagrams in Figure 17, it is important to remember that the length of each axis corresponds to the relative concentration of a major constituent in relation to other samples, not other constituents within the same sample. The higher the concentration relative to other samples, the longer the axis. If two or more wells have similar concentrations of the major constituents, the star diagrams will be similar.

The star diagrams depicted in Figure 17 were chosen to give a representative picture of the types of patterns present within each cluster. Table 2 provides a summary of the characteristics of each cluster or water type.

The following discussion describes the process used to delineate the most significant ground-water quality domains within the study area. The establishment of water-quality domains will help demonstrate how water quality differs across the region and help identify source areas for ground water discharging from Manatee and Fanning Springs.

Constituent	Group 1a	Group 1b	Group 2	Group 3
	Domain I – Recharge		Domain II – Wetlands/Swamps	Domain III – Upwelling
Temp (C)	22.3	22.2	21.6	21.8
Sp. Cond (μS/cm)	404	632	484	735
pH (s.u.)	7.1	6.91	7.02	7.09
DO	2.43	3.23	0.26	0.61
Alkalinity	184	200	221	174
Calcium	77.8	118	91.3	134
Chloride	5.89	10.4	6.41	11.3
DOC	0.47	0.68	6.72	2.54
Fluoride	0.10	0.10	0.05	0.27
Potassium	0.32	2.93	0.17	0.90
Magnesium	3.28	6.13	1.93	25.7
Sodium	3.50	6.20	4.35	8.97
Ammonia	0.02	0.02	0.15	0.07
Nitrate+Nitrite	0.36	3.46	0.01	0.01
Phosphorus	0.06	0.08	0.06	0.04
Silica	6.97	7.25	9.16	11.2
Sulfate	9.10	18.9	1.48	209
TDS	230	352	318	546
TKN	0.05	0.08	0.48	0.14
TOC	0.40	0.55	6.40	2.04

Table 2. Median analyte concentrations for the three water-quality domains in the Manatee Fanning Springs study area. Concentrations in mg/l unless otherwise noted.

General Characteristics of Water-Quality Groups



Group 1a

Group 1a represents ground-water samples that have recently recharged the aquifer. These samples typically contain relatively low concentrations of major ions and TDS, and in some instances have pH values below 6 s.u. Group 1a wells typically contain elevated levels of phosphorus, DO and low concentrations of TOC and TKN.



Group 1b

Group 1b represents ground-water samples that have also recently recharged the aquifer. These samples, however, typically contain relatively high levels of potassium and nitrate. Given the association of the variables in this group, wells represented in Group 1b are likely influenced by anthropogenic sources of nitrate.



Group 2

Group 2 represents ground-water samples that are enriched in organic compounds, namely TOC, TKN, and ammonia. These samples typically have relatively low concentrations of DO and sulfate due to biologic uptake in the chemically reduced recharge.



Group 3

Group 3 represents ground-water samples that typically contain relatively high levels of magnesium, fluoride, silica, and sulfate. The chemical maturity of the ground water in this group is evident in its elevated levels of TDS.



Manatee



Fanning

Comparing the star diagrams of Manatee and Fanning Springs to that of the star diagrams for the water-quality groups above shows that both springs closely match the water-quality patterns of Group 1a and 1b. This similarity suggests that the spring source areas lie in regions represented by Groups 1a and 1b - the Recharge Domain.

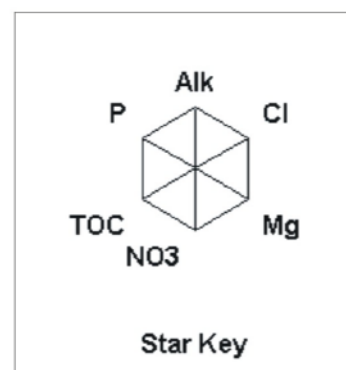


Figure 17. Star diagrams for representative water types in the Manatee-Fanning Springs study area. The star diagrams for Manatee and Fanning Springs are also shown.

Domain I: Recharge Domain

Domain I, the Recharge Domain, covers a large portion of the springshed (Figure 18), where low-permeability Hawthorn Group sediments are thin to non-existent (Figure 8), sinkholes are abundant (Figure 7), and recharge to the Upper Floridan aquifer is moderate to high (Figure 9). Water-quality samples in this domain are broken into two groups, 1a and 1b, primarily on their potassium and nitrate concentrations. Geochemically, the Recharge Domain is identified by lower median concentrations of calcium, chloride, sodium, DOC, and TDS (Table 1). The water-quality samples from Group 1b of the Recharge Domain are identified by higher median nitrate concentrations (3.46 mg/l), potassium, and DO. The median nitrate concentration in this domain is significantly elevated above background concentrations of nitrate in the Floridan aquifer (<0.01 mg/l; Upchurch 1992).

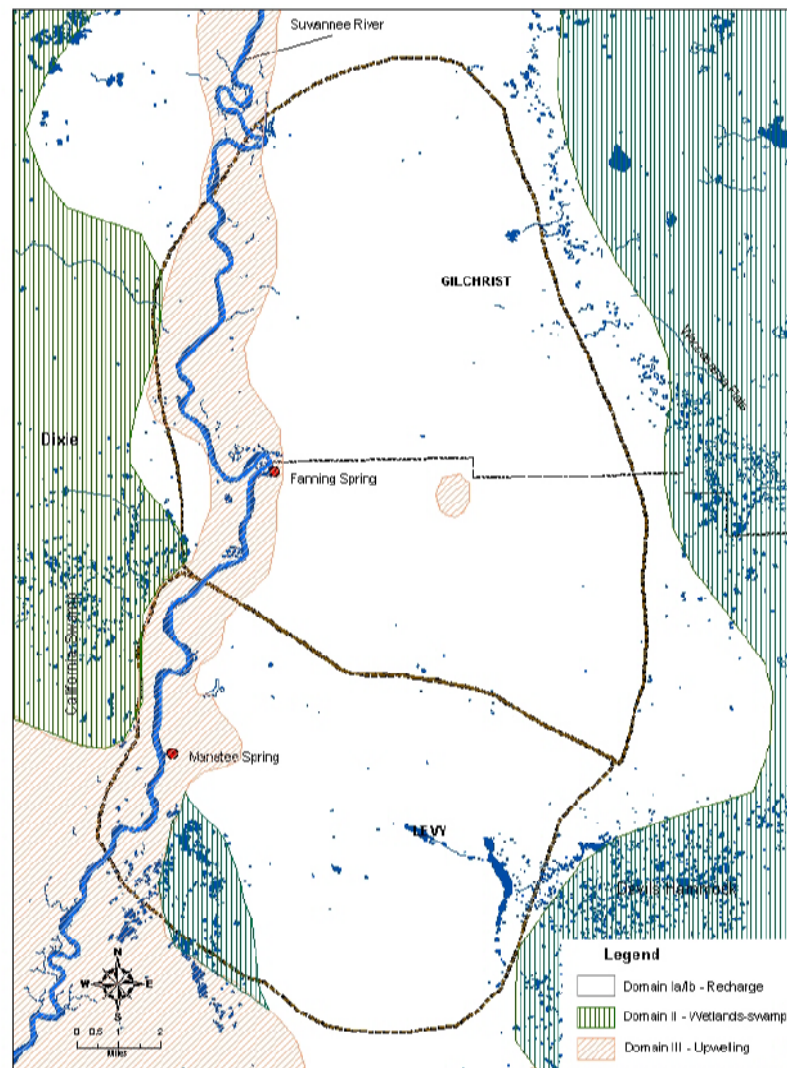


Figure 18. Water-quality domains in the Manatee-Fanning study area.

Domain II: Wetland-Swamps Domain

Domain II, the Wetland-Swamps Domain, covers much of the region along the eastern, southern, and western boundaries of the springshed (Figure 18). This domain is characterized by the widespread occurrence of wetlands and swamps (Figure 6) and the lack of significant sinkhole features (Figure 7). Geochemically, the Wetland-Swamps Domain is identified by elevated median concentrations of DOC, ammonium, TKN, and TOC (Table 1). Elevated concentrations of these four constituents reflect reducing conditions in the aquifer as a result of local recharge through swamps and other areas of highly organic surface waters and organic-rich soils (Lawrence and Upchurch, 1976; Upchurch, 1990). The Wetland-Swamps Domain is also identified by low median concentrations of DO and sulfate (Table 1). Low concentrations of DO and sulfate suggest chemically reduced ground-water recharge.

Domain III: Upwelling Domain

Domain III, the Upwelling Domain, is found in the western half of the springshed along the Suwannee River and in areas near Manatee Springs. This domain is characterized by regional discharge of ground water to the Suwannee River. The Upwelling Domain along the Suwannee River and near Manatee Springs is identified by elevated median concentrations of calcium, magnesium, sulfate, potassium, fluoride, and TDS (Table 1). These six constituents reflect the influence of chemically mature ground water and upward movement of ground water from deeper flow paths in the Floridan aquifer. In isolated instances, these chemically mature ground water signatures may be influenced by ground-water withdrawals in the lower permeable sections of the Floridan aquifer (i.e., Avon Park Formation).

DELINEATION OF SPRING-WATER SOURCE AREAS

Water-quality data collected in the study area suggest that the regional ground-water system and Manatee-Fanning Springs have very similar chemical compositions. However, there are subtle chemical differences between many of the samples that enable one to distinguish chemical patterns unique to groups of samples across the region. These patterns indicate source areas that yield chemical fingerprints that can be used to identify spring-water source areas.

Because the ground water discharging from Manatee and Fanning Springs differs slightly, the chemistry of the spring water was compared to the chemistry of the three water-quality domains described above. This method was particularly useful in determining the source areas for ground water discharging from Rainbow Springs (Jones and others, 1996), Crystal Springs (Champion and DeWitt, 2000), and Ichetucknee Springs (Upchurch and Champion, 2003b). Figure 17 shows both the star diagrams for the springs and for the water-quality domains described above.

Fanning Springs

A comparison of the star diagrams indicates that Domain Ib, the Recharge Domain, is supplying most of the water to Fanning Springs. The high recharge rates in Domain Ib have produced ground water with very low TDS and low magnesium, sodium, and chloride.

Using this domain strategy, the elevated levels of nitrate in Fanning Springs most likely originate in recharge areas to the east of the Springs. Nitrate concentrations in Domain Ib are elevated above background levels in the Floridan aquifer and, in several wells, exceed 3 mg/l. The levels of nitrate in Fanning Springs most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the springs from adjacent areas.

Manatee Springs

A comparison of the star diagrams indicates that Domains Ia and Ib, the Recharge Domains, are supplying most of the water to Manatee Springs. The high recharge rates in Domain I have produced ground water with very low TDS and low magnesium, sodium, and chloride. Note that the Manatee Springs star diagram is similar to Domain Ia water with small magnesium and nitrate “tails.”

Using this domain strategy, the elevated levels of nitrate in Manatee Springs most likely originate in recharge areas to the east and southeast of the Springs. Nitrate concentrations in Domain I are elevated above background levels in the Floridan aquifer and, in several wells, exceed 3 mg/l. The levels of nitrate in Manatee Springs most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the springs from adjacent areas.

SUMMARY AND CONCLUSIONS

The Floridan aquifer in the study area was divided into three water-quality domains, with each possessing certain chemical characteristics that reflect different water types and hydrochemical facies within the aquifer. Differences in water quality across the region are subtle and appear to be related to the presence or absence of confining layers, sinkhole distribution, and recharge to and discharge from the Floridan aquifer. Each of the four domains is summarized below.

Domain I: Recharge Domain

Domain I, the Recharge Domain, covers a large portion of the springshed (Figure 18), where low-permeability Hawthorn Group sediments are thin to non-existent, sinkholes are abundant, and recharge to the Upper Floridan aquifer is moderate to high. Water-quality samples in this domain are broken into two main groups, 1a and 1b, primarily on their potassium and nitrate concentrations. Geochemically, the Recharge Domain is identified by lower median concentrations of calcium, chloride, sodium, DOC, and TDS.

The water-quality samples from Group 1b of the Recharge Domain are identified by higher median nitrate concentrations (3.46 mg/l), potassium, and DO. The median nitrate concentration in this domain is significantly elevated above background concentrations of nitrate in the Floridan aquifer (<0.01 mg/l; Upchurch 1992).

Domain II: Wetland-Swamps Domain

Domain II, the Wetland-Swamps Domain, covers much of the region along the eastern, southern, and western boundaries of the springshed (Figure 18). This domain is characterized by the widespread occurrence of wetlands and swamps and the lack of significant sinkhole features. Geochemically, the Wetland-Swamps Domain is identified by elevated median concentrations of DOC, ammonium, TKN, and TOC. Elevated concentrations of these four constituents reflect reducing conditions in the aquifer, as a result of local recharge through swamps and other areas of highly organic surface waters and organic-rich soils (Lawrence and Upchurch, 1976; Upchurch, 1990). The Wetland-Swamps Domain is also identified by low median concentrations of DO and sulfate. Low concentrations DO and sulfate suggest biologic uptake in chemically reduced ground-water recharge.

Domain III: Upwelling Domain

Domain III, also called the Upwelling Domain, is found in the western half of the springshed, along the Suwannee River and in areas near Manatee Springs (Figure 18). This domain is characterized by regional discharge of ground water to the Suwannee River. The Upwelling Domain along the Suwannee River and near Manatee Springs is identified by elevated median concentrations of calcium, magnesium, sulfate, potassium, fluoride, and TDS. These six constituents reflect the influence of chemically mature ground water and upward movement of ground water from deeper flow paths in the Floridan aquifer. In isolated instances, these chemically mature ground water signatures may be influenced by ground-water withdrawals in the lower permeable sections of the Floridan aquifer (i.e., Avon Park Formation).

Sources of Spring Water

A comparison of the star diagrams indicates that Domain I, the Recharge Domain, is supplying most of the water to Manatee and Fanning Springs. The high recharge rates in Domain I has produced ground water with very low TDS and low magnesium, sodium, and chloride.

Using this domain strategy, the elevated levels of nitrate in Manatee and Fanning Springs most likely originate in recharge areas to the east of the Springs. Nitrate concentrations in Domain I are elevated above background levels in the Floridan aquifer and, in several wells, exceed 3 mg/l. The levels of nitrate in the Manatee and Fanning Springs most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the springs from adjacent areas.

Nitrate concentrations at Manatee and Fanning Springs have gradually increased over the last several decades, suggesting that water-quality trends in this spring are slow to change. With the implementation of best management practices (BMPs), it is anticipated that trends will reverse over time. Long-term monitoring is needed to detect these possible changes to water quality at the springs or to follow the current increasing trends in nitrate concentrations. The springs should be sampled at least twice a year to monitor intermediate- to long-term trends in water quality. This sampling program should include analyses for nutrients (e.g., nitrate), major ions (e.g., calcium), trace constituents (e.g., iron), and periodically for nitrogen isotopes to determine the effects of changing land use and to determine the effectiveness of remedial efforts to protect water quality at the springs.

These BMPs should be encouraged to reduce the use of fertilizer near the springs. This is particularly important given the proximity of agricultural land uses to the springs. BMPs for turf fertilization in residential and golf course areas, as well as septic and centralized sewage disposal, will need to be addressed as commercial and residential development proceeds in the springshed.

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**Ground Water Chemistry
and
Origin of Water Discharging
from**

TROY SPRING

Lafayette County, Florida

Prepared for the
SUWANNEE RIVER WATER MANAGEMENT DISTRICT
Live Oak, Florida

By
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4509 George Road
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March 30, 2005



Endorsement

This report, entitled "Ground Water Chemistry and Origin of Water Discharging from Troy Spring, Lafayette County, Florida," was prepared for the Suwannee River Water Management District by the undersigned individuals under Contract No. 03/04-058. Opinions and conclusions expressed in this report are those of the authors only. The data and conclusions presented herein do not necessarily reflect opinions or policy of the District.

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INTRODUCTION

Troy Spring is one of north Florida's most valuable natural resources. The spring is one of the State's many first-magnitude springs, as well as one of the most popular state parks in the region. The spring is important to the natural and scenic beauty of the area, and to the region's rich historical heritage. However, protecting Troy Spring and others like it will likely prove difficult without a thorough understanding of the geology and hydrology of the region surrounding the spring and adjacent Suwannee River.

Since the 1970's, much information has been gathered concerning large spring systems in north Florida and the importance of karst to water quality in the Floridan aquifer. Lawrence and Upchurch (1976), for example, determined that karst features could be used to deduce the vulnerability of ground water to contamination, and the extent to which ground-water recharge affects water quality in the Floridan aquifer near the town of Lake City in Columbia County. Similar results were obtained by Ceryak and others (1983) and Crane (1986) in two regional studies of the upper and lower Suwannee River Basin, respectively. More recently, nitrogen-isotope data collected by Katz and others (1999) suggested that Troy Spring discharges nitrate that is derived from a mixture of artificial fertilizers and wastewater. It has also been discovered that flow through large spring systems, such as Troy Spring, can be amazingly rapid. For example, a dye trace from Rose Creek Sink to the Ichetucknee Springs in Columbia County resulted in a transport rate of approximately one mile per day (Karst Environmental Services, 1997)!

An important step in understanding the hydrology of Troy Spring (Figure 1) is to define the spring drainage basin, or springshed (Copeland, 2003). A springshed is defined as the areas within which ground- and surface-water basins contribute to the discharge of a spring. The inclusion of surface-water drainage basins in the definition may be important to the Troy Spring system because several creeks, especially Little River (Figure 1), are known to discharge to ground water near the Troy Spring ground-water basin. Contaminants transported to the ground-water system from surface-water basins that extend beyond the ground-water basin may constitute a significant threat to the spring system.

The chemistry of groundwater in the study area is affected by a number of geologic, hydrologic, and anthropogenic factors. Factor analysis (principal components analysis, PCA) is a useful tool for sorting out hydrogeologic process-response relationships within a sample population of groundwater quality data. In this paper, PCA of ground-water chemical data is used to group chemical constituents into specific clusters, or factors, that reflect processes that affect the chemical composition of ground water in the study area. A graphical analysis of these factors is then utilized in order to define specific source areas for spring water.

DESCRIPTION OF STUDY AREA

The Troy Spring study area encompasses several hundred square miles of northeastern Lafayette County and southwestern Suwannee County (Figure 1). This region contains portions of both the middle reach of the Suwannee River watershed and the ground-water basins that contribute subsurface flow to the spring (Upchurch and Champion, 2004a). While Troy Spring is south of the river, the Troy Spring springshed lies to the north of the Suwannee River and encompasses approximately 220 square miles of southern and central Suwannee County. The ground-water basin was identified and described by Upchurch and Champion

(2004a) who used geostatistical analysis to define the basin boundaries. The Suwannee River Water Management District (SRWMD) is currently monitoring the Troy Spring springshed, which will greatly refine the basin delineations (Upchurch and others, 2001).

Note that most of the surface-water portion of the springshed appears to lie within the ground-water basin (Figure 2). However, a number of surface-water basins extend outside of the ground-water basin, including Little River and Blue Lake Slough. For this reason, the study area was selected to include both surface- and ground-water basins and to somewhat extend outside of these basins.

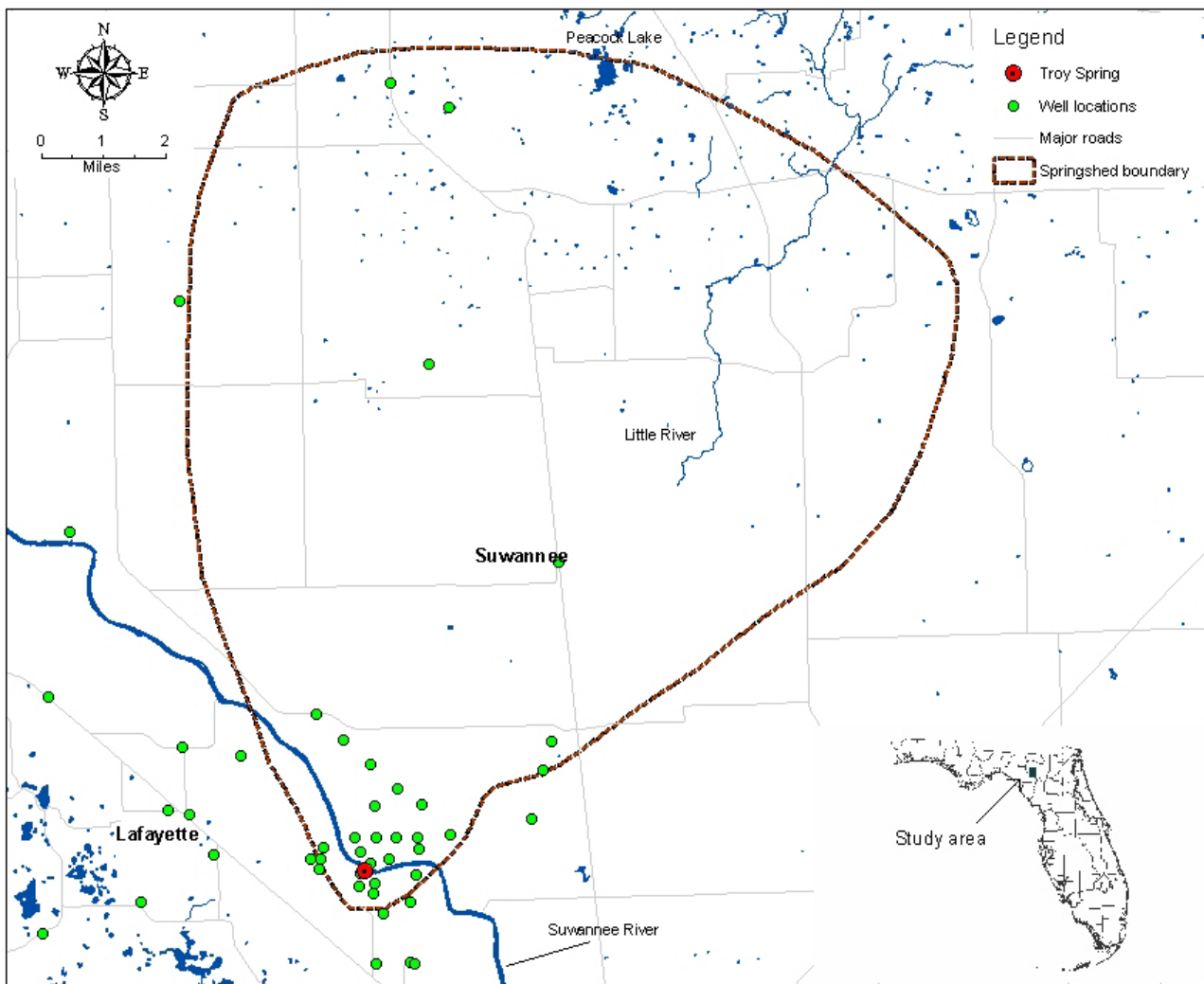


Figure 1. Location of the study area and the Troy Spring springshed (modified from Upchurch and Champion, 2004a).

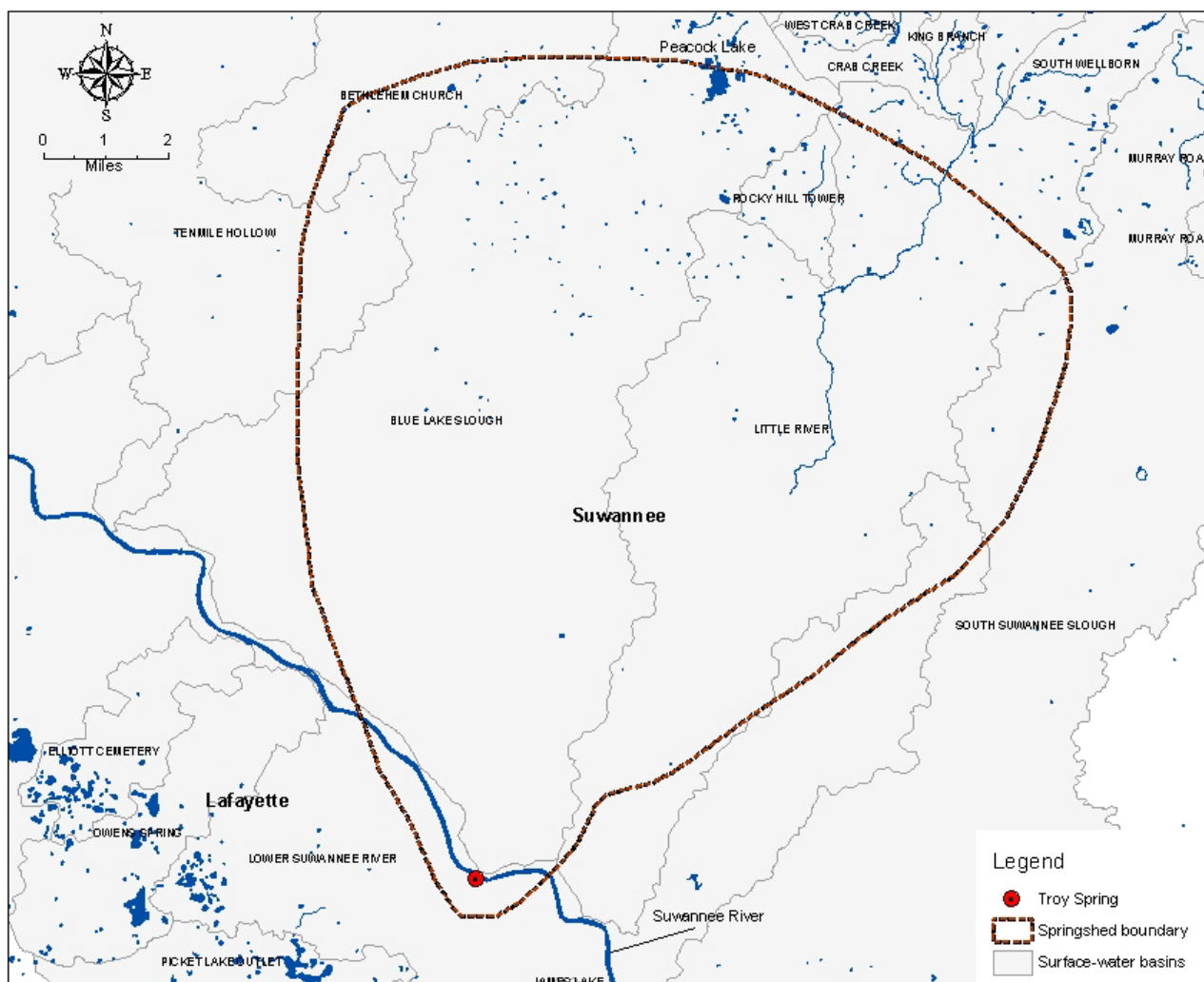


Figure 2. Surface-water basins in the study area and within the Troy Spring springshed. Shaded basin are within the Suwannee River watershed.

Population and Water Use

The population of Suwannee County in 2003 was approximately 36,695 (U.S. Census Bureau, 2005). However, the Troy Spring springshed is a sparsely populated region and contains no significant centers of population. Therefore, it is estimated that only a few thousand residents live in the Troy Spring basin. Given the predominant land uses in the region, it is reasonable to assume that agricultural interests comprise a large percentage of the population and land use in the springshed.

According to estimates by Marella (1999), ground water was withdrawn from the Floridan aquifer in Suwannee County at the rate of approximately 29.0 million gallons per day (mgd) in 1995. Agricultural withdrawals, rural self-supplied, and public water-supply systems accounted for approximately 80 percent (23.2 mgd), 11.4 percent (3.3 mgd) and 4.8 percent (1.4 mgd), respectively, of the total withdrawals in the County (Marella, 1999). Cumulatively, these withdrawals accounted for more than 96 percent of the water use in the County in 1995.

Land Use

Land use in the study area was identified using the 1996 USGS Arcview™ land-use coverage (Florida Geographic Data Library, 2004). The Troy Spring springshed is a sparsely populated region. The major land uses in the study area (Figure 3) include evergreen forests, temperate hardwood forests, pine plantations, areas of forest regeneration, improved pasture, and row crops (Upchurch and Champion, 2003a). Together, these five land uses cover approximately 80 percent of the Troy Spring springshed. Row crops, in particular, are concentrated in the central and western extent of the springshed nearest the spring (Figure 3). Intermixed among the row crops are large tracts of pine plantations, improved pasture, and forest regeneration. Temperate hardwood forests are scattered throughout the region, with a particularly large concentration along the western bank of the Suwannee River (Upchurch and Champion, 2003a).

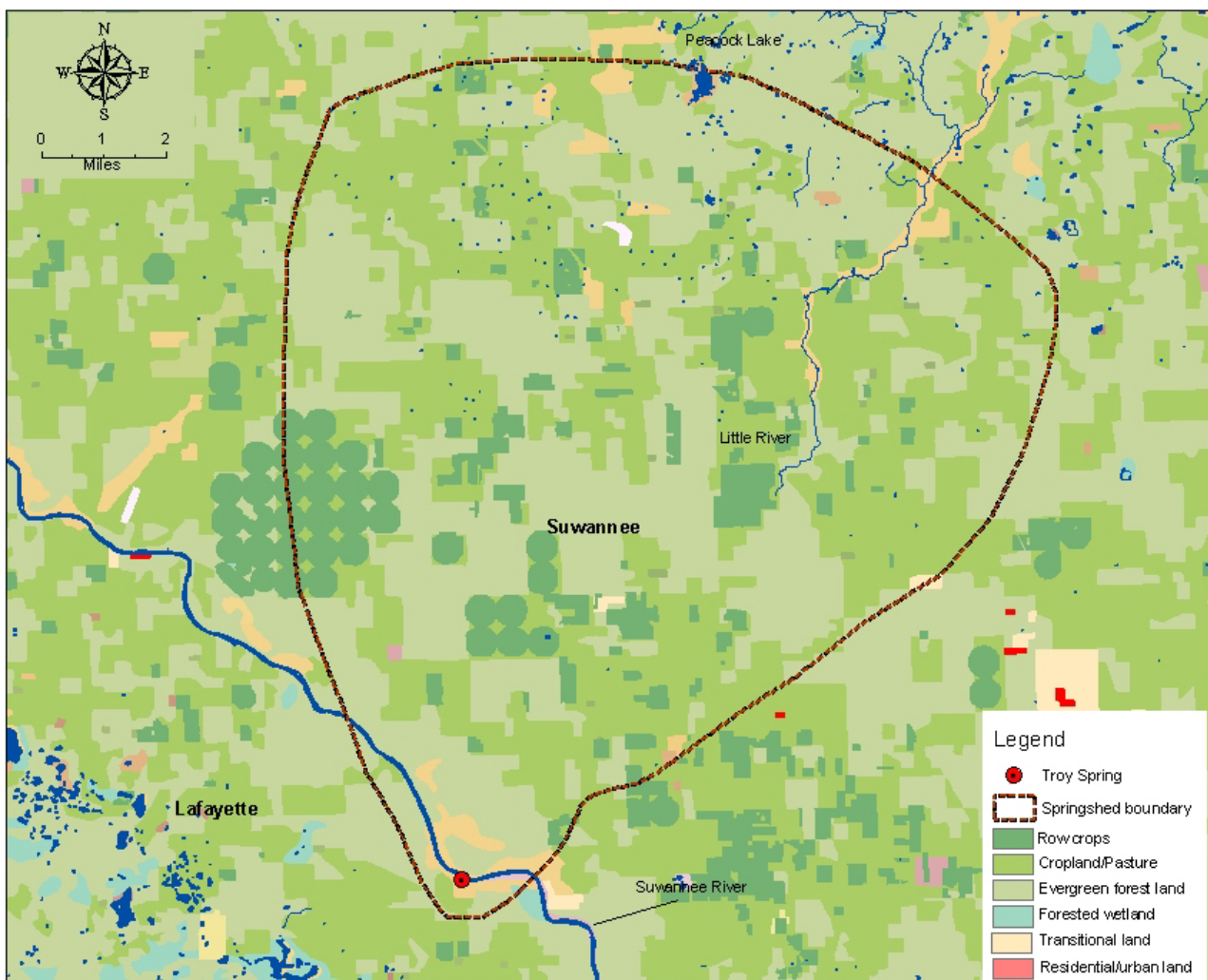


Figure 3. Major land uses in the Troy Spring study area (Florida Geographic Data Library, 2004).

Topography, Physiography, and Drainage

The topography of the Troy Spring study area varies considerably, from approximately 25 feet above sea level along the banks of the Suwannee River to areas in excess of 175 feet above sea level in upland regions to the northeast of the springshed (Figure 4). In the immediate vicinity of Troy Spring, however, elevations are approximately 25 feet above sea level.

White (1970) divided Suwannee County into two physiographic regions: the Gulf Coast Lowlands and the Northern Highlands (Figure 5). The Northern Highlands is an upland area (typically greater than 150 feet above sea level) capped by relatively impermeable, clay-rich sediments, which result in considerable surface-water runoff and development of lakes and wetlands (Figure 6). In contrast, the Coastal Lowlands (typically less than 100 feet above sea level) is a mature karst plain characterized by complete, rapid infiltration of runoff, and few, if any, lakes or wetlands (Figure 6). Sinkholes in the Coastal Lowlands are typically small in area, but they are numerous (Upchurch, 2002).

Between the Northern Highlands and Coastal Lowlands is a transitional region characterized by an abundance of sinkholes, sinkhole lakes, and sinking streams (Figure 7). This transitional region was named the Cody Scarp by Puri and Vernon (1964). Surface elevations along the Cody Scarp are generally between 100 and 150 feet above NGVD, and within the study area, a large portion of the surface runoff from the Northern Highlands flows down the Cody Scarp, where it drains rapidly into the Floridan aquifer. Because of the relatively thick cover within the Cody Scarp, sinkholes and sinkhole-related karst features tend to be large (Upchurch, 2002).

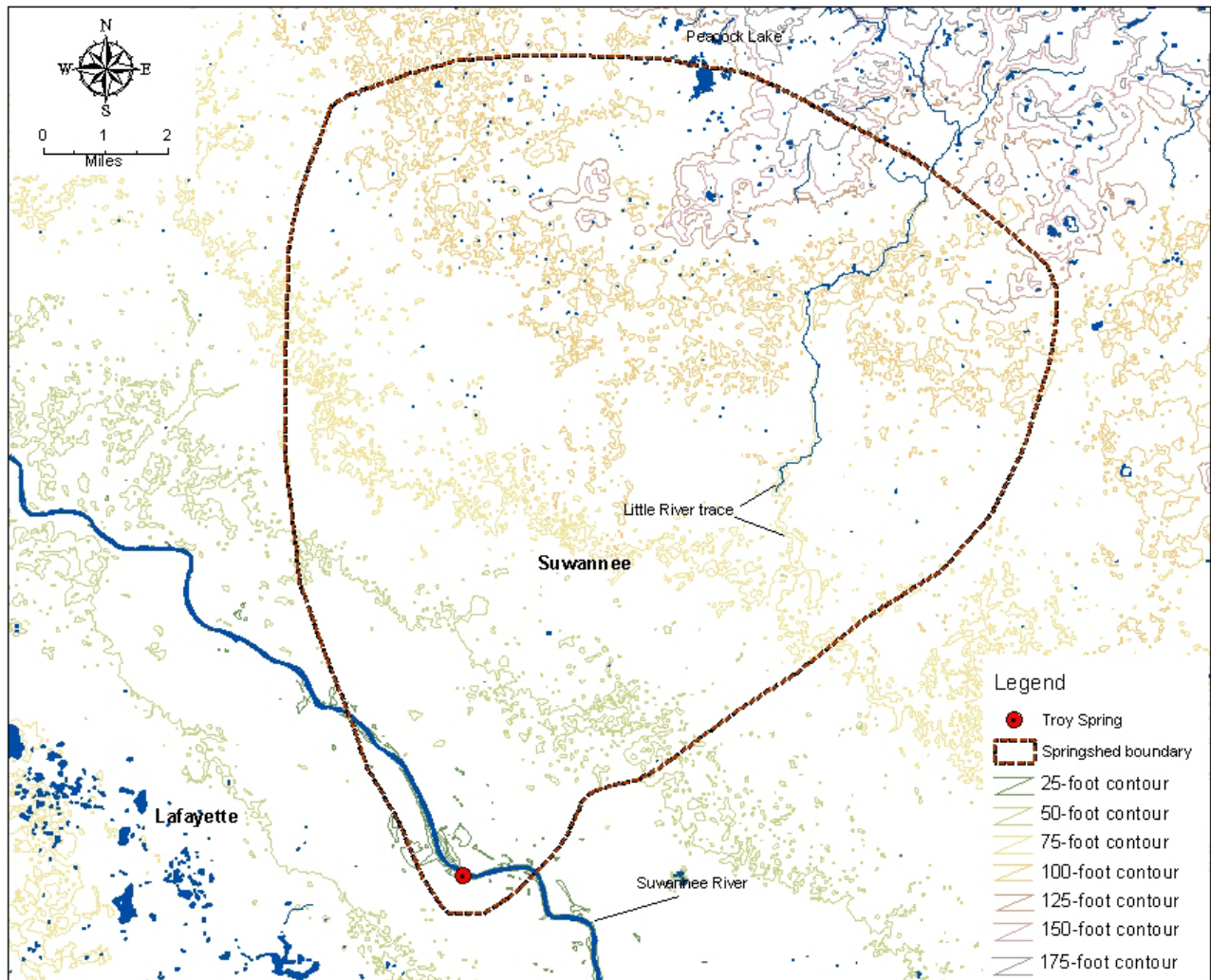


Figure 4. Land-surface elevations in the Troy Spring study area (Florida Geographic Data Library, 2004).

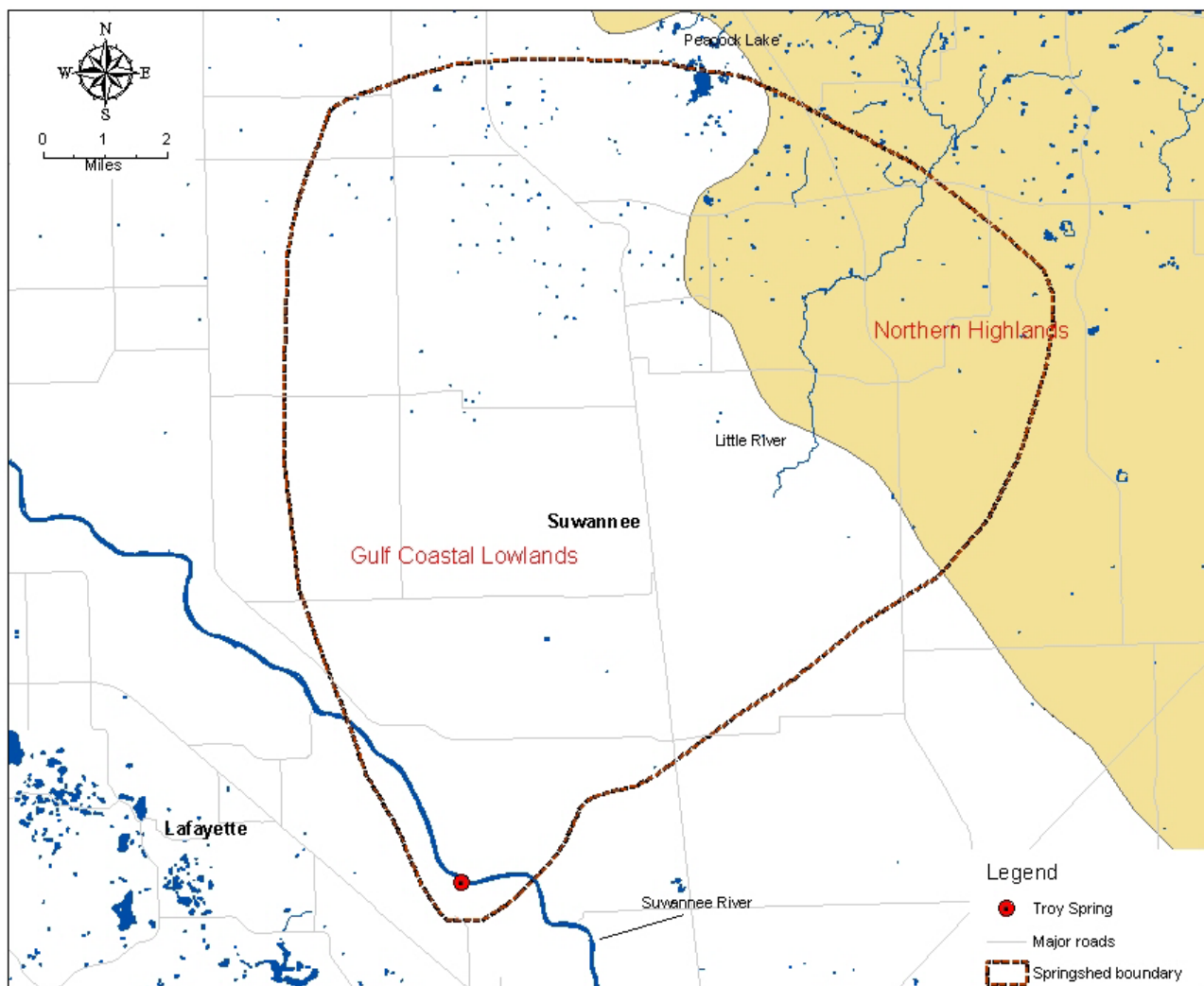


Figure 5. Physiographic provinces within the Troy Spring study area (modified from White, 1970).

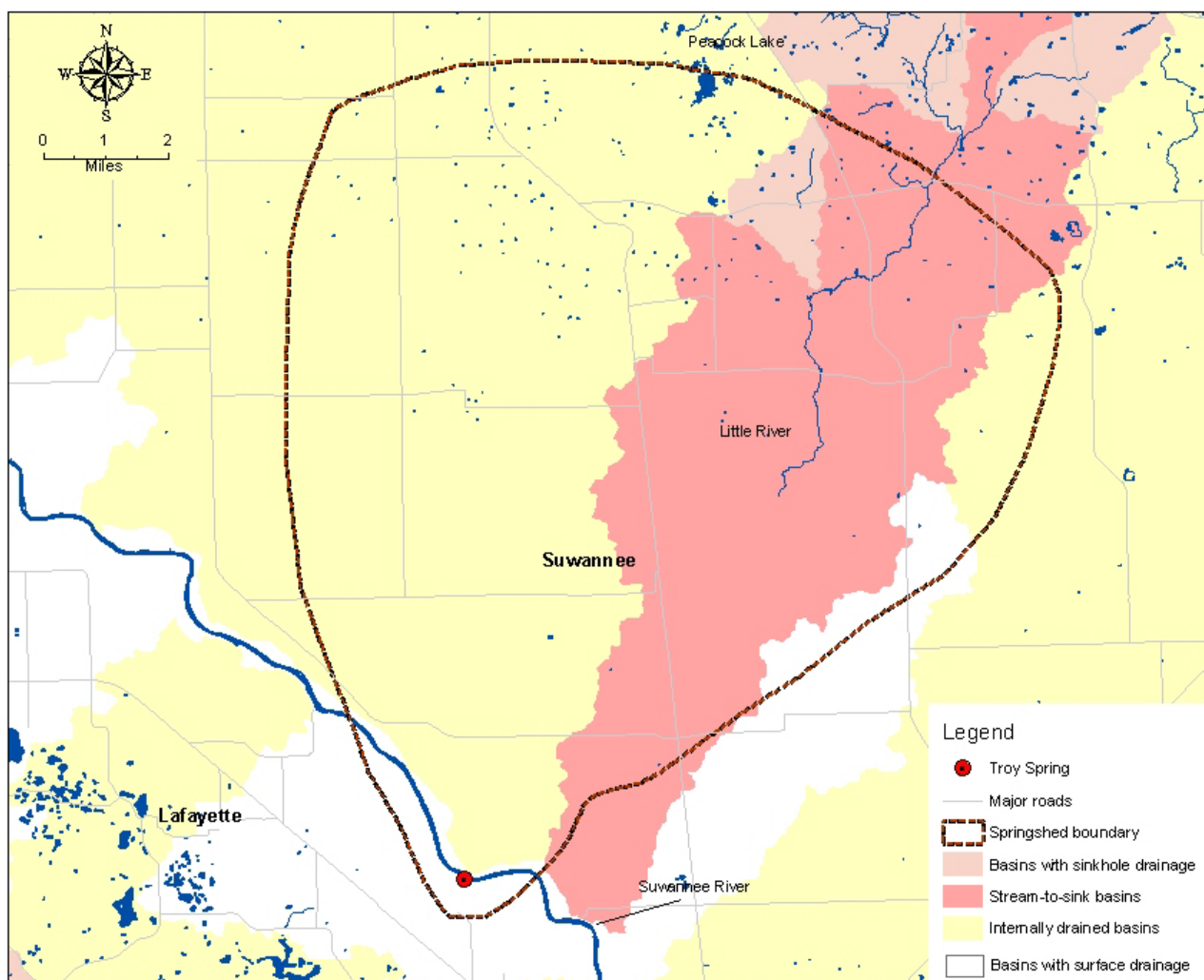


Figure 6. Significant hydrologic features within the Troy Spring study area. Basin descriptions modified from SRWMD (unpublished data).

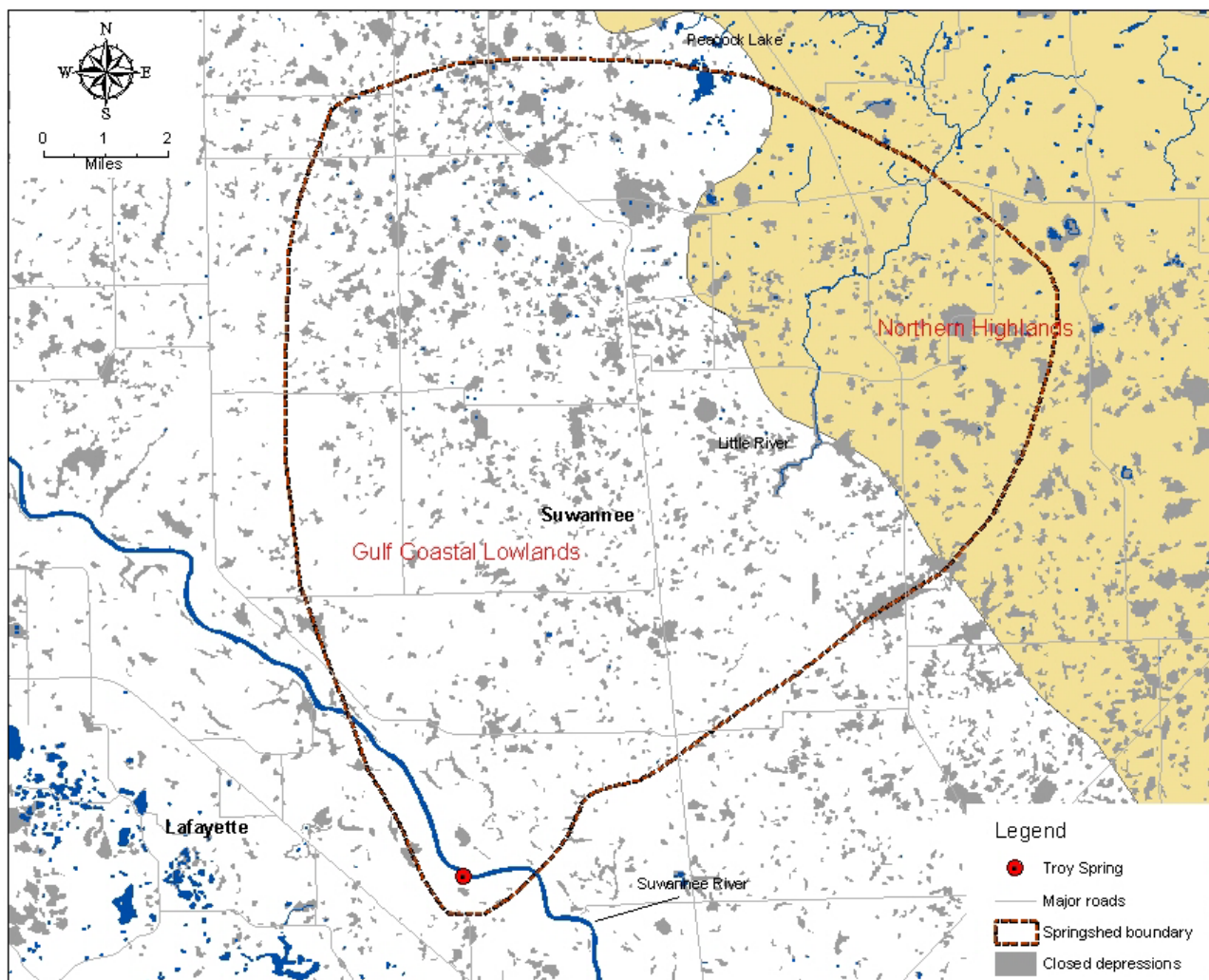


Figure 7. Sinkholes and closed depressions within the Troy Springs study area.

Geology

Figure 8 is a geologic map showing the stratigraphic units at or near land surface in the study area. Thick sequences of limestone are exposed at or very near (within 10-20 feet) the land surface in many parts of the study area, especially along the Suwannee River. Where limestone is near land surface, the thin veneer of sediment that covers the limestone consists of Quaternary-age, unconsolidated to poorly indurated, siliciclastic deposits dominated by quartz sand. These sands are primarily marine terrace deposits.

The uppermost limestone units in the study area include the Ocala Limestone and Avon Park Formation, both of Eocene age. The major carbonate unit in the study area is the Ocala Limestone, which lies at or near land surface throughout much of the region (Figure 8). Based on well cuttings, Crane (1986) described the Ocala Limestone in the study area as consisting of several lithologies of marine origin. The deepest of these lithologies is a medium to well-indurated calcarenite composed almost entirely of Miliolid foraminifera. Above this unit lies a medium to well-indurated calcarenite composed of the foraminifera *Operculinoides* sp. and Miliolids. Capping these two lower lithologies is a unit that is described as a poorly to moderately indurated, calcarenite composed of the foraminifera *Lepidocyclina* sp. Much like the underlying Avon Park Formation, the upper surface of the Ocala Limestone is highly variable and karstic (Crane, 1986).

The Avon Park Formation is the oldest rock unit that crops out in the State of Florida. In the study area, the early Eocene age Avon Park Formation consists of moderate to well-indurated, sugary dolostone, and moderately to well-indurated calcilutite, calcarenite and calcirudite. Thin seams of peat are often associated with the more dolomitized sections of the Avon Park Formation. In deeper, more calcitic sections of the Avon Park, Miliolids and foraminifers, especially *Dictyoconus americanus*, are often present (Crane, 1986). Gypsum is also present in small amounts in the Avon Park Formation, though it typically occurs several hundred feet below sea level in the study area (Crane, 1986). The Ocala Limestone and the Avon Park Formation comprise the Floridan aquifer in the Troy Spring Springshed.

In the Northern Highlands, the carbonate units of the Upper Floridan aquifer are overlain by interbedded phosphatic sands, clays, and dolostones of the Statenville and Coosawhatchie formations of the Hawthorn Group (Scott and others, 2001) (Figure 8). Due to the clayey composition of these two formations, the permeability of the units is generally low and they tend to form an intermediate confining unit above the Upper Floridan aquifer and below the surficial aquifer system. Silicified fossils are common to both formations, and significant deposits of phosphorite are economically important in the Statenville Formation (Scott, 2001).

Weathering of phosphorite in the Hawthorn Group sediments has resulted in dissolution of carbonate-fluorapatite and re-precipitation of carbonate-hydroxylapatite in localized crusts and nodules in the Ocala Limestone (Upchurch, 1992, 2002). These deposits of re-precipitated phosphate, which were locally termed “hard-rock phosphate,” were extensively mined throughout northern Florida from the late 1880’s through the 1960’s (Dinkins, 1969). None of the mines were large because the deposits were localized in karst features. Meyer (1962) noted that phosphate-ore deposits were once mined near Fort White in Columbia County.

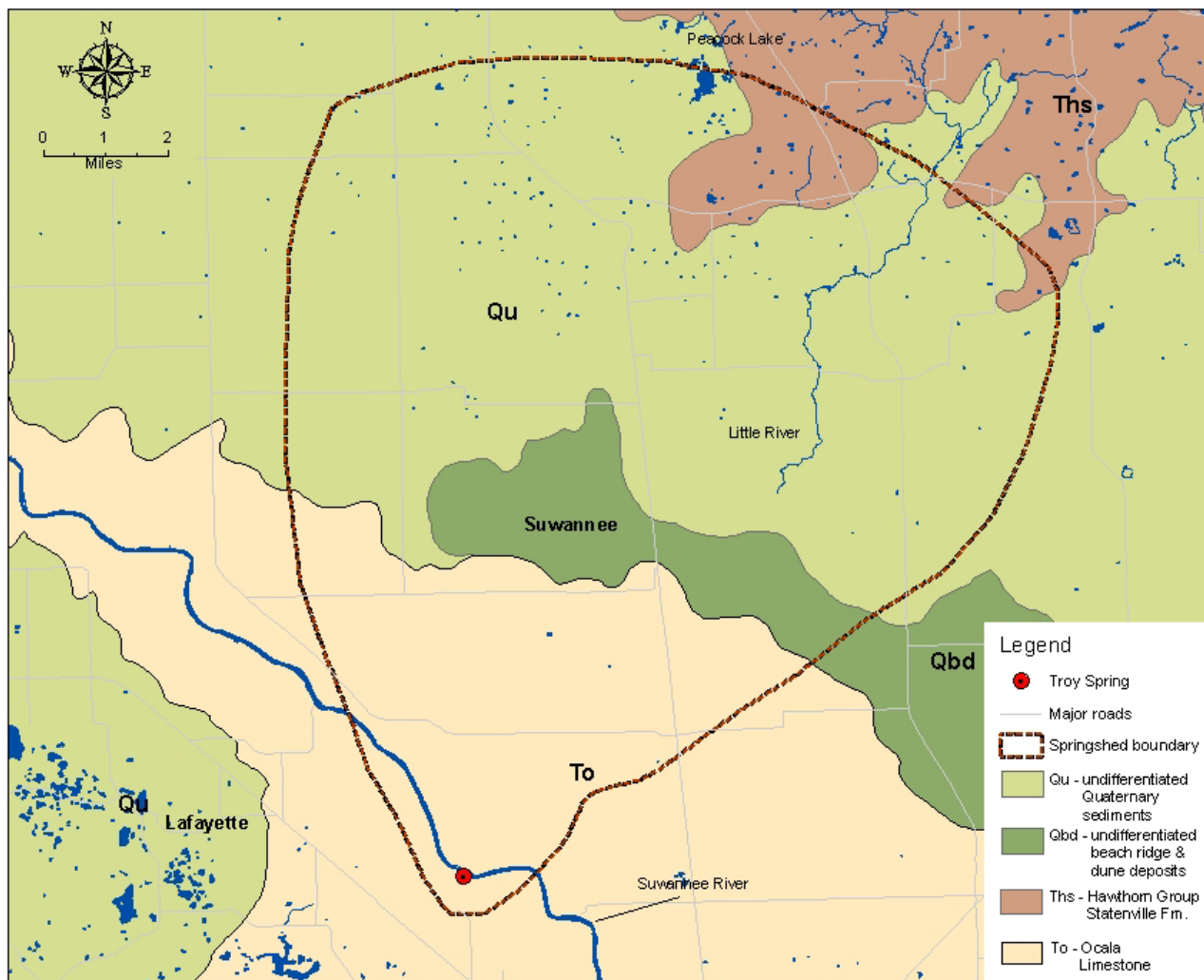


Figure 8. Geologic map of the Troy Spring study area (modified from Scott and others, 2001).

Surface-Water Hydrology

Surface-water features are not abundant in the Troy Spring springshed (Figure 6). The lack of streams and rivers throughout the Troy Spring springshed results from a well-developed underground drainage system in the Floridan aquifer. This is due to the shallow depth of the limestone, the highly porous nature of the overlying soils, and high relative recharge across the springshed (Figure 9). Recharge is relatively high in the springshed because Hawthorn Group sediments are generally absent and the limestone is at or near land surface.

The Little River (Figure 1) is a good example of a sinking stream in the study area. This stream drains surface water from upland areas, across the Cody Scarp, and into sinkholes, where the water recharges the Floridan aquifer. Because of the direct connection to the Floridan aquifer, any contaminants washed into Little River have a high probability of reaching the Floridan aquifer and the springs along the Suwannee River

The Little River Trace (Figure 4) is a former karstic valley created as the stream eroded its way into the Cody Scarp, which once extended further south than at present. As the stream system eroded its way northward, it cut down through the Hawthorn Group. When the stream cut its way down to limestone and dolostone under the Hawthorn, its flow was captured by drainage into sinkholes. Thus, the Little River Trace is a dry stream valley formed as the Cody Scarp retreated. The valley normally carries water only during extremely heavy rainfall events. At these times, the ability of the sinkholes along the Trace to take in water may be exceeded and flooding can result.

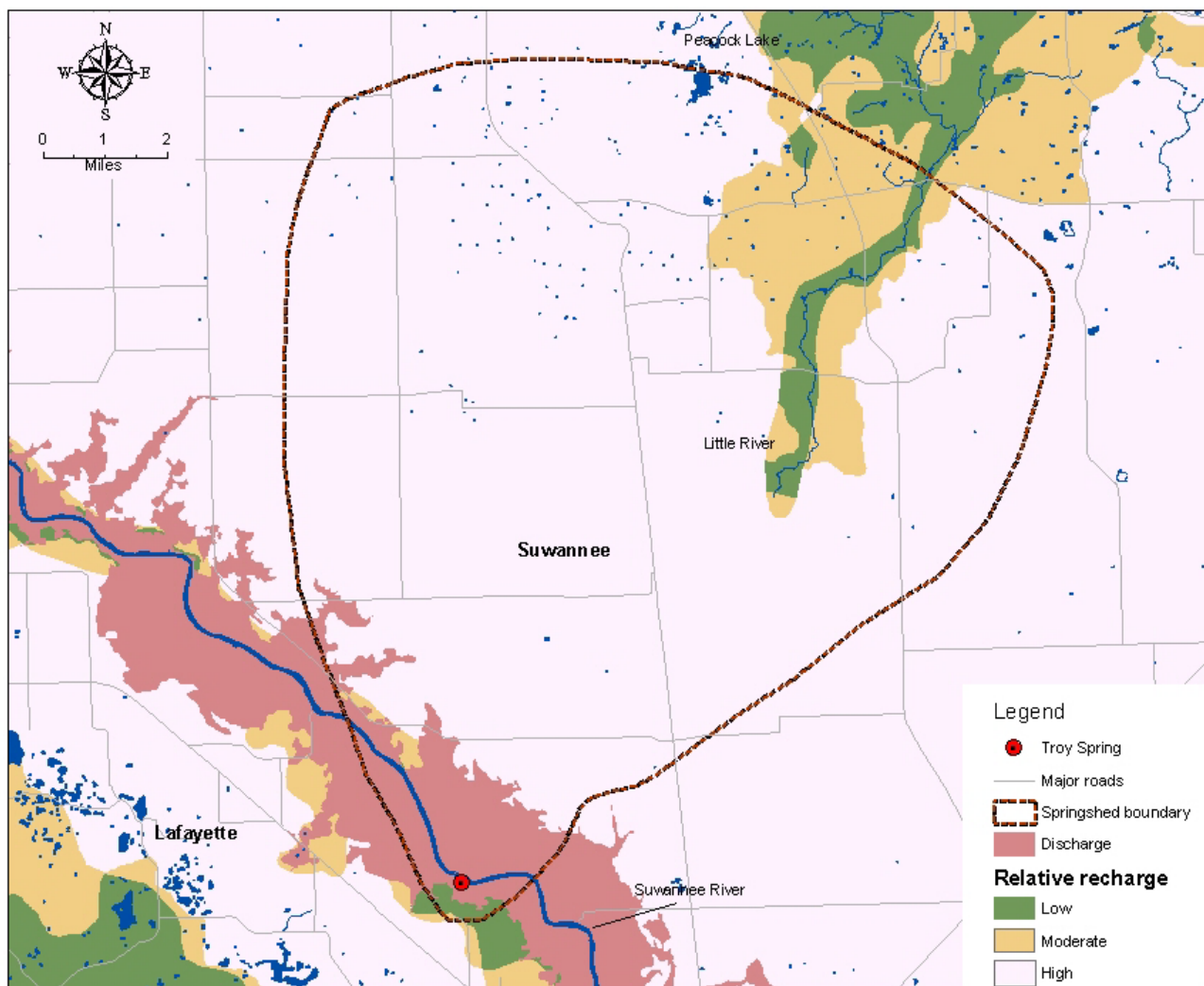


Figure 9. Relative recharge to the Floridan aquifer in the Troy Spring study area (Florida Geographic Data Library, 2004)

Karst and Ground-Water Hydrology

Karst - A prerequisite to comprehending the ground-water hydrology of the study area is an understanding of the dominant role that karst processes play in moving ground water through the Floridan aquifer. The Troy Spring springshed is an area of intensive karst development, characterized by numerous sinkholes, lack of surface drainage, and undulating topography (Figures 4, 6, and 7). In karst areas, the dissolution of limestone has created enlarged cavities along fractures in the limestone, which eventually collapse or reach the surface and form sinkholes. Sinkholes capture surface-water runoff and funnel it underground (e.g., Little River), which further promotes dissolution of limestone. This leads to progressive integration of voids beneath the surface over time and allows increasingly larger amounts of water to be transported through the ground-water system.

Dissolution is most active near the water table or the zone of water-table fluctuation. In this zone, carbonic acid contained in atmospheric precipitation and generated by equilibration with soil carbon dioxide reacts with limestone and dolostone (Carroll, 1970). Because the altitude of the water table has shifted in response to changes in sea level over the last 30 million years, many vertical and lateral paths have developed in the underlying carbonate strata in the study area. Many of these paths or conduits lie below the present water table (the Floridan aquifer is essentially unconfined in the Coastal Lowlands) and greatly facilitate ground-water flow.

Ground water may flow rapidly through conduits and passages with the limestone, or slowly through minute pore spaces within the rock matrix. Dye-trace studies in Columbia County show that ground water near Ichetucknee Springs may travel approximately one mile per day in active conduits in the Floridan aquifer (Karst Environmental Services, 1997). Similar velocities were recorded near Sulphur Springs in Hillsborough County (Stewart and Mills, 1984). Studies such as these clearly indicate that ground water has the potential to flow rapidly and traverse great distances in a short amount of time in karst environments near major springs.

Because the flow in these karst conduits is rapid and direct, dispersion, dilution, and retardation of contaminants is likely to be minimal and the springs are vulnerable. For example, when Lawrence and Upchurch (1976) sampled the Floridan in the vicinity of Lake City, they described a plume of surface water under Alligator Lake that extended to the southwest for several miles. Shortly after completion of the study, the lake drained and residents down gradient reported colored water, organic debris, and other indicators of lake water. We now know that Alligator Lake is part of the headwaters of the Ichetucknee Springs system and that the plume of surface water was migrating in a karst conduit system to the springs.

In contrast, recent studies by the USGS and SRWMD have demonstrated that much of the spring water in northern Florida (and the study area) has been in the Floridan aquifer for an average of 10-25 years (Katz and others, 1999). This estimate is based on age-dating techniques using chlorofluorocarbons (CFC's) derived from the use of aerosol propellants and refrigerants. These CFC compounds, released into the atmosphere over the last 50 years, have dissolved in precipitation that recharges ground water (Katz and Hornsby, 1998). The occurrence of CFC's in spring water in the study area indicates that, while a portion of the ground water moves quickly through conduits in the Floridan aquifer, much of the water percolates more slowly through the soil and into the aquifer. Once the water recharges the

aquifer, it begins moving through the smaller pores and openings in the limestone before reaching an active conduit or spring vent. The slower movement of ground water through the aquifer is known as diffuse flow. Because of the diffuse flow and ability of the limestone matrix to improve ground-water quality, the springs are typically clear and free of most contaminants.

It is important to understand that rapid conduit flow and slower diffuse flow are, in fact, very useful in deciphering the hydrology of springs in karst regions like the study area. Older ground water that appears to dominate much of the spring flow mixes with younger ground water traveling through active conduits near the spring. Two recent studies by the St. Johns River Water Management District and the SRWMD demonstrate and support this mixing model of ground water at springs (Katz and Hornsby, 1998; Toth, 1999). Therefore, the mixing of ground waters must not be overlooked when assessing the origin, health, and history of spring waters in karst environments such as that found in the study area.

Recharge - Recharge to the Floridan aquifer is directly related to the amount of confinement of the system. The highest recharge rates occur where the Floridan is unconfined or poorly confined, as in those areas where the aquifer is at or near land surface. Such conditions occur throughout the study area. Recharge may also be high in areas where the confining layers are breached by karst features, such as sinkholes (Figure 7). Other factors affecting recharge rates include the development of surface-water drainage, variations in water-level gradients between surface water, the surficial aquifer and the Floridan aquifer, and aquifer permeability. Low recharge rates occur where confining materials overlying the aquifer retard downward vertical movement of water, or where an upward water-level gradient exists between the Floridan and surficial aquifers. Figure 9 shows the recharge potential of the Floridan aquifer in the study area.

Potentiometric Surface - The potentiometric surface of the Floridan aquifer in the study area is shown in Figure 10. This map was created by statistically analyzing water levels from approximately 60 monitor wells within the study area. This geostatistical analysis consisted of two steps. First, a structural analysis was performed to determine the pattern of variance with distance between sample pairs. Structural analysis allows for estimating the spatial distribution of uncertainty and development of contouring “rules.” Then, by kriging the data using these “rules” of uncertainty estimation, a traditional contour map and a map showing levels of uncertainty in the contour map are produced. The ground-water basin is then delineated from the contour map, and the uncertainty map is used to define areas that would benefit from additional monitoring locations. The geostatistical analysis conducted by Upchurch and Champion (2004a) provided an accurate picture of the basin’s shape.

Some distinctive features are visible on the potentiometric surface map. Most importantly, the low relief areas in the potentiometric surface along the Suwannee River represent regions of well-developed karst and high hydraulic conductivity. The steep isopleths to the west and southwest of Troy Spring reflect areas where the Floridan aquifer has lower permeabilities and flow is less dynamic.

The steep isopleths that lie to the west of the springshed in Lafayette County also indicate a region where the Floridan aquifer has lower permeabilities and flow is less dynamic.

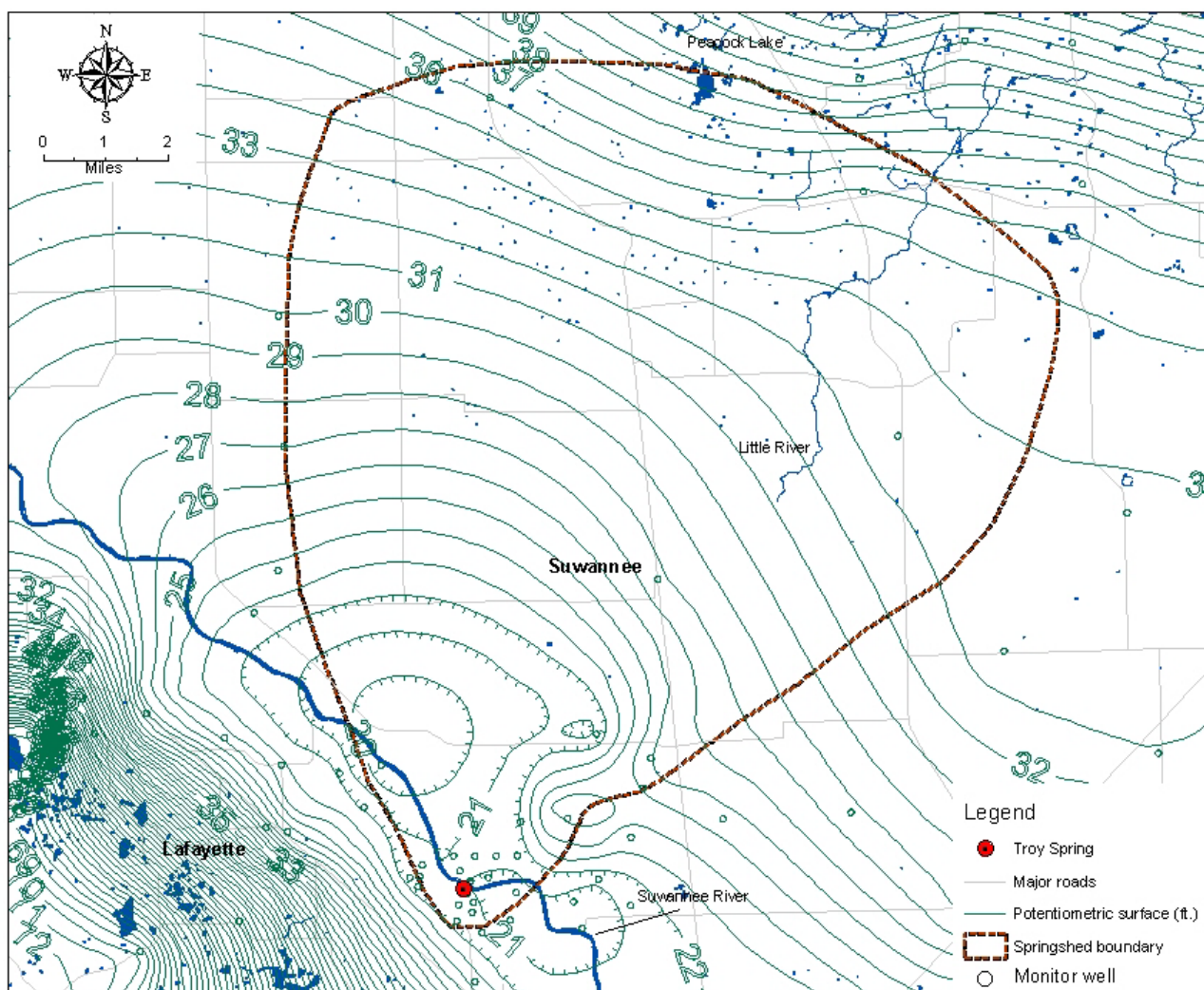


Figure 10. Potentiometric surface of the Floridan aquifer in the Troy Spring study area (modified from Upchurch and Champion, 2004a).

GROUND-WATER CHEMISTRY

Previous ground-water investigations have indicated that the chemistry of ground water in north Florida is affected by a number of geologic, hydrologic, and anthropogenic (man-made) factors. These include 1) residence time, which affects the dissolution of limestone, 2) the thickness and mineralogy of the Hawthorn Group sediments, 3) recharge rates (Lawrence and Upchurch, 1976; Crane, 1986; Upchurch, 1992), and 4) the presence of agricultural and other land uses in areas near the spring (Katz and others, 1999).

Water quality discharging from springs in north Florida has been characterized in a number of studies, including Rosenau and others (1977), Hornsby (1998), Katz and others (1999), Scott and others (2002), and Upchurch and Champion (2003a, 2003b, 2004).

Ground-water quality within the study area has been characterized by Upchurch (1990, 1992). The SRWMD updates the results of nitrate monitoring in its Groundwater Quality Monitoring Reports on an annual basis (Hornsby and Ceryak, 1999; Hornsby and others, 2003), as well.

Several studies have examined the connectivity of surface and ground water in north Florida, including Skiles (1991), Hirth (1995), and Martin and Gordon (1998). These studies, and the well-known Rose Creek Sink dye trace (Karst Environmental Services, 1997), clearly demonstrate the sensitivity of the ground-water system to surface-water events.

Floridan aquifer ground water is characterized as a calcium-bicarbonate water type because of interactions with the limestone of the aquifer. Because of the preponderance of karst in the Troy Spring springshed, Floridan aquifer water contains numerous indicators of interaction with surface water, including color, high organic carbon, and high dissolved oxygen (Upchurch, 1990). These surface-water indicators demonstrate that the aquifer is highly vulnerable to human activities.

DELINEATION OF GROUND-WATER QUALITY DOMAINS

Study Area Monitor-Well Network

The most important tool in determining the chemical composition and source areas for spring water in the study area was the water-quality data obtained from a regional monitor-well network designed and sampled by staff at the Suwannee River Water Management District. The monitor-well network totaled 61 existing wells (Figure 1), consisting of dedicated monitor wells and wells used for domestic and public supply.

Factor Analysis

Factor analysis is used to sort out hydrogeologic process-response relationships from commonly collected ground-water data. It has been applied to the Floridan aquifer system by Lawrence and Upchurch (1976; 1982), Ceryak (1977), Dalton (1978), and Dalton and Upchurch (1978). Factor analysis combines variables that are correlated into clusters in order of the amount of variance explained. Using the SYSTAT[®] software, principal components

analysis (PCA), a form of factor analysis coupled with Varimax rotation, was performed on 20 chemical analytes for the 61 well samples (Figure 1).

The PCA combines chemical variables into groups, or factors, each representing a statistically independent chemical process. Factor loadings are calculated for each chemical variable. Factor loadings show how heavily each analyte correlates to each factor. Most chemical variables are specific to a single process, or factor, though a chemical variable may load heavily on more than one factor if it is important in more than one process.

The PCA also allows calculations of a factor score for each sample, which reflects the relative importance of a given factor at that sample site. Extreme negative scores (<-1) reflect water essentially unaffected by a given process (factor), positive scores ($>+1$) reflect water most affected, and near zero scores reflect water affected to an “average” degree by the chemical process or factor. The factor scores can be contoured on maps in order to evaluate the spatial importance of each chemical process represented by each factor.

The final PCA revealed six chemically distinct, factors, or geochemical processes. These six factors accounted for 78.3 percent of the total variability present in the water sample data. Table 1 shows the factor loadings for the 20 chemical variables. Figures 11 through 16 show contour maps of factor scores for each factor.

Factor I includes the analytes specific conductance, alkalinity, calcium, total dissolved solids (TDS), and dissolved oxygen (D.O). Factor I is therefore a lithologically controlled factor reflecting the dissolution of carbonate minerals in the Floridan aquifer. Figure 11 shows the spatial distribution of factor scores for Factor I. Low Factor I scores indicate areas where dissolution of limestone has not reached a maximum (equilibrium), or where conduit flow has limited water-rock interactions in the aquifer. Factor I scores are low throughout much of the area due to relatively rapid flow and recharge to the aquifer (Figure 9), and the internally drained nature of the springshed (Figure 6). High Factor I scores may indicate areas of relative stagnation of the aquifer where there has been more dissolution of the formation, or where diffuse flow dominates the flow system in the aquifer. Several isolated areas of high Factor I scores can also be seen on Figure 11. These areas include the highland areas north of the springshed and west in Lafayette County, where the potentiometric surface of the Floridan aquifer suggests sluggish flow through the subsurface (Figure 10).

Factor II includes total organic carbon (TOC), temperature, total Kjeldahl nitrogen (TKN), and dissolved organic carbon (DOC). These constituents result from the recharge of organic-rich ground water to the Floridan. Therefore, Factor II is a pathway/origin factor (Lawrence and Upchurch, 1976). The spatial distribution of Factor II scores is shown in Figure 12. Factor II scores generally range from 0 to 1 throughout the region, suggesting that Factor II processes are prevalent on a regional scale.

Factor III includes nitrate, potassium, and sulfate. These constituents result from the leaching of inorganic fertilizers and soil amendments in the study area. Therefore, Factor III is an anthropogenic (man-made) factor resulting from land uses in the region. High Factor III scores are found in two major regions of the study area. One region is in Lafayette County and extends northward into Suwannee County. Land uses in this region are generally represented by crop/pasture land, some row crops, and evergreen forestland (Figure 13). The second region of high Factor III scores lies to the north and northeast of Troy Spring in the springshed. Land uses in this region also include crop/pasture land, row crops, and evergreen

forestland (Figure 13). However, the row crops, particularly center-pivot irrigation fields, are prevalent in this region.

Factor IV includes phosphorus, turbidity, and iron. The association of these constituents and their spatial distribution (Figure 14) suggests that this factor reflects the recharge of chemically reduced, organic-rich ground water to the Floridan aquifer. This factor, much like Factor II, is a pathway/origin factor (Lawrence and Upchurch, 1976). Factor IV scores are generally low throughout the region. However high Factor IV scores are shown in Lafayette County where numerous lakes and forested wetlands (Figure 13) are located. These water bodies are likely sources of chemically reduced, organic-rich ground water.

Factor V includes magnesium and fluoride. These two constituents represent the dissolution of magnesium-rich minerals and carbonate-fluorapatite. Since the Miocene cover has been largely eroded from much of the springshed, it is unlikely that Factor V represents the weathering of magnesium-rich clays in the Hawthorn Group. Instead, it is likely that the association of magnesium in this particular factor represents the dissolution of magnesium-rich carbonates within the Floridan aquifer with some contribution from residual Hawthorn Group sediments. Factor V scores are low throughout much of the region (Figure 15), primarily due to the lack of magnesium-rich carbonates (dolomite) in the near-surface Ocala Limestone and the general lack of Hawthorn Group sediments in the springshed. While scattered outliers and remnants of the Hawthorn are likely present in the region, these deposits are too small to have a significant impact on regional water quality in the springshed.

Factor VI includes -pH, chloride, and sodium. The negative sign on the variable pH reflects negative correlations between pH and sodium and chloride. Factor VI represents the recharge of marine aerosols (Upchurch, 1992) to the Floridan aquifer. Figure 16 shows the spatial distribution of Factor VI scores. Factor VI scores are lowest in Lafayette County, where recharge is largely inhibited by shallow clay (Figure 9). The highest Factor VI scores are found along the northern boundary of the springshed and to the southeast of Troy Spring. These areas are regions of high recharge to the Floridan aquifer (Figure 9) and the marine aerosol signature of the recharge water is most likely to be preserved upon recharge.

Variable	Units	Range	Factor Loadings					
			I	II	III	IV	V	VI
FACTOR I								
Sp. Conductance	µS/cm	116-724	0.932	0.095	0.205	-0.020	-0.159	0.059
Alkalinity	mg/l	38.6-344	0.923	0.108	-0.103	-0.053	-0.180	0.094
Calcium	mg/l	16.8-117	0.901	0.094	0.082	-0.017	0.231	0.055
Total Dissolved Solids (TDS)	mg/l	79-476	0.841	-0.040	0.227	0.060	-0.007	0.182
Dissolved Oxygen (DO)	mg/l	0.02-8.58	-0.514	0.206	0.228	0.137	0.104	0.145
FACTOR II								
Total Organic Carbon (TOC)	mg/l	0.64-26.0	0.003	-0.950	-0.038	0.102	0.067	-0.069
Dissolved Organic Carbon (DOC)	mg/l	0.85-30.9	-0.044	-0.927	0.033	0.093	0.082	-0.030
Total Kjeldahl Nitrogen (TKN)	mg/l	0.11-1.34	-0.102	-0.891	-0.079	0.081	-0.030	0.198
Temperature	C	19.1-24.6	-0.056	0.634	0.119	0.452	0.089	0.048
FACTOR III								
Nitrate	mg/l	0.00-13.3	0.062	0.089	0.909	-0.067	0.051	0.034
Potassium	mg/l	0.05-7.94	-0.028	-0.122	0.880	-0.071	0.169	-0.101
Sulfate	mg/l	0.18-49.8	0.196	0.169	0.783	-0.168	-0.178	0.064
FACTOR IV								
Phosphorus	mg/l	0.02-0.57	-0.020	-0.163	-0.092	0.873	-0.051	0.076
Turbidity	mg/l	0.14-135	-0.104	0.070	-0.141	0.861	0.106	0.015
Iron	mg/l	0.01-6.01	0.299	-0.403	-0.267	0.519	0.135	-0.361
FACTOR V								
Magnesium	mg/l	0.52-40.9	0.149	0.149	0.056	0.058	-0.864	0.041
Fluoride	mg/l	0.03-0.31	-0.029	-0.084	-0.112	-0.149	-0.796	-0.119
FACTOR VI								
pH	s.u.	5.62-9.67	-0.329	0.124	-0.015	-0.113	-0.120	-0.755
Chloride	mg/l	2.17-37.1	0.496	-0.408	0.310	0.362	0.068	-0.418
Sodium	mg/l	1.63-13.6	0.414	-0.422	0.324	0.214	0.015	-0.334
PERCENT OF TOTAL VARIANCE EXPLAINED			21.1	18.3	13.6	11.4	8.2	5.7

Table 1. Factor loadings for the 20 chemical variables used in the factor analysis. Bold factor loadings reflect the variables most closely associated within each factor. Negative factor loadings suggest an inverse relationship between a particular variable and other variables within the factor.

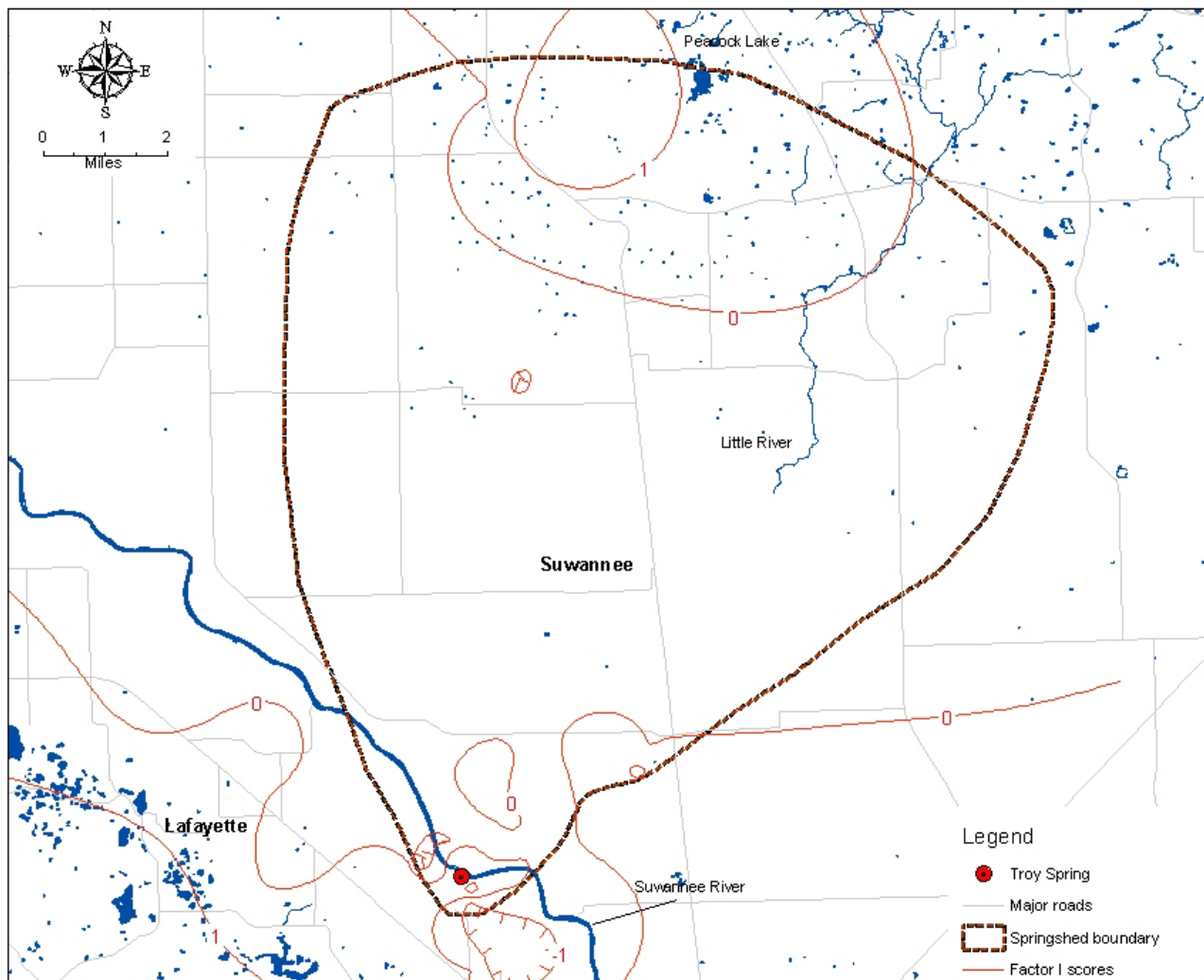


Figure 11. Factor I (alkalinity, sp. conductance, calcium, TDS, and -DO) scores in the Troy Spring study area.

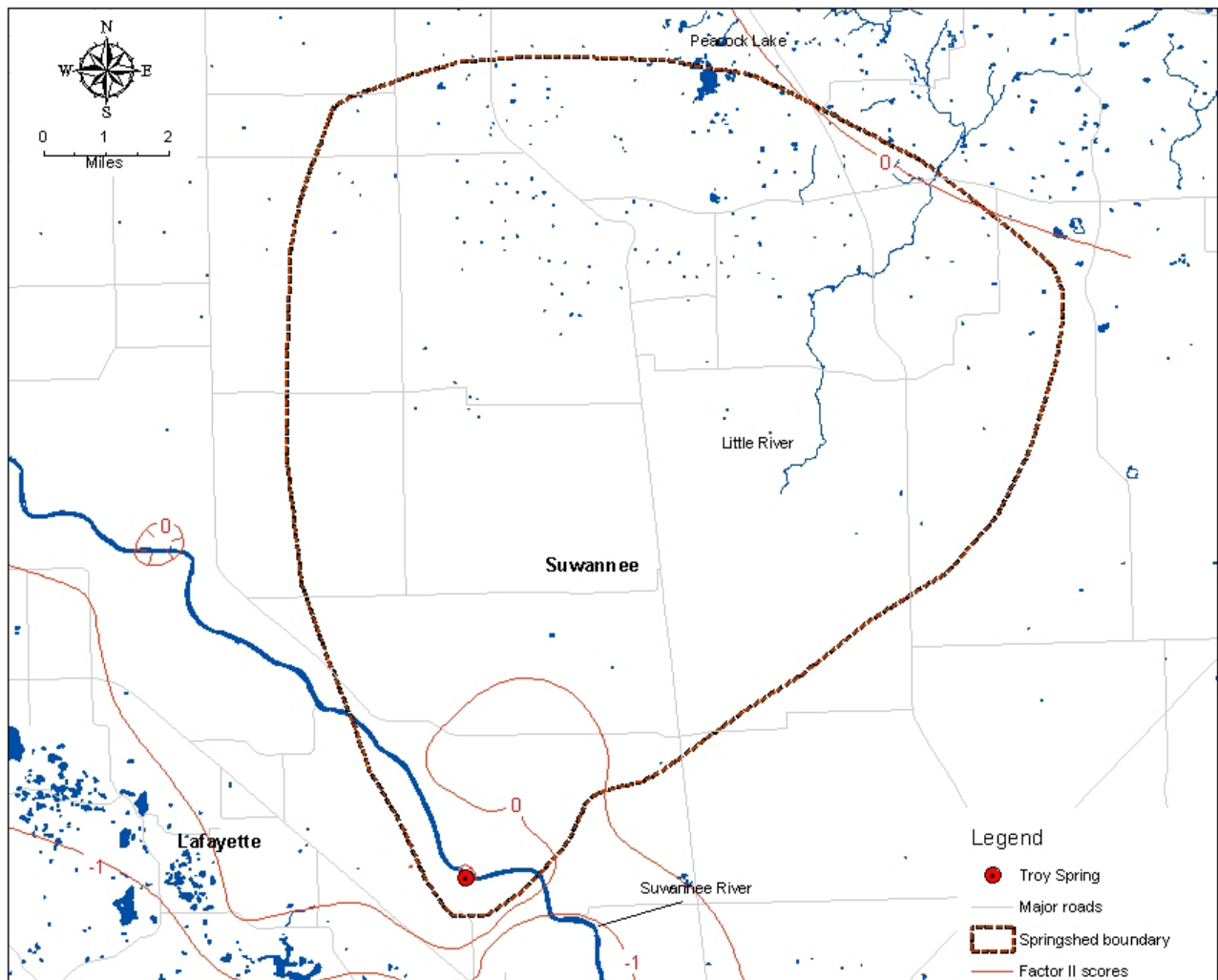


Figure 12. Factor II (TOC, DOC, TKN, and temperature) scores in the Troy Spring study area.

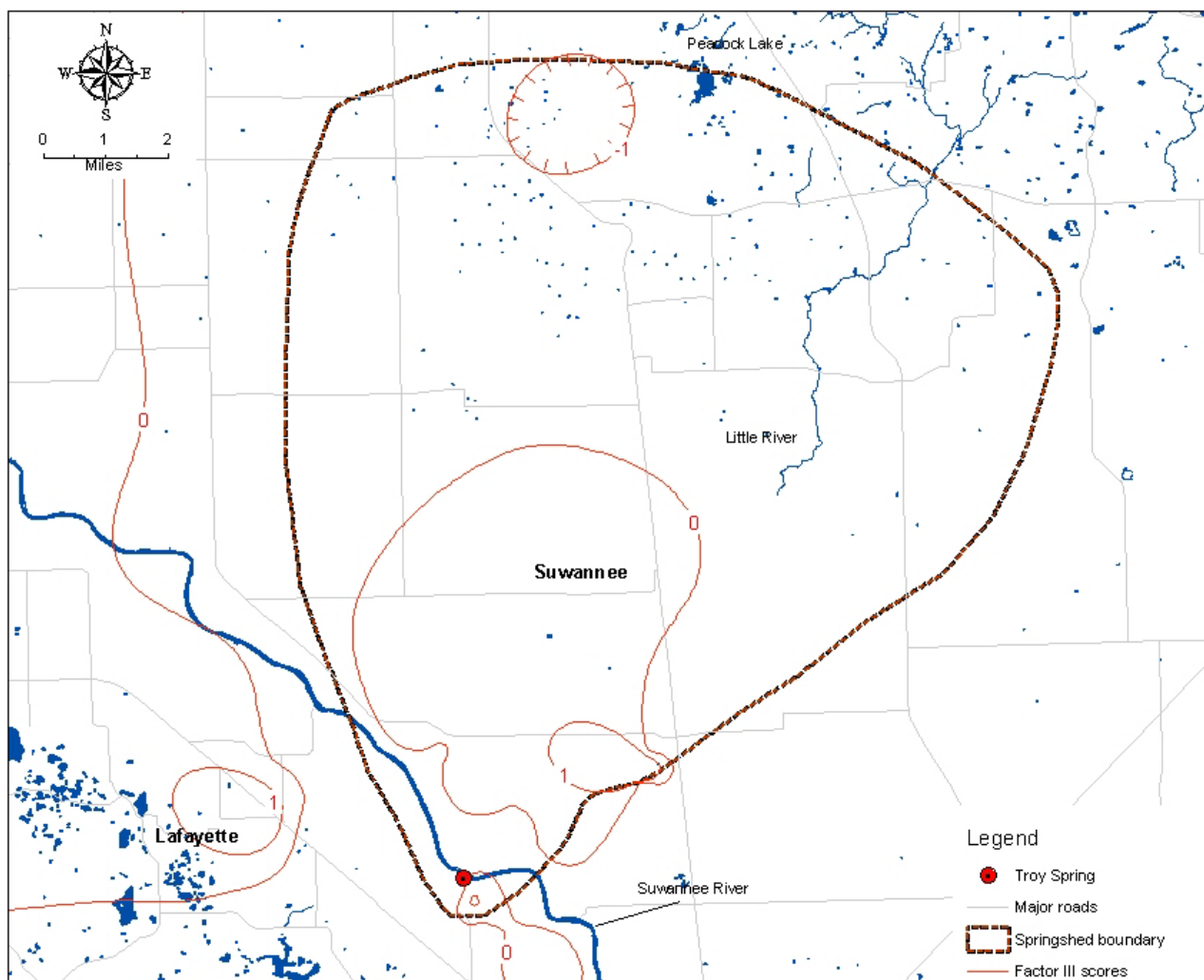


Figure 13. Factor III (nitrate, potassium, and sulfate) scores in the Troy Spring study area.

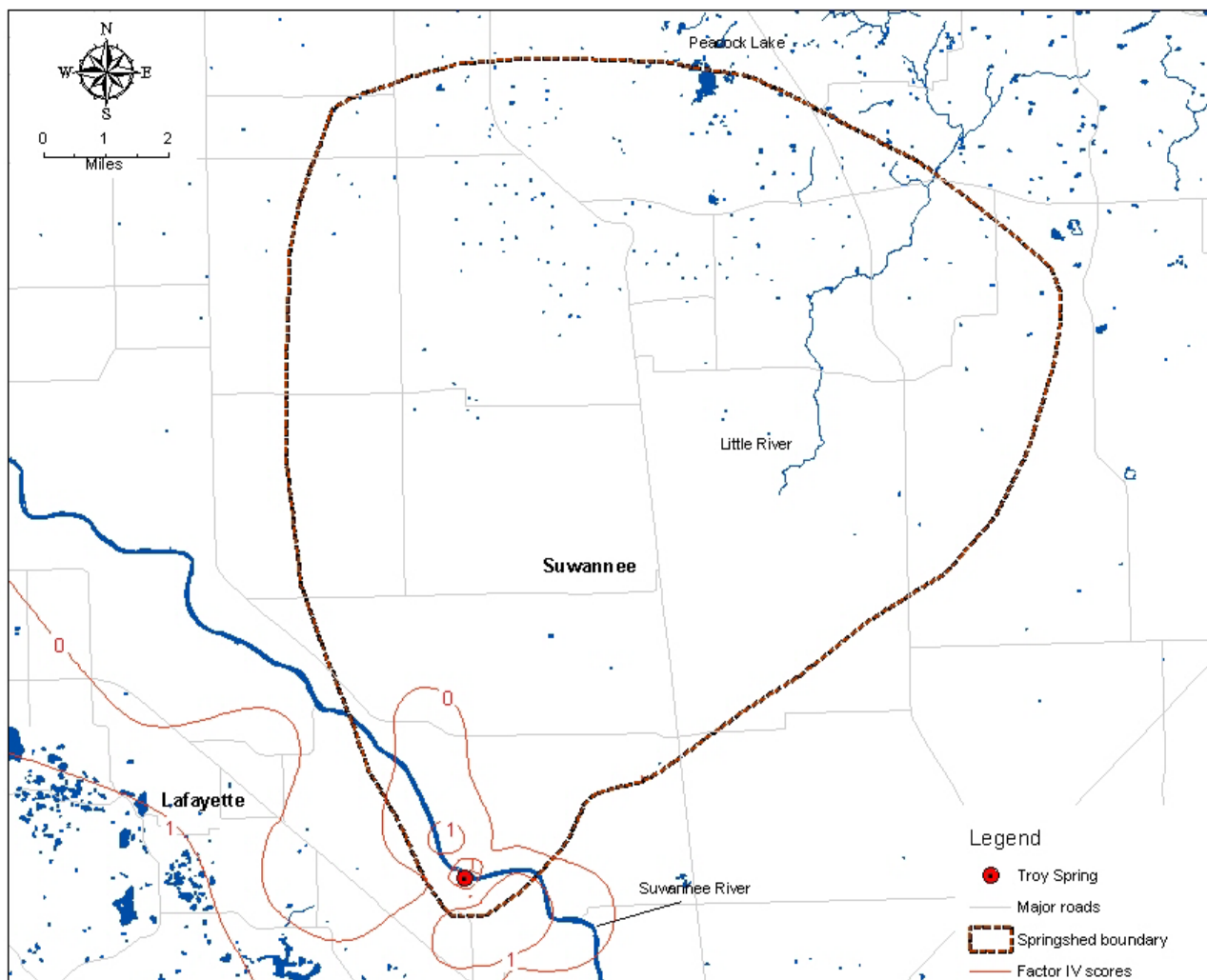


Figure 14. Factor IV (phosphorus, turbidity, and iron) scores in the Troy Spring study area.

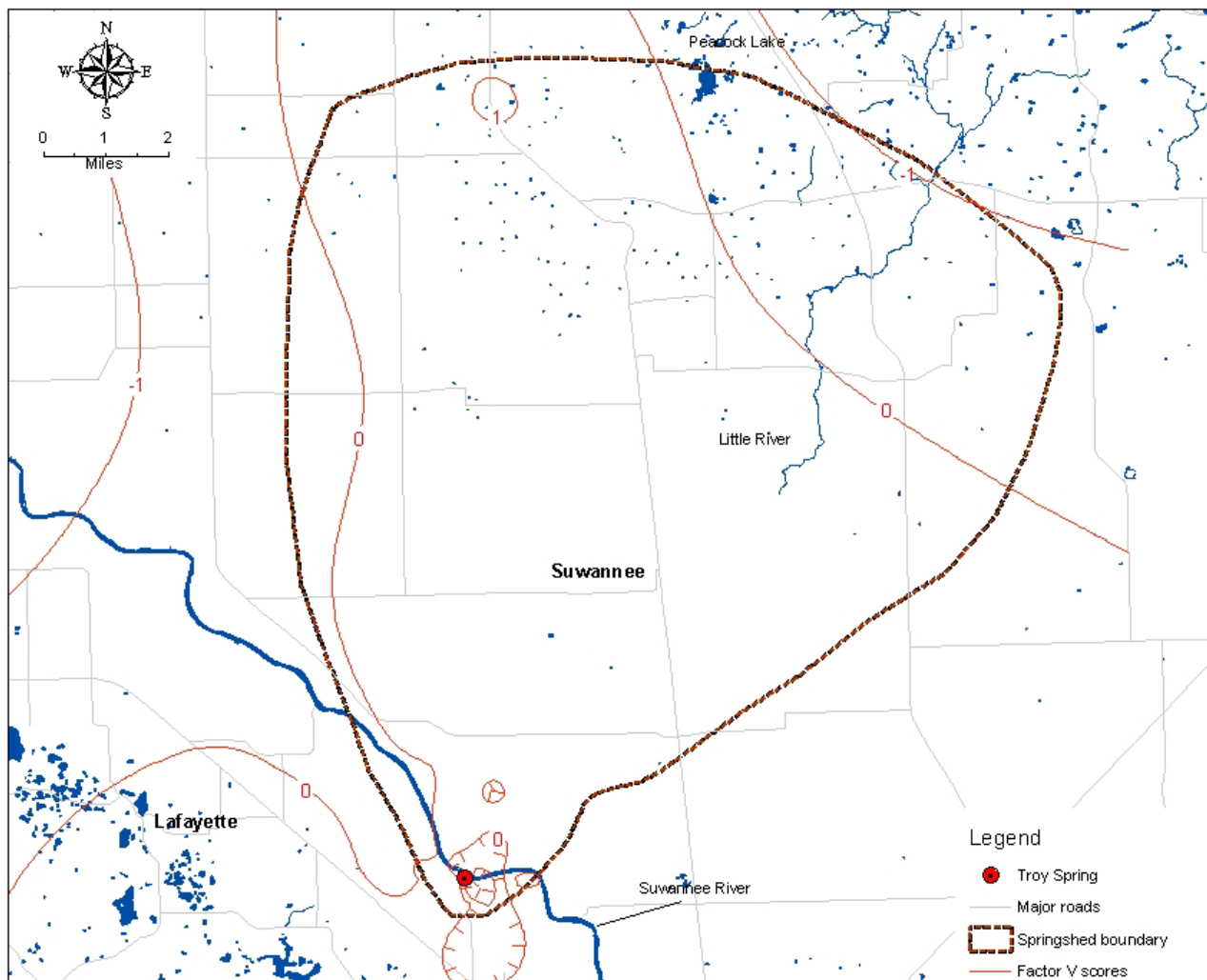


Figure 15. Factor V (magnesium and fluoride) scores in the Troy Spring study area.

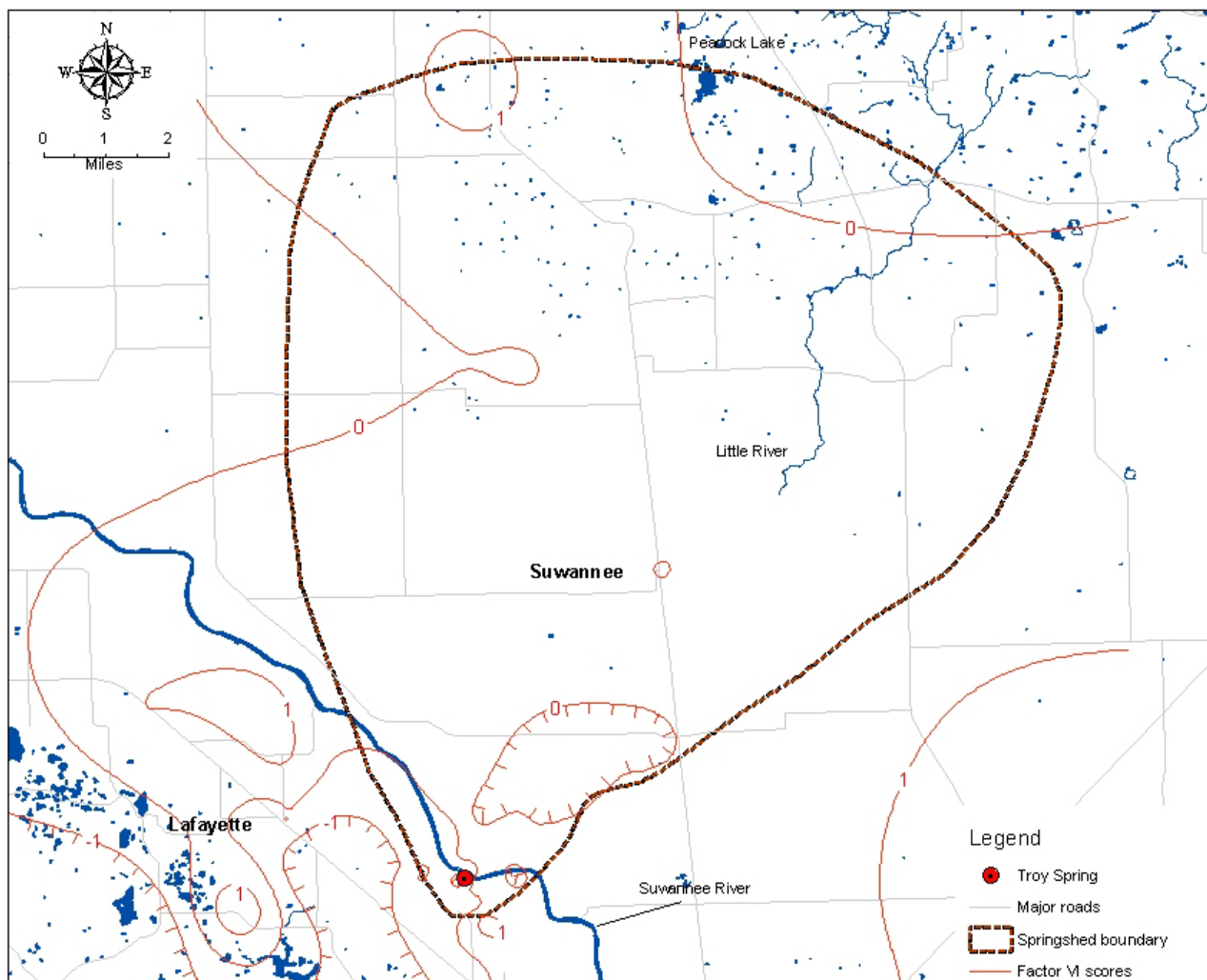


Figure 16. Factor VI (chloride, sodium, and -pH) scores in the Troy Spring study area.

Hydrochemical Facies Analysis

Hydrochemical facies analysis (Upchurch, 1992) is an excellent way to place a series of water-quality analyses into a spatial context. The analysis depends on pattern recognition techniques. In order to place the patterns into chemical groups and identify the spatial patterns of water types, a hierarchical analysis was performed using the SYSTAT[®] software. The initial hierarchical analysis produced seven clusters. The sample groups were then paired down and simplified to those shown in Figure 17.

Using Stanford Graphics[®] software, individual samples are plotted on “star” diagrams, which show the relative proportions of ions in the sample (Jones, et al., 1996). Star diagrams were used in preference to other pattern-recognition methods (i.e., Stiff diagrams) because star diagrams allow use of non-standard combinations of chemicals, and minor constituents can be emphasized. The analytes selected for use in the star diagrams were based on the PCA; one analyte was chosen on the basis of factor loading strength to represent each of the six factors.

Figure 17 displays summary star diagrams for each of the water-quality groups in the study area. It is important to remember when looking at the star diagrams in Figure 17 that the length of each axis corresponds to the *relative* concentration of a constituent in relation to other samples, not other constituents within the same sample; the higher the concentration relative to other samples, the longer the axis. If two or more samples have similar concentrations of the constituents represented, the star diagrams will be similar.

The star diagrams in Figure 17, therefore, were chosen to illustrate the types of patterns present within each cluster. Table 2 provides a summary of the characteristics of each cluster or water type. These water types were then used to delineate water-quality domains in the study area. While the hierarchical clusters (Groups 1a, 1b, 2, and 3) do not correspond exactly to the four water-quality domains described below, there is a general tendency for certain chemical traits to be shared and similar to both clusters and domains.

The following discussion describes the process used to delineate the most significant ground-water quality domains within the study area. Due to geologic or anthropogenic controls, hydrochemical domains are usually geochemically distinct. However, due to the geologic structure of the study area and high recharge rates, several of the domains overlap and share similar spatial distributions. The establishment of water-quality domains helps demonstrate how water quality differs across the region and identifies dominant source areas for ground water discharging from Troy Spring. The water-quality domains take into account the factor and hierarchical analyses presented above. In other words, the water-quality domains in the Troy Spring springshed and study area are composite domains based on water-quality patterns identified within both the factor and hierarchical analyses.

Constituent	Group 1a	Group 1b	Group 2	Group 3
	Domain I or Domain IV		Domain II	Domain III
Temp (C)	22.3	22.2	22.0	22.0
Sp. Cond (µS/cm)	369	345	541	350
pH (s.u.)	6.83	7.03	6.71	7.23
DO	3.5	0.9	2.3	1.6
Alkalinity	173	181	280	170
Calcium	65.5	69.2	90.0	50.2
Chloride	4.1	6.0	7.8	5.4
DOC	1.8	7.1	3.4	2.2
Iron	0.06	0.14	1.02	0.07
Fluoride	0.06	0.07	0.08	0.1
Potassium	0.42	0.94	0.37	0.31
Magnesium	5.7	5.5	5	14.5
Sodium	3.0	4.7	4.7	3.2
Nitrate+Nitrite	0.40	0.56	0.03	0.29
Phosphorus	0.07	0.08	0.1	0.06
Sulfate	7.6	6.4	6.6	6.9
TDS	213	198	325	195
TKN	0.11	0.34	0.17	0.11
TOC	1.2	6.1	1.9	1.2
Turbidity	1.8	2.2	8.8	2.4

Table 2. Median analyte concentrations for the water-quality domains identified in the Troy Spring study area. Concentrations in mg/l unless otherwise noted.

General Characteristics of Hierarchical Groups



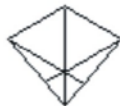
Group 1a

Group 1a represents ground-water samples that typically contain relatively low concentrations of major ions and TDS, suggesting relatively recent recharge. Group 1a samples typically contain elevated levels of D.O. and low concentrations of TOC. Group 1a wells are usually found in Domain I and Domain IV



Group 1b

Group 1b represents ground-water samples that typically contain relatively high levels of DOC, iron, potassium, TKN, and TOC. Given the association of these variables in this group, samples represented in Group 1b are likely influenced by organic-rich recharge. Group 1b wells are usually found in Domain I



Group 2

Group 2 represents ground-water samples that typically contain relatively high levels of alkalinity, calcium, TDS, and turbidity. The chemical maturity of the ground water in this group is evident because of TDS and alkalinity. Group 2 wells are generally found in Domain II.



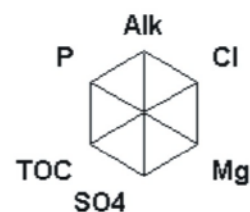
Group 3

Group 3 represents ground-water samples that typically contain relatively high concentrations of fluoride and magnesium. Water quality in this group is similar to that of Group 1a samples, suggesting similar recharge mechanisms. Group 3 wells are generally found in Domain III.



Troy Spring

Comparing the star diagram of Troy Spring water to that of the star diagrams for the water-quality groups above shows that Troy Spring closely matches the water-quality pattern of Group 1a. The spring, however, contains slightly higher levels of sulfate.



Star Key

Figure 17. Star diagrams for representative water types in the Troy Spring study area. The star diagram for Troy Spring is also shown.

Domain I

Domain I covers a large portion of the springshed and study area (Figure 18), where low-permeability Hawthorn Group sediments are thin to non-existent (Figure 8), sinkholes are abundant (Figure 7), and recharge to the Floridan aquifer is moderate to high (Figure 9). Because of these geologic and hydrologic factors, Domain I is the region of greatest recharge to the Floridan aquifer. Geochemically, this recharge can be identified by relatively low concentrations of sodium, chloride, sulfate, magnesium, TOC, and total dissolved solids. The Group 1a pattern (Figure 17) represents water in Domain I.

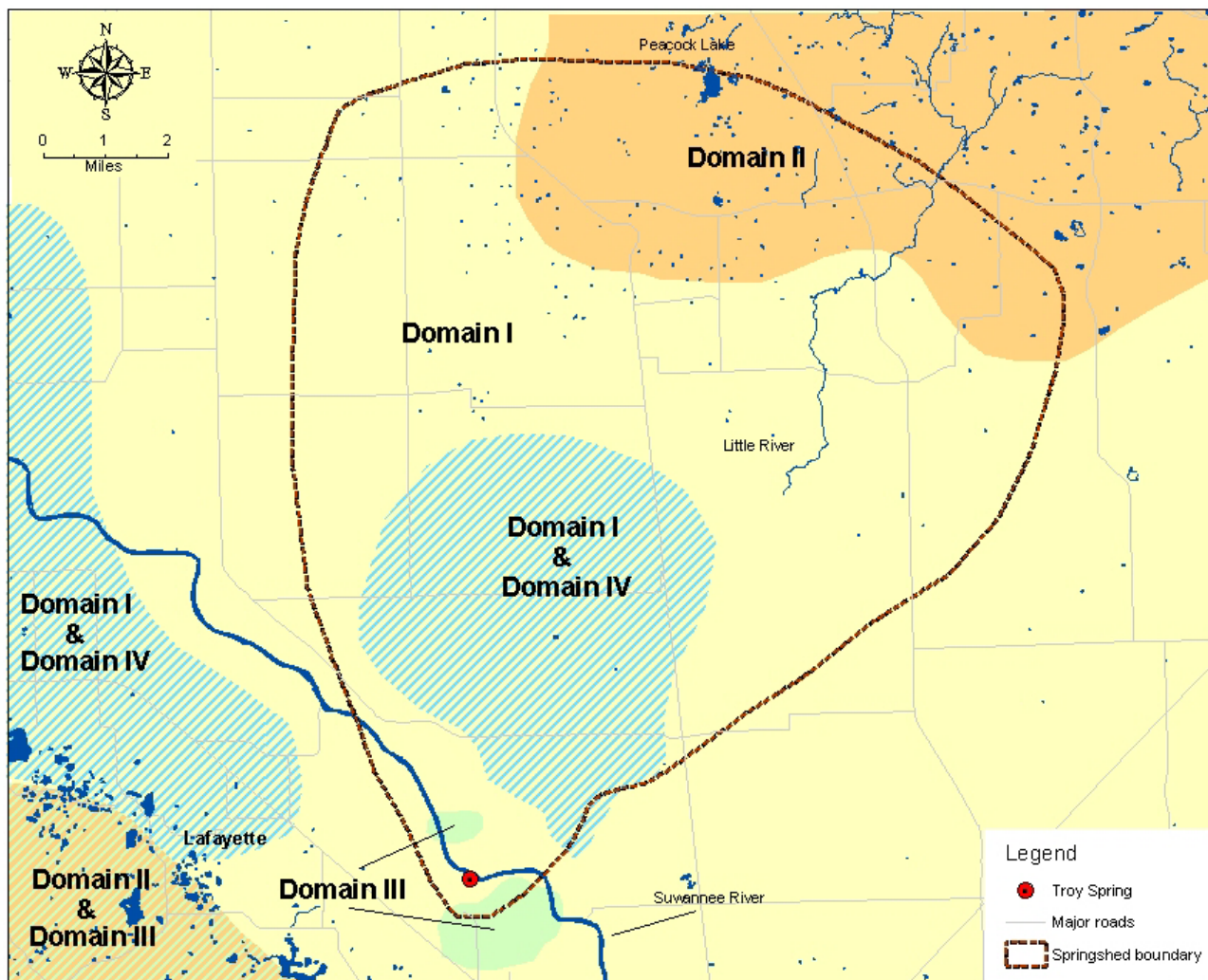


Figure 18. Spatial distribution of water-quality domains within the Troy Spring study area.

Domain II

Domain II covers much of the upland along the northeast boundary of the springshed and low, swampy areas toward the southwest, in Lafayette County (Figure 18). This domain is characterized by the widespread occurrence of perched wetlands and swamps in Lafayette County (Figure 6) and the Miocene Statenville Formation in upland areas (Figure 8). Because of these geologic and hydrologic factors, Domain II represents the region of low to moderate recharge to the Floridan aquifer (Figure 9). In Lafayette County, the chemical signatures of Domain II are mixed with those of Domain III, which is described below. Geochemically, the lower recharge rates in Domain II lead to chemical signatures that can be identified by elevated concentrations of TDS, calcium, and alkalinity.

Domain III

Domain III is found primarily in Lafayette County, to the west of the Troy Spring springshed, and in isolated areas along the Suwannee River (Figure 18). This domain is characterized by ground water containing elevated concentrations of phosphorus, iron, and turbidity. Where this domain occurs along the Suwannee River, it suggests resurgence or discharge of ground water from Domain III areas to the west of the river. It may also reflect the bank storage of ground water that has inherited surface-water characteristics during high flows in the adjacent river channel. This reversal of flow causes surface water to directly recharge the local aquifer system (Upchurch, 1990).

Domain IV

Domain IV is closely associated with Domain I and occurs in two regions of the study area (Figure 18). Domain IV is characterized by ground water that has recharged the Floridan aquifer and contains elevated levels of nitrate. The concentrations of nitrate measured in the Troy Spring springshed are significantly elevated above background concentrations of nitrate in the Floridan aquifer (<0.01 mg/l; Upchurch 1992). Land uses in the study area (Figure 8) and water-quality investigations conducted by the USGS (Katz and others, 1999) suggest that the nitrate discharging from Troy Spring is derived from a mixture of inorganic and organic nitrogen sources. These sources include fertilizers applied to agricultural land uses (e.g., row crops and pastures), septic tanks, and waste lagoons.

DELINEATION OF SPRING-WATER SOURCE AREAS

Water-quality data collected in the study area suggest that the regional ground-water system and Troy Spring have very similar chemical compositions. However, there are subtle chemical differences between many of the samples that enable one to distinguish chemical patterns unique to groups of samples across the region. These patterns indicate source areas that yield chemical fingerprints that can be used to identify dominant spring-water source areas.

Because the ground water discharging Troy Spring differs slightly, the chemistry of the spring water was compared to the chemistry of the three water-quality domains described above. This method was particularly useful in determining the source areas for ground water discharging from Rainbow Springs (Jones and others, 1996), Crystal Springs (Champion and DeWitt, 2000), and Ichetucknee Springs (Upchurch and Champion, 2003b). Figure 17 shows both the star diagrams for spring water and the hierarchical groups described above.

Troy Spring

A comparison of the star diagrams indicates that the regions surrounding Group 1a wells are supplying most of the water to Troy Spring. These wells are closely associated with areas where high recharge rates in Domain I and Domain IV have produced ground water with very low total dissolved solids and low magnesium, sodium and chloride, and elevated levels of nitrate.

Using this domain and hierarchical analysis strategy, the elevated levels of nitrate in Troy Spring most likely originate in recharge areas to the north in Suwannee County. Nitrate concentrations in Domain I/Domain IV are elevated above background levels in the Floridan aquifer and, in several wells, exceeds 1 mg/l. The levels of nitrate in the Troy Spring most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the spring from adjacent areas.

SUMMARY AND CONCLUSIONS

The Floridan aquifer in the study area was divided into four water-quality domains, with each possessing certain chemical characteristics that reflect different water types and hydrochemical facies within the aquifer. Differences in water quality across the region are subtle and appear to be related to the presence or absence of confining layers, sinkhole distribution, and recharge to and discharge from the Floridan aquifer. Each of the four domains is summarized below and their locations are depicted in Figure 18.

Domain I

Domain I covers a large portion of the springshed and study area (Figure 18), where low-permeability Hawthorn Group sediments are thin to non-existent, sinkholes are abundant, and recharge to the Floridan aquifer is moderate to high. Because of these geologic and hydrologic factors, Domain I is the region of greatest recharge to the Floridan aquifer. Geochemically, this recharge is identified by relatively low concentrations of sodium, chloride, sulfate, magnesium, TOC, and total dissolved solids.

Domain II

Domain II covers much of the upland areas along the northeast boundary of the springshed and areas of perched swamps and streams southwest of the spring in Lafayette County (Figure 18). This domain is characterized by the widespread occurrence of wetlands

and swamps in Lafayette County and the Miocene Statenville Formation in upland areas. Because of these geologic and hydrologic factors, Domain II is a region of low to moderate recharge to the Floridan aquifer. In Lafayette County, the chemical signatures of Domain II are mixed with those of Domain III described below. Geochemically, the lower recharge rates in Domain II lead to chemical signatures that can be identified by elevated concentrations of TDS, calcium, and alkalinity.

Domain III

Domain III is found primarily in Lafayette County to the west of the Troy Spring springshed, and in isolated areas along the Suwannee River (Figure 18). This domain is characterized by ground water containing elevated concentrations of phosphorus, iron, and turbidity. Where this domain occurs along the Suwannee River, it suggests either resurgence or discharge of ground water from Domain III areas to the west of the river, or ground water that has inherited surface-water characteristics during high flows in the river.

Domain IV

Domain IV is closely associated with Domain I and occurs in two regions of the study area (Figure 18). Domain IV is characterized by ground water that has rapidly recharged the Floridan aquifer and contains elevated levels of nitrate. The concentrations of nitrate measured in the Troy Spring springshed are significantly elevated above background concentrations of nitrate in the Floridan aquifer (<0.01 mg/l; Upchurch, 1992). Land uses in the study area and water-quality investigations conducted by the USGS (Katz and others, 1999) suggest that the nitrate discharging from Troy Spring is derived from a mixture of inorganic and organic nitrogen sources. These sources include fertilizers applied to agricultural land uses (e.g., row crops and pastures), septic tanks, and waste lagoons.

Source of Troy Spring Discharge

A comparison of the star diagrams indicates that the regions surrounding Group 1a wells are supplying most of the water to Troy Spring. These wells are closely associated with areas where high recharge rates in Domain I has produced ground water with very low total dissolved solids and low magnesium, sodium and chloride, and elevated levels of nitrate.

Using this domain and hierarchical strategy, the elevated levels of nitrate in Troy Spring most likely originate in recharge areas to the north of the spring in Suwannee County. Nitrate concentrations in Domain I/Domain IV are elevated above background levels in the Floridan aquifer and, in several wells, exceeds 1 mg/l. The levels of nitrate in the Troy Spring most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the spring from adjacent areas.

Nitrate concentrations at Troy Spring have gradually increased over the last several decades, suggesting that water-quality trends in this spring are slow to change. Many of the agricultural operations in the Troy springshed are cooperating with the District and other agencies to implement best management practices and reverse the historic trend in nitrate concentrations with time. This indicates that long-term monitoring is needed to detect and

confirm these changes in water quality at the spring. With an estimated, current long-term increase of 0.01 to 0.02 mg/l per year, it is likely that many years, if not decades, will be needed to reverse long-term water-quality trends at Troy Spring and other springs in the region.

The spring should be sampled at least twice a year to monitor intermediate- to long-term trends in water quality. This sampling program should include analyses for nutrients (e.g., nitrate), major ions (e.g., calcium), trace constituents (e.g., iron), and periodically for nitrogen isotopes to determine the effects of changing land use and to determine the effectiveness of remedial efforts to protect water quality at the springs.

Best management practices (BMPs) should continue to be developed or implemented to reduce the use of fertilizer near the spring. This is particularly important given the proximity of agricultural land uses to the spring. BMPs for turf fertilization in residential and golf course areas, as well as septic and centralized sewage disposal will need to be addressed as commercial and residential development proceeds in the springshed.

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**Ground Water Chemistry
and
Origin of Water Discharging
from**

MADISON BLUE SPRING

Madison County, Florida

Prepared for the
SUWANNEE RIVER WATER MANAGEMENT DISTRICT
Live Oak, Florida

By
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4509 George Road
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March 30, 2005



Endorsement

This report, entitled "Ground Water Chemistry and Origin of Water Discharging from Madison Blue Spring, Madison County, Florida," was prepared for the Suwannee River Water Management District by the undersigned individuals under Contract No. 03/04-058. Opinions and conclusions expressed in this report are those of the authors only. The data and conclusions presented herein do not necessarily reflect opinions or policy of the District.

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INTRODUCTION

Madison Blue Spring is one of north Florida's most valuable natural resources. The spring is one of the State's many first-magnitude springs, as well as one of the most popular parks in the region. The spring is important to the natural and scenic beauty of the area, and to the region's rich historical heritage. Protecting Madison Blue Spring and others like it requires a thorough understanding of the geology and hydrology of the region surrounding the spring and Withlacoochee River.

Since the 1970's, much information has been gathered concerning large spring systems in north Florida and the importance of karst to water quality in the Floridan aquifer. Lawrence and Upchurch (1976), for example, determined that karst features could be used to deduce the vulnerability of ground water to contamination, and the extent to which ground-water recharge affects water quality in the Floridan aquifer near the town of Lake City in Columbia County. Similar results were obtained by Ceryak and others (1983) and Crane (1986) in two regional studies of the upper and lower Suwannee River Basin, respectively. More recently, nitrogen-isotope data collected by Katz and others (1999) suggested that Madison Blue Spring discharges nitrate that is derived from a mixture of artificial fertilizers and wastewater. It has also been discovered that flow through large spring systems, such as Madison Blue Spring, can be rapid. For example, a dye trace in Columbia County from Rose Creek Sink to the Ichetucknee Springs resulted in a transport rate of approximately one mile per day (Karst Environmental Services, 1997) and a dye trace at Madison Blue Spring (Water Resources Associates, Inc., 2004) resulted in transport from the Spring to Pot Spring, which is approximately 0.8 miles southeast of Madison Blue Spring, within 24 hours.

An important step in understanding the hydrology of Madison Blue Spring (Figure 1) is to define its spring recharge basin, or springshed (Copeland, 2003). A springshed is defined as the areas within ground-water and surface-water basins that contribute to the discharge of a spring. The inclusion of surface-water drainage basins in the definition may be important to the Madison Blue Spring system because several large, surface-water drainage basins (e.g., SE Madison Karst; Water Resource Associates, Inc., 2004) are known to cross into the Madison Blue Spring ground-water basin (Figure 2). Contaminants transported to the ground-water system from surface-water basins that extend beyond the ground-water basin may constitute a significant threat to the spring system.

Of interest is an understanding of the chemical composition and source areas for spring water in the study area. The chemistry of ground water in the study area is affected by a number of geologic, hydrologic, and anthropogenic factors. Principal components analysis (PCA) is a useful tool for sorting out hydrogeologic process-response relationships within a sample population of ground-water quality data (Lawrence and Upchurch, 1976, 1982). In this paper a PCA of ground-water chemistry data was used to group chemical constituents into specific factors that reflect differences in the chemical composition of ground water in the study area. A graphical analysis of these factors was then utilized to define specific hydrogeochemical source areas and processes for spring water in the study area.

DESCRIPTION OF STUDY AREA

The Madison Blue Spring study area encompasses approximately 245 square miles of eastern Madison County and western Hamilton County (Figure 1). This region contains both the lower reach of the Withlacoochee River north watershed and the ground-water basin that contributes subsurface flow to the spring (Upchurch and Champion, 2004a). The Madison Blue Spring springshed lies to the west of the Withlacoochee River and encompasses approximately 100 square miles of eastern Madison County. The ground-water basin was identified and described by Upchurch and Champion (2004a), who used geostatistical analysis to better define the basin boundaries. The Suwannee River Water Management District (SRWMD) is currently monitoring the Madison Blue Spring springshed, which will greatly refine the basin delineation (Upchurch and others, 2001).

Note that most of the surface-water portion of the springshed appears to lie within the ground-water basin (Figure 2). However, several surface-water basins extend outside of the ground-water basin. For this reason, the study area was selected to include both surface- and ground-water basins and to extend somewhat outside of these basins.

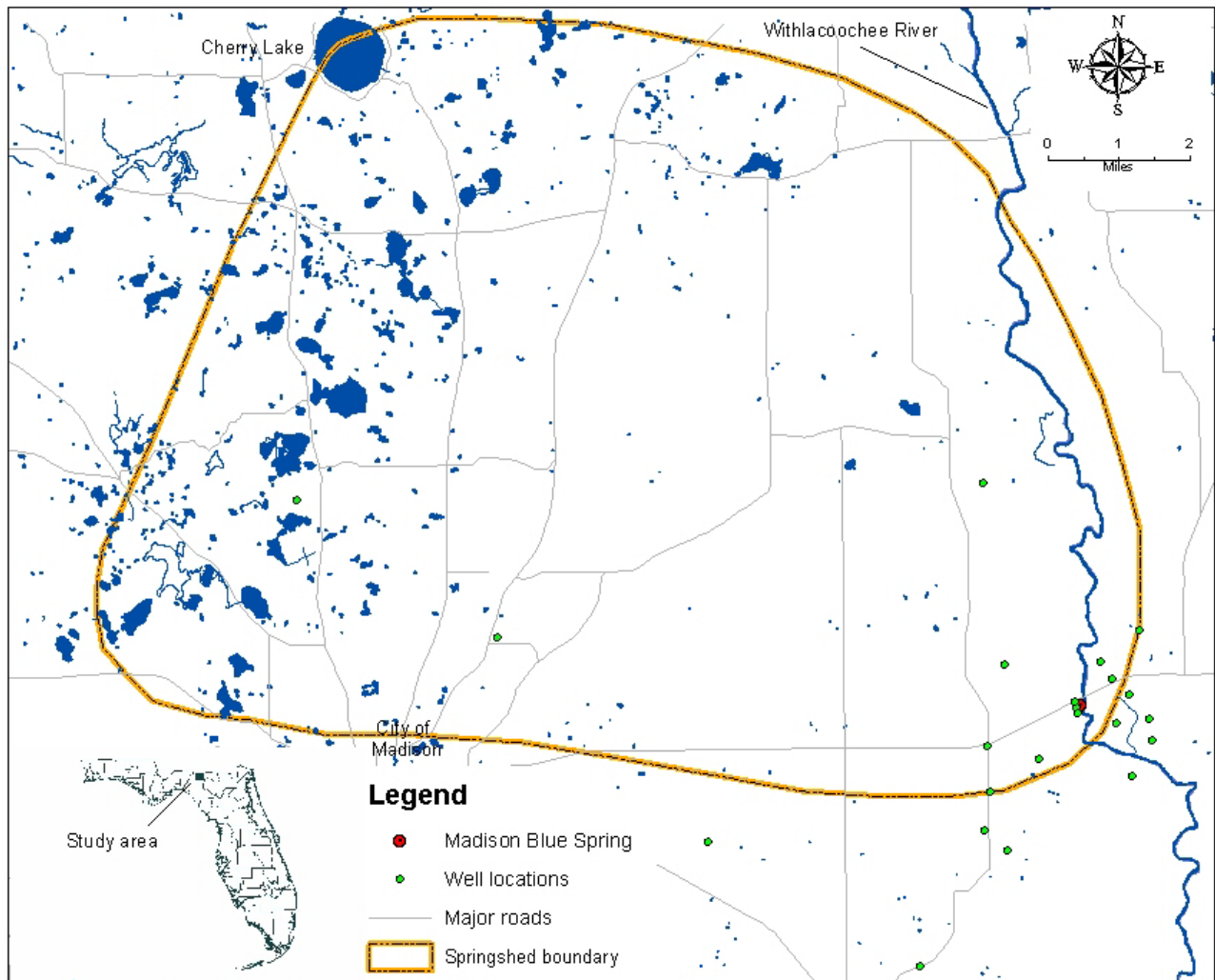


Figure 1. Location of the study area and the Madison Blue springshed in Madison County (modified from Upchurch and Champion, 2004a).

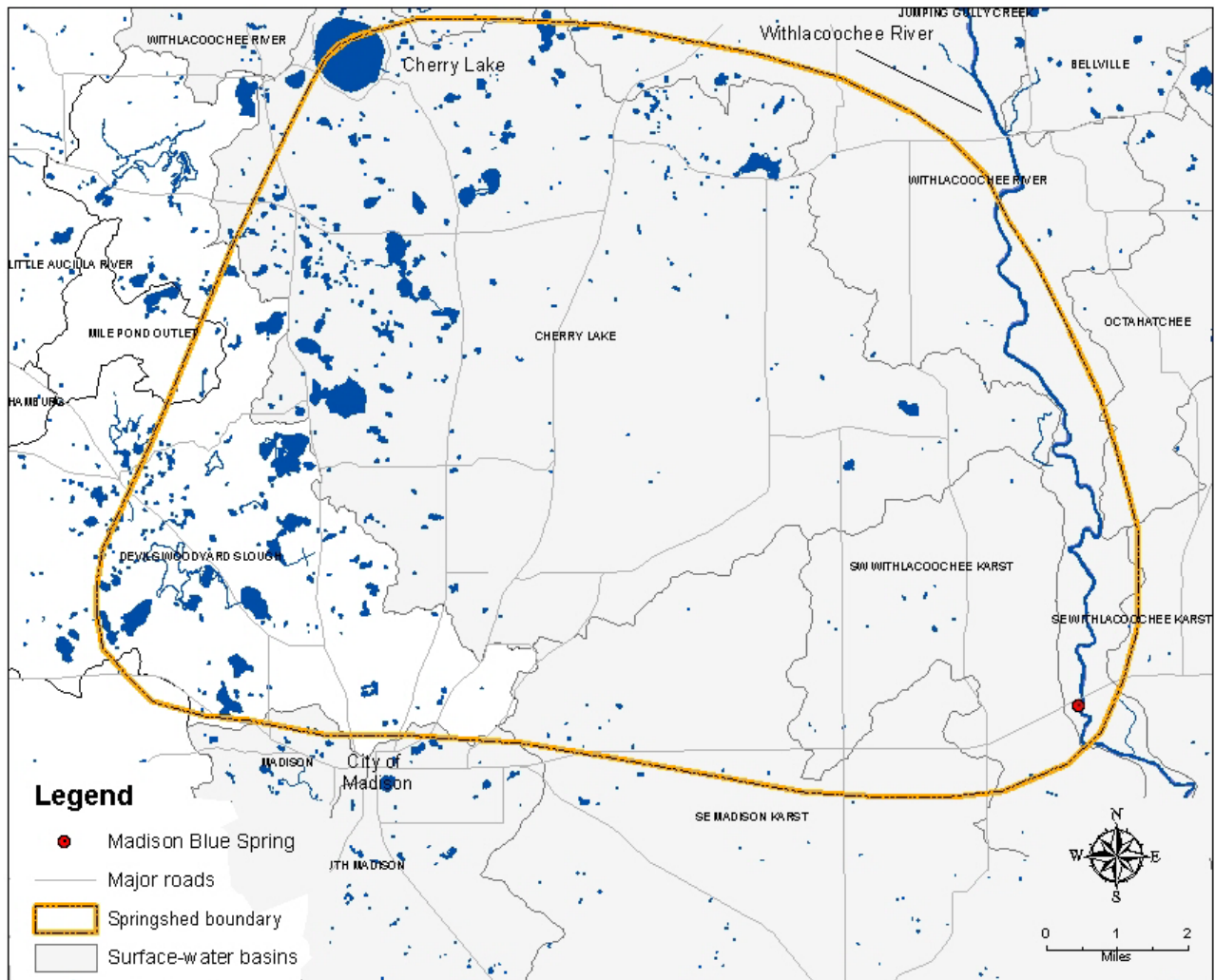


Figure 2. Surface-water basins in the study area and within the Madison Blue Spring springshed. Shaded basins are within the Suwannee River watershed

Population and Water Use

The City of Madison, the largest population center in the study area, contains approximately 3,100 residents. Since 1960, the population of Madison County has decreased 14 percent, from approximately 16,516 to 14,197 (U.S. Census Bureau, 2002). With a population density of approximately 27 persons per square mile, the County retains a decidedly rural and agricultural character.

According to estimates by Marella (1999), ground water was withdrawn from the Floridan aquifer in Madison County at the rate of approximately 8.7 million gallons per day (mgd) in 1995. Agricultural withdrawals, rural self-supplied, and public water-supply systems accounted for approximately 62 percent (5.4 mgd), 17.2 percent (1.5 mgd) and 18.4 percent (1.6 mgd), respectively, of the total withdrawals in the County (Marella, 1999). Cumulatively, these withdrawals accounted for more than 97 percent of the water use in the County in 1995.

Land Use

Land use in the study area was identified using the 1996 USGS Arcview™ land-use coverage (Florida Geographic Data Library, 2004). The Madison Blue Spring springshed is a sparsely populated region. The major land uses in the springshed (Figure 3) include temperate hardwood forests, pine plantations, areas of forest regeneration, improved pasture, and row crops (Upchurch and Champion, 2004a). Together, these five land uses cover approximately 80 percent of the springshed. Row crops, in particular, are concentrated in the southern extent of the springshed nearest the spring. Interspersed among the row crop areas are large tracts of pine plantations, and smaller tracts of improved pasture and forest regeneration. Temperate hardwood forests are scattered throughout the region, with a large forested area along the western bank of the Withlacoochee River. (Upchurch and Champion, 2004a).

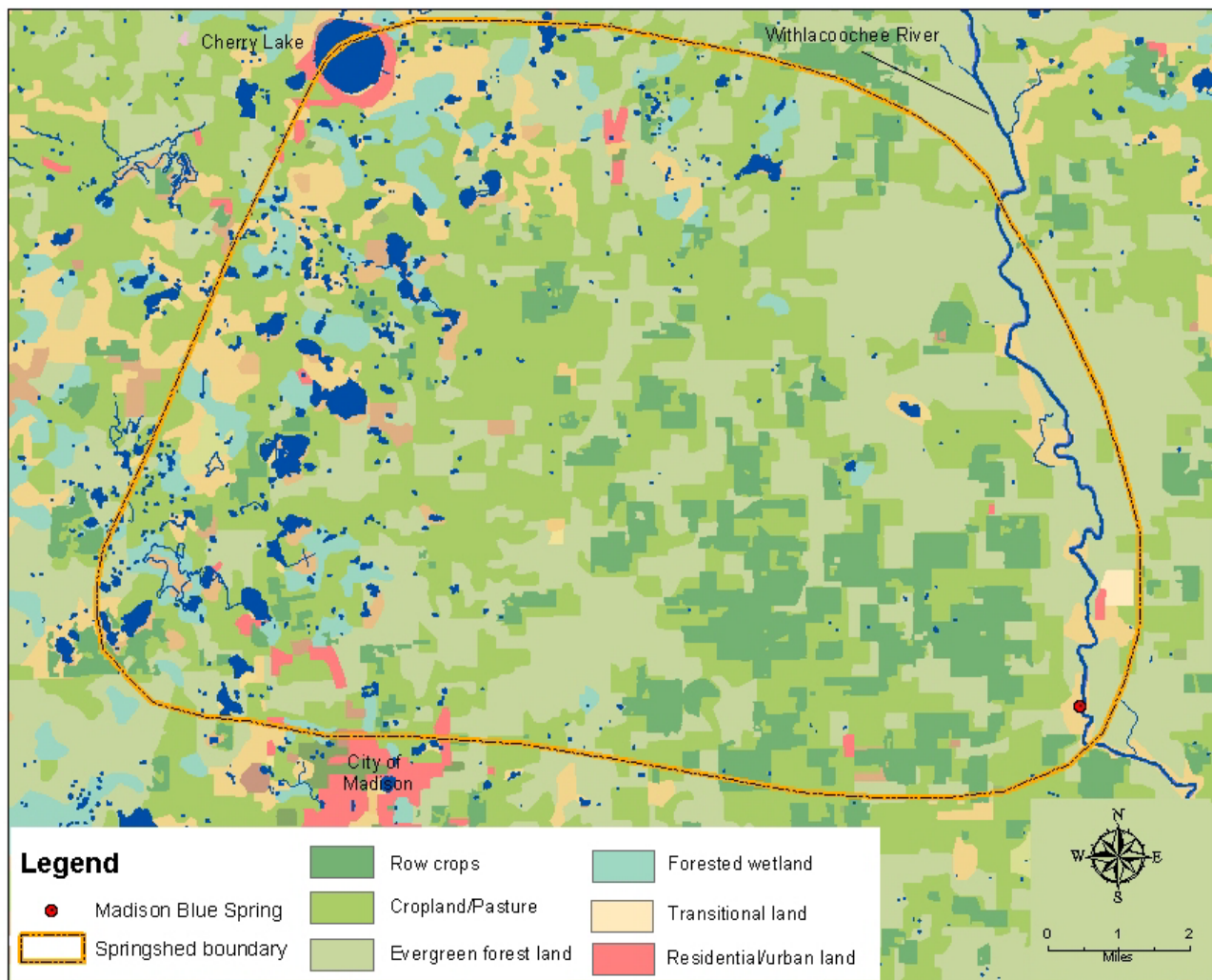


Figure 3. Major land uses in the Madison Blue Spring study area (Florida Geographic Data Library, 2004).

Topography, Physiography, and Drainage

The topography of the Madison Blue Spring study area varies considerably, from less than 100 feet above sea level along the banks of the Withlacoochee River to areas in excess of 200 feet above sea level in upland regions to the northwest of the springshed (Figure 4). In the immediate vicinity of Madison Blue Spring, however, elevations are approximately 50 to 100 feet above sea level.

White (1970) divided Madison County into two physiographic regions: the Gulf Coast Lowlands and the Tallahassee Hills portion of the Northern Highlands Physiographic Province (Figure 5). The Tallahassee Hills is an upland area (typically greater than 150 feet above sea level) capped by relatively impermeable, clay-rich sediments, which result in surface-water runoff and development of lakes and wetlands (Figure 6). In contrast, the Coastal Lowlands (typically less than 100 feet above sea level) is a mature karst plain characterized by rapid infiltration of runoff and few, if any, lakes or wetlands (Figure 6). Sinkholes in the Coastal Lowlands are typically small in area, but they are numerous (Upchurch, 2002).

Between the Northern Highlands and Coastal Lowlands is a transitional region characterized by an abundance of sinkholes, sinkhole lakes, and sinking streams (Figure 7). This transitional region was named the Cody Scarp by Puri and Vernon (1964). Surface elevations along the Cody Scarp are generally between 100 and 150 feet above NGVD, and within the study area, a large portion of the surface runoff from the Northern Highlands/Tallahassee Hills flows down the Cody Scarp, where it drains rapidly into the Floridan aquifer. Because of the remaining thick cover within the Cody Scarp, sinkholes and sinkhole-related karst features tend to be large (Upchurch, 2002).

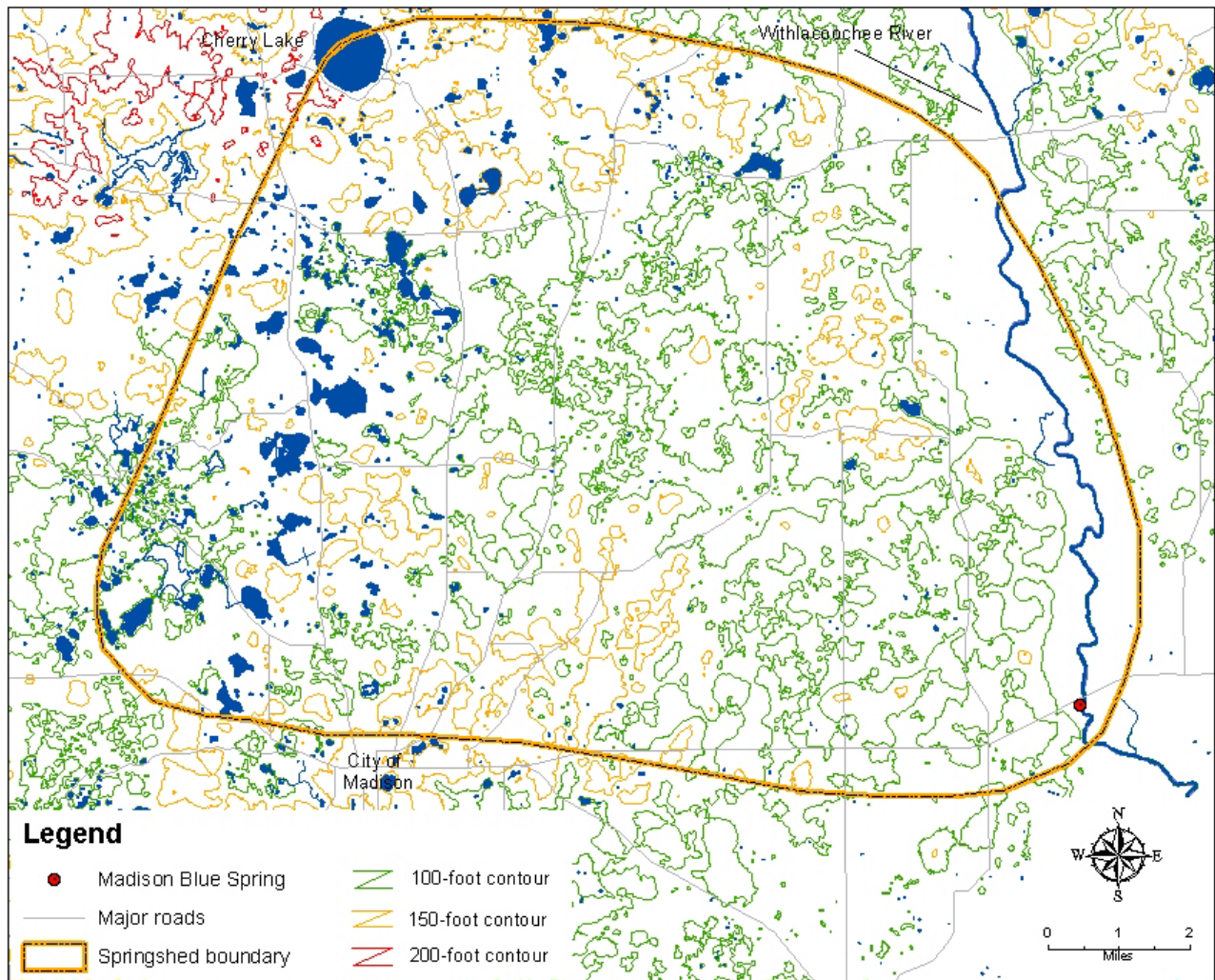


Figure 4. Land-surface elevations in the Madison Blue Spring study area (Florida Geographic Data Library, 2004).

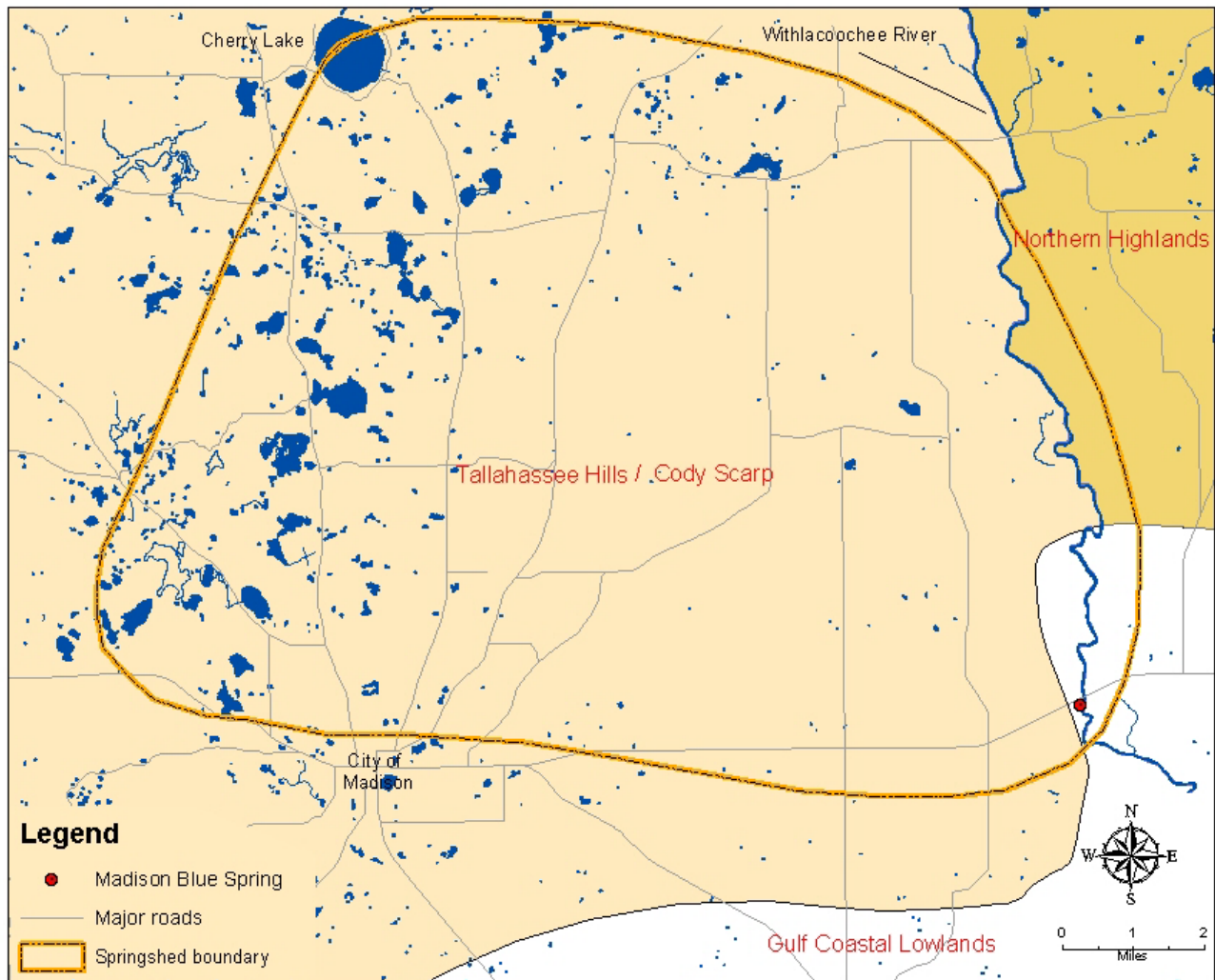


Figure 5. Physiographic provinces within the Madison Blue Spring study area (modified from White, 1970).

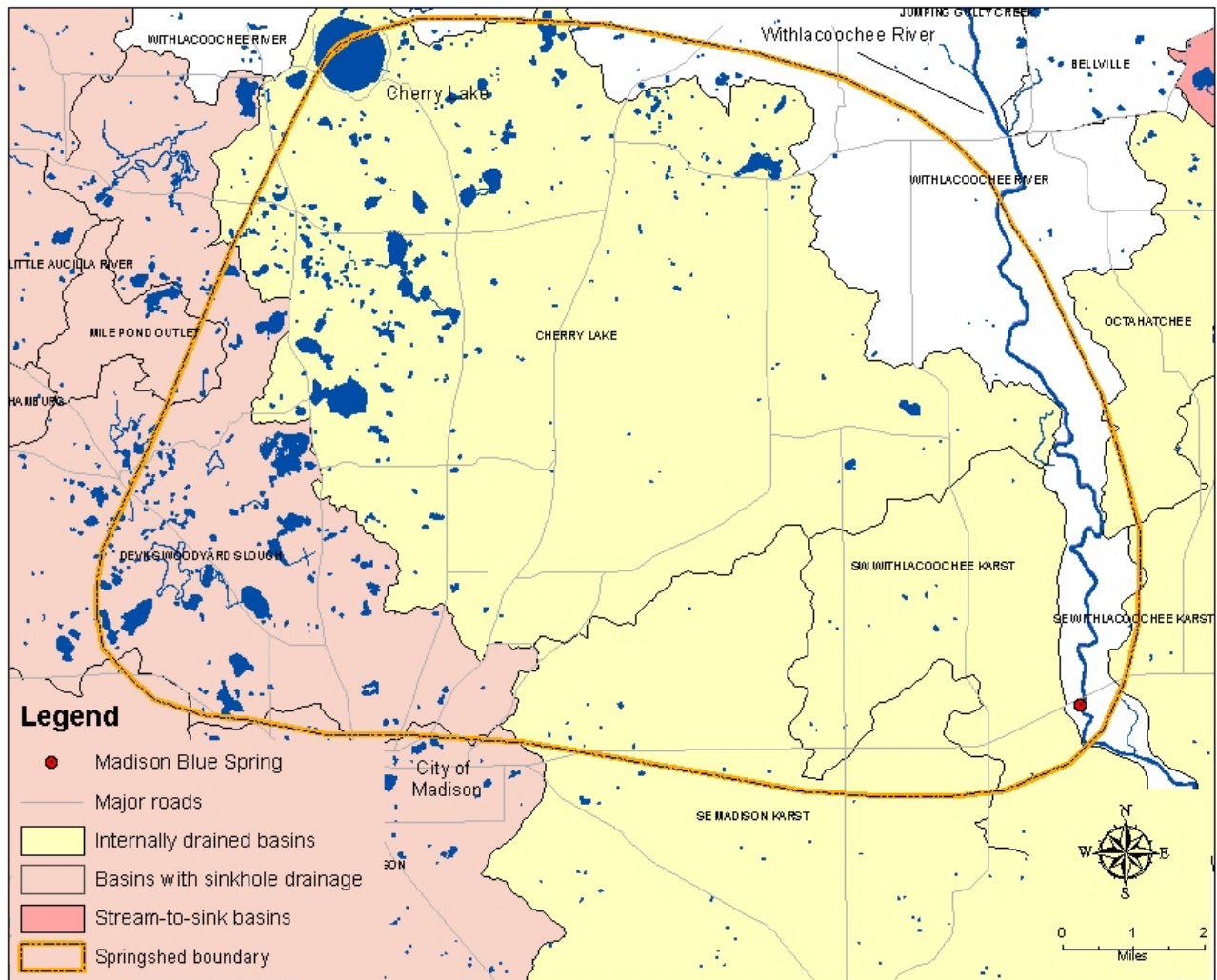


Figure 6. Significant hydrologic features within the Madison Blue Spring study area. Basin descriptions modified from SR WMD (unpublished data).

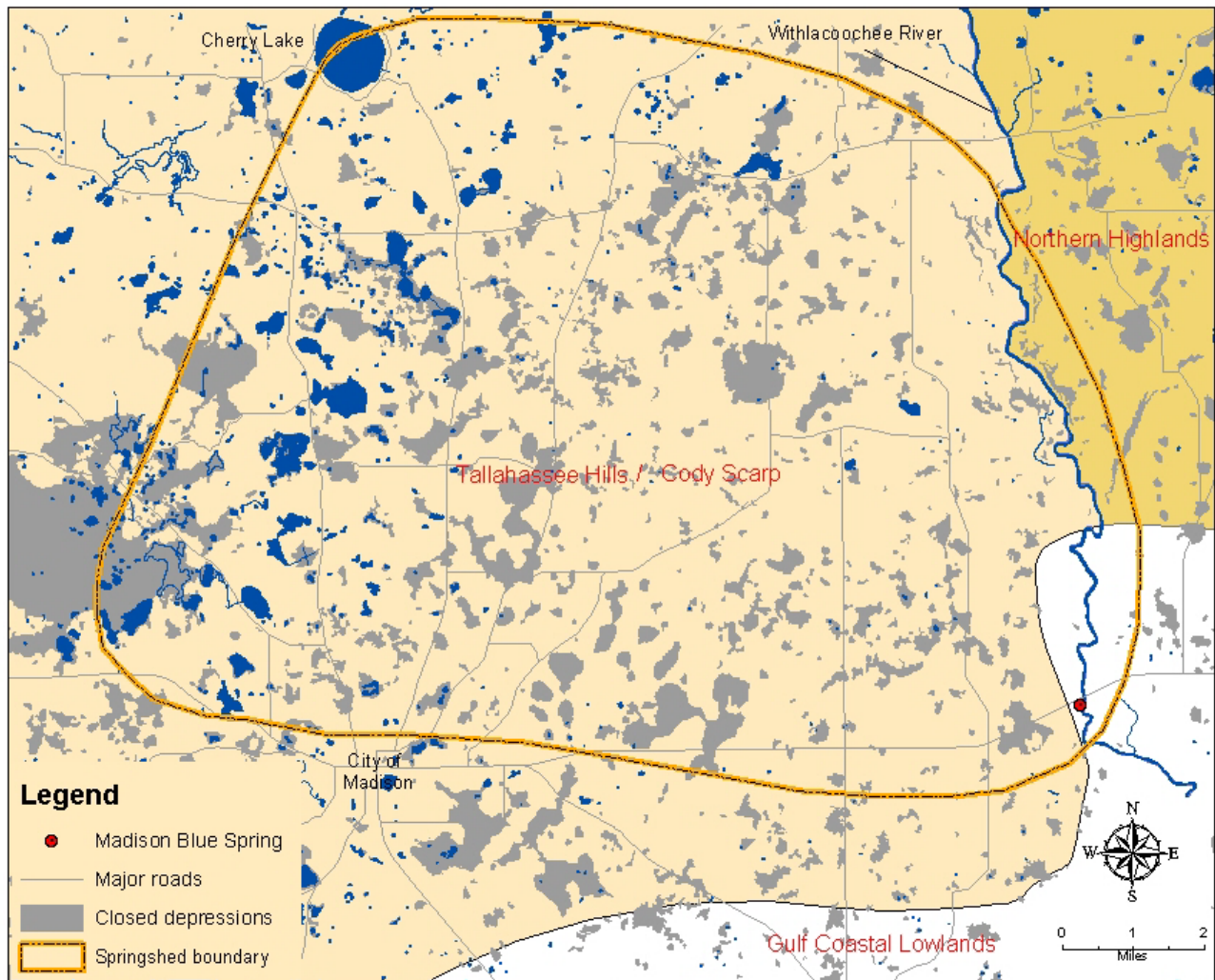


Figure 7. Sinkholes and closed depressions within the Madison Blue Springs study area.

Geology

Figure 8 is a geologic map showing the stratigraphic units at or near land surface in the study area. Thick sequences of limestone are exposed at or very near (10-20 feet) the land surface in many parts of the study area, especially along the Withlacoochee River. Where limestone is near land surface, the thin veneer of sediment that covers the limestone consists of Quaternary-age, unconsolidated to poorly indurated, siliciclastic deposits dominated by quartz sand. These sands are primarily marine terrace deposits.

The uppermost limestone units in the study area include the Suwannee and Ocala Limestones of Oligocene and Eocene age, respectively. Below the Ocala Limestone is the Eocene Avon Park Formation. The major carbonate unit in the study area is the Suwannee Limestone, which lies at or near land surface throughout much of the region (Figure 8). Based on well cuttings, Crane (1986) described the Suwannee Limestone in the study area as consisting of several lithologies of marine origin: a dark yellowish-brown, moderately to well-indurated, sucrosic dolomite; a white-to-pale orange, poorly to moderately indurated, fossiliferous calcilutite; a yellow-gray, moderately to well-indurated, fossiliferous calcilutite; and a white, moderately to well-indurated, highly porous, and fossiliferous calcarenite. The upper surface of the Suwannee Limestone is marked by karst features, and in some areas, has been eroded and is no longer present in the subsurface (Crane, 1986).

Below the Suwannee Limestone (where present), lies the Ocala Limestone. Based on well cuttings, Crane (1986) described the Ocala Limestone in the study area as consisting of several lithologies of marine origin. The deepest of these lithologies is a medium to well-indurated calcarenite composed almost entirely of Miliolid foraminifera. Above this unit lies a medium to well-indurated calcarenite composed of the foraminifera *Operculinoides* sp. and Miliolids. Capping these two lower lithologies is a unit that is described as a poorly to moderately indurated calcarenite composed of the foraminifera *Lepidocyclina* sp. Much like the underlying Avon Park Formation, the upper surface of the Ocala Limestone is highly variable and karstic (Crane, 1986).

The Avon Park Formation is the oldest rock unit that crops out in Florida. In the study area, the early Eocene age Avon Park Formation consists of moderate to well-indurated, sugary dolostone, and moderately to well-indurated calcilutite, calcarenite and calcirudite. Thin seams of peat are often associated with the more dolomitized sections of the Avon Park Formation. In deeper, more calcitic sections of the Avon Park, Miliolids and foraminifers, especially *Dictyoconus americanus*, are often present (Crane, 1986). Gypsum is also present in small amounts in the Avon Park Formation, though it typically occurs several hundred feet below sea level in the study area (Crane, 1986). The Ocala Limestone and the Avon Park Formation comprise the Floridan aquifer in the Madison Blue Spring springshed.

In the Northern Highlands, the carbonate units of the Floridan aquifer are overlain by interbedded phosphatic sands, clays, and dolostones of the Statenville and Torreya formations of the Hawthorn Group (Scott and others, 2001) (Figure 8). Due to the clayey composition of these two formations, the vertical hydraulic conductivity of the units is generally low and they tend to form an intermediate confining unit above the Floridan aquifer and below the surficial aquifer system. Silicified fossils are common to both

formations, and significant deposits of phosphorite are economically important in the Statenville Formation (Scott, 2001) east of the study area.

Weathering of phosphorite in the Hawthorn Group sediments has resulted in dissolution of carbonate-fluorapatite and re-precipitation of carbonate-hydroxylapatite in localized crust and nodules in the Ocala Limestone (Upchurch, 1992, 2002). These deposits of re-precipitated phosphate, which were locally termed “hard-rock phosphate,” were extensively mined throughout northern Florida from the late 1880’s through the 1960’s (Dinkins, 1969). None of the mines were large because the deposits were localized in ancient karst features. Meyer (1962) noted that phosphate ore deposits were once mined near Fort White in Columbia County.

In the Northern Highlands, the phosphatic sands, clays, and dolostones of the Statenville and Torreya formations of the Hawthorn Group are overlain by sand, clay, and clayey sands of the Pliocene age Miccosukee Formation (Scott and others, 2001) (Figure 8). Due to its clayey composition, the permeability of the Miccosukee is generally low. Therefore, the Miccosukee is part of the intermediate confining unit above the Floridan aquifer. The more permeable zones in the Miccosukee may form a local surficial aquifer system. As noted by Yon (1966), Miccosukee sediments were likely formed in a deltaic environment with channel and fill deposits exhibiting irregular and variable bedding, cross-bedded sands, and fossils of land vertebrates.

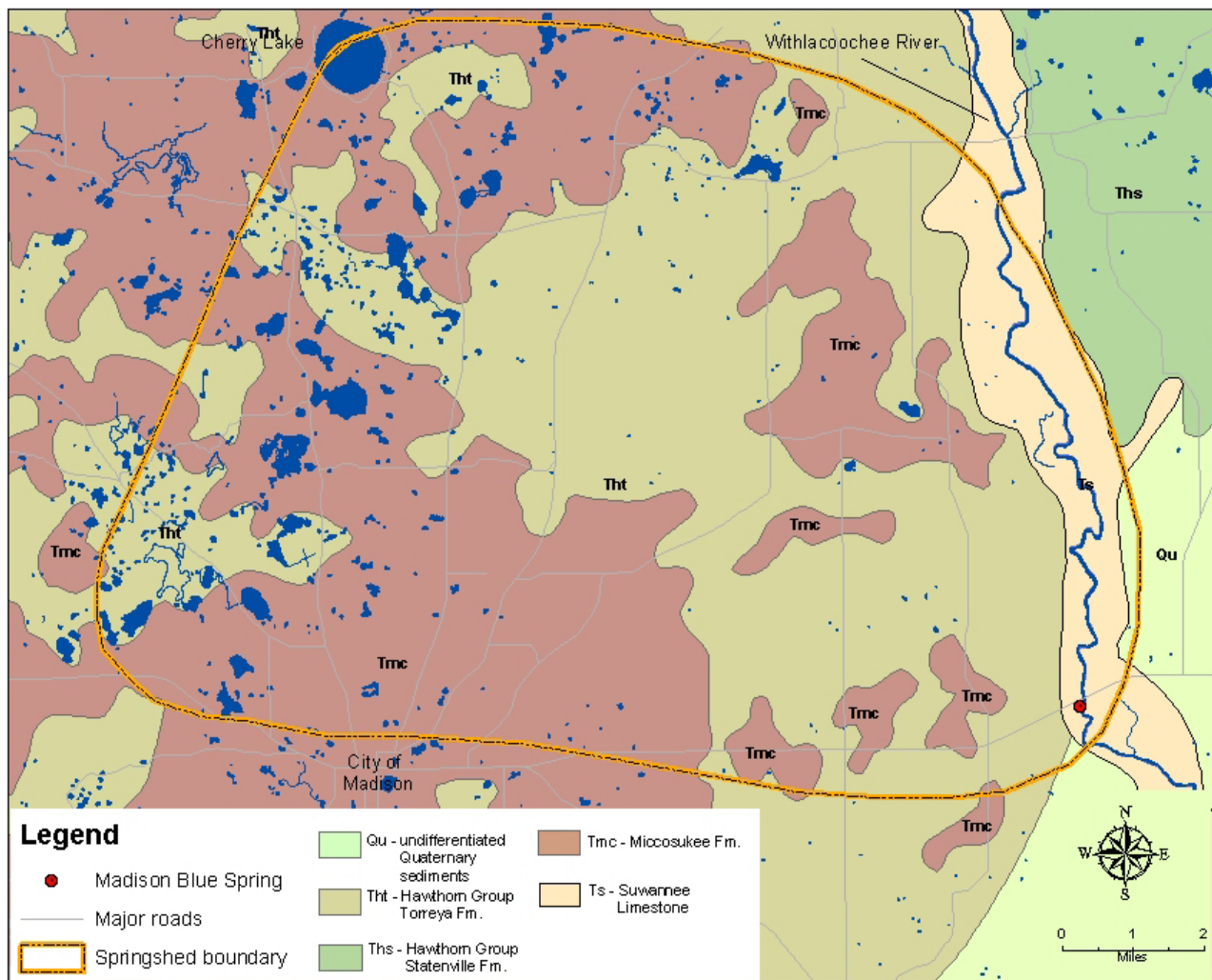


Figure 8. Geologic map of the Madison Blue Spring study area (modified from Scott and others, 2001).

Surface-Water Hydrology

Surface-water features are not particularly abundant in the Madison Blue Spring springshed (Figure 6). This is due to the shallow depth of the limestone in some areas, the highly porous nature of the overlying soils (especially where sinkholes are abundant), and high relative aquifer recharge across the springshed (Figure 9). Therefore, the absence of streams and rivers throughout the Madison Blue Spring springshed reflects a well-developed underground drainage system in the Floridan aquifer. Recharge is relatively high in the springshed because Hawthorn Group sediments are either absent or perforated by numerous sinkhole features (Figure 7) that allow for relatively high recharge rates.

Karst and Ground-Water Hydrology

Karst - A prerequisite to characterizing the ground-water hydrology of the study area is an understanding of the dominant role that karst processes play in moving ground water through the Floridan aquifer. The Madison Blue Spring springshed is an area of intensive karst development, characterized by numerous sinkholes, lack of surface drainage, and undulating topography (Figures 4, 6, and 7). In karst areas, the dissolution of limestone has created enlarged cavities along fractures in the limestone, which eventually collapse or reach the surface and form sinkholes. Sinkholes capture surface-water runoff and funnel it underground, which promotes further dissolution of limestone. This leads to progressive integration of voids beneath the surface over time and allows increasingly larger amounts of water to be transported through the ground-water system.

Dissolution is most active near the water table or zone of water-table fluctuation. In this zone, carbonic acid contained in atmospheric precipitation and generated by reaction with soil carbon dioxide reacts with limestone and dolostone (Carroll, 1970). Because the altitude of the water table has shifted in response to changes in sea level over the last 30 million years, many vertical and lateral paths have developed in the underlying carbonate strata in the study area. Many of these paths or conduits lie below the present water table (the Floridan aquifer is essentially unconfined in the Coastal Lowlands) and greatly facilitate ground-water flow.

Ground water may flow rapidly through conduits and passages within the limestone, or slowly through minute pore spaces within the rock matrix. Dye-trace studies in Columbia County show that ground water near Ichetucknee Springs may travel approximately one mile per day in active conduits in the Floridan aquifer (Karst Environmental Services, 1997). Similar velocities were recorded near Sulphur Springs in Hillsborough County (Stewart and Mills, 1984). A similar, un-timed dye-tracer test from Madison Blue Spring to Pot Spring, 0.8 miles southeast, resulted in similar travel times. Studies such as these clearly indicate that ground water has the potential to flow rapidly and traverse great distances in a short amount of time in karst environments near major springs.

Because the flow in these karst conduits is rapid and direct, dispersion, dilution, and retardation of contaminants is likely to be minimal. Consequently, the springs are vulnerable to contamination within the springshed. For example, when Lawrence and

Upchurch (1976) sampled the Floridan in the vicinity of Lake City, they described a plume of surface water under Alligator Lake that extended to the southwest for several miles. Shortly after completion of the study, the lake drained and the residents down gradient reported colored water, organic debris, and other indicators of lake water. We now know that Alligator Lake is part of the headwaters of the Ichetucknee Springs and that the plume of surface water was migrating in a karst conduit system to the springs.

In contrast, recent studies by the USGS and SRWMD have demonstrated that much of the spring water in northern Florida (and the study area) has been in the Floridan aquifer for an average of 10-25 years (Katz and others, 1999). This estimate is based on age-dating techniques using chlorofluorocarbons (CFC's) derived from the use of aerosol propellants and refrigerants. These CFC compounds, released into the atmosphere over the last 50 years, have dissolved in precipitation that recharges ground water (Katz and Hornsby, 1998). The occurrence of CFC's in spring water in the study area indicates that, while a portion of the ground water moves quickly through conduits in the Floridan aquifer, much of the water percolates slowly through the soil and into the aquifer. Once the ground water recharges the aquifer, it begins moving through the smaller pores and openings in the limestone before reaching an active conduit or spring vent. The slower movement of ground water through the aquifer is known as diffuse flow. Because of the diffuse flow and ability of the limestone matrix to improve ground-water quality, the springs are typically clear and free of most contaminants.

Rapid conduit flow and slower, diffuse flow are processes that make it possible to decipher the hydrology of springs in karst regions, such as the study area. Older ground water mixes with younger ground water traveling through active conduits near the spring. Two recent studies by the St. Johns River Water Management District and the SRWMD demonstrate and support this mixing model of ground water at springs (Katz and Hornsby, 1998; Toth, 1999). Therefore, the mixing of ground waters must not be overlooked when assessing the origin, health, and history of spring waters in karst environments such as the study area.

Recharge - Recharge to the Floridan aquifer is directly related to the confinement of the system. The highest recharge rates occur where the Floridan is unconfined or poorly confined, including those areas where the aquifer is at or near land surface. Such conditions occur throughout the study area. Recharge may also be high in areas where the confining layers are breached by karst features, such as sinkholes (Figure 7). Other factors affecting recharge rates include the development of surface-water drainage, variations in water-level gradients between surface water, the surficial aquifer and the Floridan aquifer, and aquifer permeability. Low recharge rates occur where confining materials overlying the aquifer retard downward vertical movement of water, or where an upward water-level gradient exists between the Floridan and surficial aquifers. Figure 9 shows the estimated recharge potential of the Floridan aquifer in the study area.

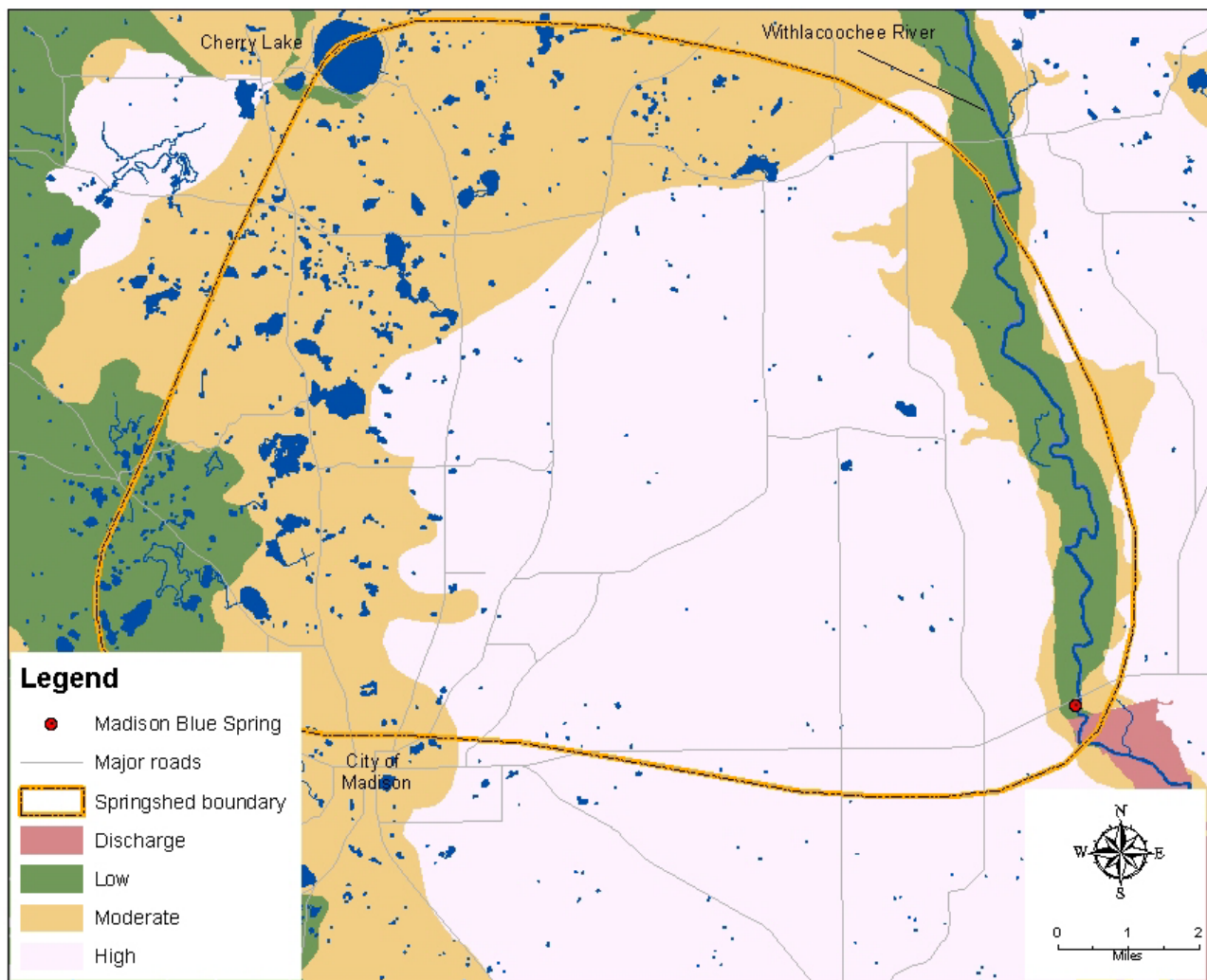


Figure 9. Relative recharge to the Floridan aquifer in the Madison Blue Spring study area (SRWMD, 2004)

Potentiometric Surface - The potentiometric surface of the Floridan aquifer in the study area is shown in Figure 10. This map was created by statistically analyzing water levels from approximately 40 monitor wells within the study area. This geostatistical analysis consisted of two steps. First, a structural analysis is performed to determine the pattern of variance with distance between sample pairs. Then, by kriging the data using these “rules” of uncertainty estimation, a traditional contour map and a map showing levels of uncertainty in the contour map are produced. The ground-water basin is then delineated from the contour map, and the uncertainty map is used to define areas that would benefit from additional monitoring locations. The geostatistical analysis conducted by Upchurch and Champion (2004a) provided an accurate picture of the basin’s shape, especially near the spring.

Some distinctive features are visible on the potentiometric surface map; the most important being the consistent gentle gradient that slopes downward from the northwest to the spring. This area represents a region of well-developed karst and high hydraulic conductivity. Areas where isopleths are somewhat closer together, such as in the vicinity of Madison, are regions of slightly lower hydraulic conductivity. Regions of higher hydraulic conductivity appear to be separated by this slightly lower hydraulic conductivity zone. Higher hydraulic conductivities appear to be located in areas near Mile Pond Outlet and the Little Aucilla River basins, as well as near the spring in the Southeast Madison Karst and Southwest Withlacoochee Karst basins (Figure 2; Upchurch and Champion, 2004a).

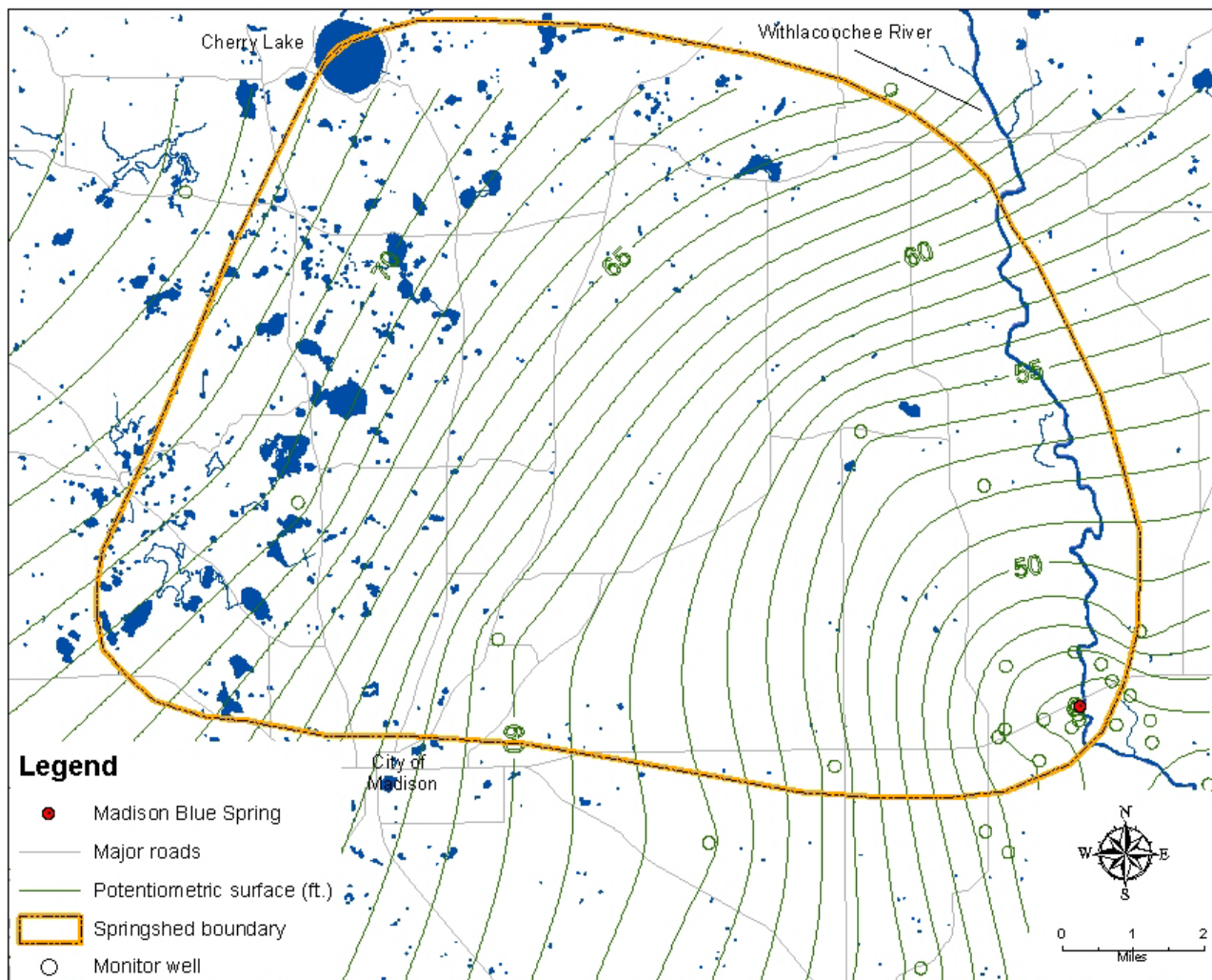


Figure 10. Potentiometric surface of the Floridan aquifer in the Madison Blue Spring study area (modified from Upchurch and Champion, 2004a).

GROUND-WATER CHEMISTRY

Previous ground-water investigations have indicated that the chemistry of ground water in north Florida is affected by a number of geologic, hydrologic, and anthropogenic (man-made) factors. These include 1) residence time in the aquifer, which affects the amount of dissolution of limestone, 2) the thickness and mineralogy of the Hawthorn Group sediments, 3) recharge rates (Lawrence and Upchurch, 1976; Crane, 1986; Upchurch, 1992), and 4) the presence of agricultural and other land uses in areas near the spring (Katz and others, 1999). In addition, data presented by Katz and others (1999) suggest that much of the water discharging from the spring has moved through a relatively short, shallow flow system, and has been in the Floridan aquifer for only a few decades at most.

Water quality discharging from springs in north Florida has been characterized in a number of studies, including Rosenau and others (1977), Hornsby (1998), Katz and others (1999), Scott and others (2002), and Upchurch and Champion (2003a, 2003b, 2004a).

Ground-water quality within the study area has been characterized by Upchurch (1990, 1992). The SRWMD updates the results of nitrate monitoring in its Ground Water Quality Monitoring Reports on an annual basis (Hornsby and Ceryak, 1999), as well.

Several studies have examined the connectivity of surface and ground water in north Florida, including Skiles (1991), Hirth (1995), and Martin and Gordon (1998). These studies, and the well-known Rose Creek Sink dye trace (Karst Environmental Services, 1997), clearly demonstrate the sensitivity of the ground-water system to surface-water events.

Floridan aquifer ground water is characterized as a calcium-bicarbonate water type because of interactions with the limestone of the aquifer. Because of the preponderance of karst in the Madison Blue Spring springshed, Floridan aquifer water contains numerous indicators of interaction with surface water, including color, high organic carbon, and high dissolved oxygen (Upchurch, 1990). These surface-water indicators demonstrate that the aquifer is highly vulnerable to human activities.

DELINEATION OF GROUND-WATER QUALITY DOMAINS

Study Area Monitor-Well Network

The most important tools in determining the chemical composition and source areas for spring water in the study area were the water-quality data obtained from a regional monitor-well network designed and sampled by staff at SRWMD. The monitor-well network totaled 24 wells, consisting of dedicated monitor wells and wells used for domestic and public supply.

Factor Analysis

Factor analysis is used to sort out hydrogeologic process-response relationships from commonly collected ground-water data. It has been applied to the Floridan aquifer system by Lawrence and Upchurch (1976; 1982), Ceryak (1977), Dalton (1978), and Dalton and Upchurch (1978). Factor analysis combines variables that are correlated into similarity clusters in order of the amount of variance explained. Using the SYSTAT[®] software, principal components analysis (PCA), a form of factor analysis using Varimax rotation, was performed on 20 chemical analytes from the 24 well samples (Figure 1).

The PCA combines chemical variables into groups, or factors, each representing a statistically independent chemical process (Lawrence and Upchurch, 1982). Factor loadings are calculated for each chemical variable. The loadings show how well each analyte is associated with each factor. Most chemical variables are specific to a single process, or factor, though a chemical variable may load heavily on more than one factor if it is important in more than one process. The PCA also calculates a factor score for each sample, which reflects the importance of a given factor at that sample site. Extreme negative scores (<-1) reflect water essentially unaffected by a given process, positive scores ($>+1$) reflect water most affected, and near zero scores reflect water affected to an “average degree” by the chemical process or factor. The factor scores can be contoured on maps to evaluate the spatial importance of the chemical processes represented by each factor.

The final PCA revealed five chemically distinct, but not mutually exclusive, sets of chemical processes. These five factors accounted for 83.6 percent of the total variability present in the water sample data. Table 1 shows the factor loadings for the 20 chemical variables grouped by factor or process. Figures 11 through 15 show contour maps of factor scores for each factor identified.

Note in Table 1 that grouping of analytes often reflect intuitive relationships. For example, sodium, chloride, and nitrate group in Factor III is interpreted as reflecting a “sea water” aerosol component in rainfall (Upchurch, 1992). These groupings are discussed below.

Factor I includes the variables’ alkalinity, specific conductance, calcium, total dissolved solids (TDS), and -pH. The negative sign on pH indicates a negative correlation with the other analytes. Factor I is, therefore, a lithologically controlled factor reflecting the dissolution of carbonate minerals in the Floridan aquifer. Figure 11 shows the spatial distribution of factor scores for Factor I. Low Factor I scores indicate areas where conduit flow is prevalent or where dissolution of limestone has not reached a maximum. Factor I scores are low over much of the springshed, suggesting that the dissolution of limestone in this region does not reach its maximum potential before the water is discharged at the spring. High Factor I scores may indicate sluggish flow areas of the aquifer where there is a longer residence time and, therefore, more dissolution of the formation. One isolated area of high Factor I scores can be seen around the spring on Figure 11. This may represent upconing of deeper water and/or the end result of dissolution of limestone along each flow pattern.

Factor II includes the analytes total organic carbon (TOC), potassium, -temperature, total kjeldahl nitrogen (TKN), and dissolved organic carbon (DOC). These constituents result from the recharge of relatively cool, organic-rich ground water to the Floridan aquifer. This factor is interpreted as representing soil-water reactions during recharge. Therefore, Factor II is recharge controlled. The spatial distribution of Factor II scores is shown in Figure 12. Factor II scores are generally between 0 and 1 throughout the study area, suggesting that this factor, while locally significant, may be of low importance regionally.

Factor III includes chloride, nitrate, and sodium with minor sulfate and dissolved oxygen (DO). These variables reflect rapid recharge of marine aerosols (Upchurch 1992) that have been enriched in nitrate and, possibly, soil amendments from anthropogenic sources. Factor III, therefore, represents a pathway/origin factor (Lawrence and Upchurch, 1978). Factor III scores are low throughout much of the springshed (Figure 13). However, high Factor III scores are found near the spring in a region that contains abundant row crop land uses. The high Factor III scores indicate areas where ground water, immediately upgradient of the spring, is enriched in nitrate. Additional monitoring points in this region would provide for better delineation of this particular factor.

Factor IV includes magnesium, fluoride, and -D.O. These constituents, especially magnesium and fluoride, result from the weathering of carbonate-fluorapatite and magnesium-rich minerals such as dolomite and/or smectitic clays in the Hawthorn Group. The negative correlation of D.O. in this factor suggests low D.O. as a result of water moving through Hawthorn sediments. Therefore, Factor III is lithologically controlled. In the Madison Blue Spring springshed, however, the Hawthorn Group has been largely removed by erosion and may only be found in isolated outliers and residua in deep karst features or numerous sinkhole features (Figure 7). This explains why low Factor IV scores are found throughout the Madison Blue springshed (Figure 14).

Factor V includes iron, sulfate, turbidity, and phosphorus. These variables reflect the chemical maturity of Floridan aquifer ground water. Factor V, therefore, represents a pathway/origin factor (Lawrence and Upchurch, 1978). Factor V scores are low throughout much of the springshed reflecting the low concentrations of these analytes in ground water in the aquifer. Near the spring, however, Factor III scores are highest ($>+1$), suggesting that ground water enriched in iron with minor sulfate and phosphorus is found nearest the spring (Figure 15).

Variable	Units	Range	Factor Loadings				
			I	II	III	IV	V
FACTOR I							
Alkalinity	mg/l	83.6-299	0.946	-0.093	-0.077	-0.207	0.169
TDS	mg/l	123-338	0.902	-0.043	0.205	0.019	0.190
Sp. Conductance	µS/cm	204-612	0.895	-0.104	0.253	-0.201	0.244
pH	s.u.	6.92-7.63	-0.890	0.107	0.272	0.026	-0.017
Calcium	mg/l	34-111	0.862	-0.092	0.091	-0.429	0.197
FACTOR II							
Total Organic Carbon (TOC)	mg/l	0.64-6.08	-0.078	0.886	-0.072	0.101	0.133
Temperature	C	17.5-22.2	0.177	-0.828	-0.286	0.173	0.152
Total Kjeldahl Nitrogen (TKN)	mg/l	0.11-0.29	-0.057	0.826	-0.204	-0.148	0.232
Potassium	mg/l	0.18-1.56	-0.150	0.819	0.140	-0.406	-0.037
Dissolved Organic Carbon (DOC)	mg/l	0.85-8.17	0.072	0.773	0.321	0.404	-0.040
FACTOR III							
Chloride	mg/l	3.2-11.5	0.157	0.281	0.846	0.097	-0.121
Nitrate	mg/l	0.00-9.49	-0.281	-0.116	0.836	0.121	-0.041
Sodium	mg/l	2.57-7.37	0.314	0.207	0.775	-0.240	0.141
FACTOR IV							
Magnesium	mg/l	1.48-12.2	-0.256	-0.129	0.162	0.901	-0.105
Fluoride	mg/l	0.04-0.18	-0.319	-0.170	-0.081	0.802	-0.098
Dissolved Oxygen (DO)	mg/l	0.06-7.74	-0.091	-0.383	0.478	-0.578	-0.175
FACTOR V							
Iron	mg/l	0.01-2.13	0.188	0.174	-0.193	0.117	0.824
Sulfate	mg/l	0.54-15.4	0.097	-0.099	0.488	-0.029	0.693
Turbidity	mg/l	0.14-19.1	0.423	0.047	-0.070	-0.436	0.610
Phosphorus	mg/l	0.05-0.72	0.340	0.059	-0.074	-0.375	0.536
PERCENT OF TOTAL VARIANCE EXPLAINED			24.1	19.2	15.0	14.4	10.8

Table 1. Factor loadings for the 20 chemical variables used in the factor analysis. Bold factor loadings reflect the variables most closely associated within each factor. Negative factor loadings suggest an inverse relationship between a particular variable and other variables within the factor.

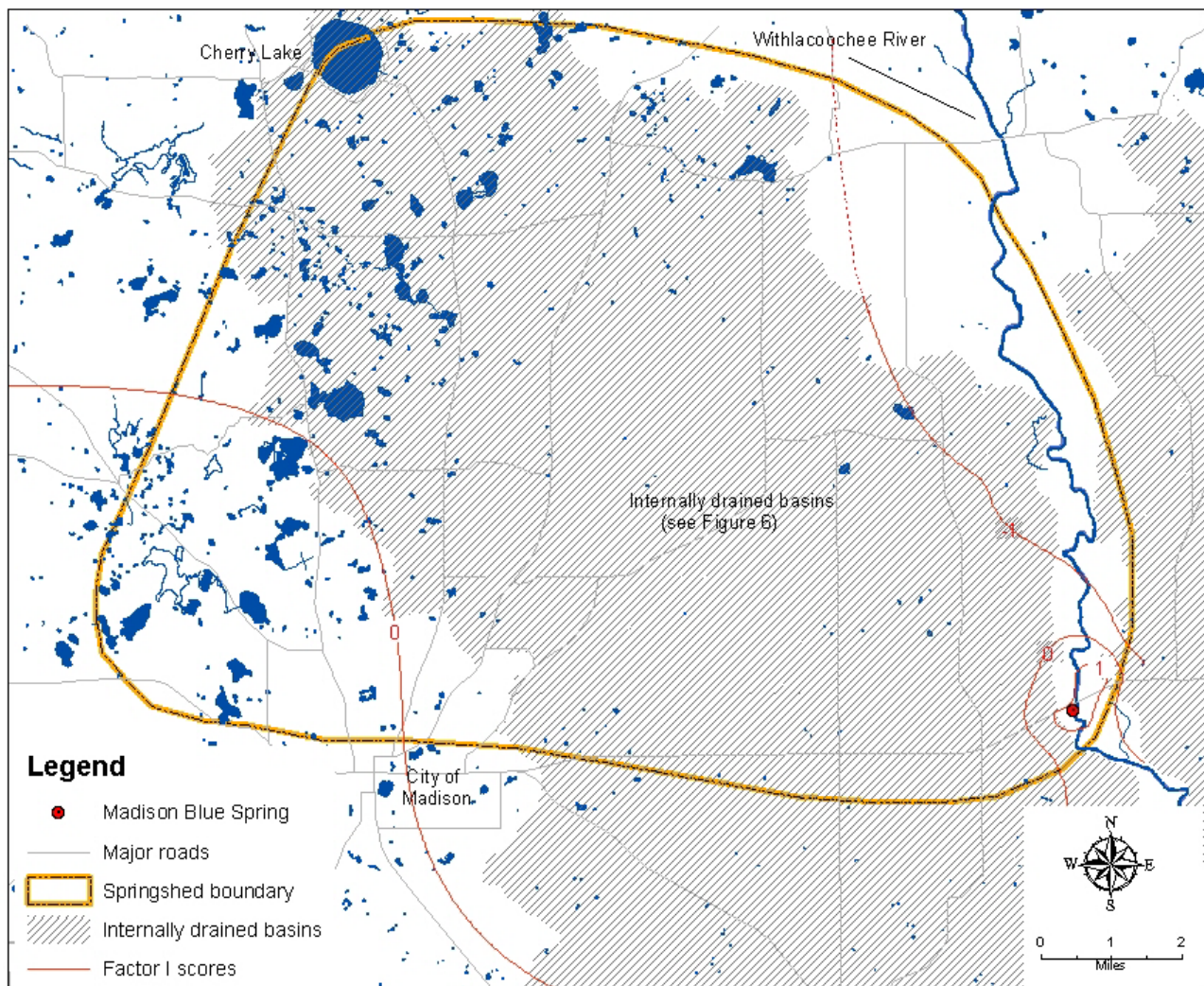


Figure 11. Factor I (alkalinity, sp. conductance, calcium, TDS, and -pH) scores in the Madison Blue Spring study area.

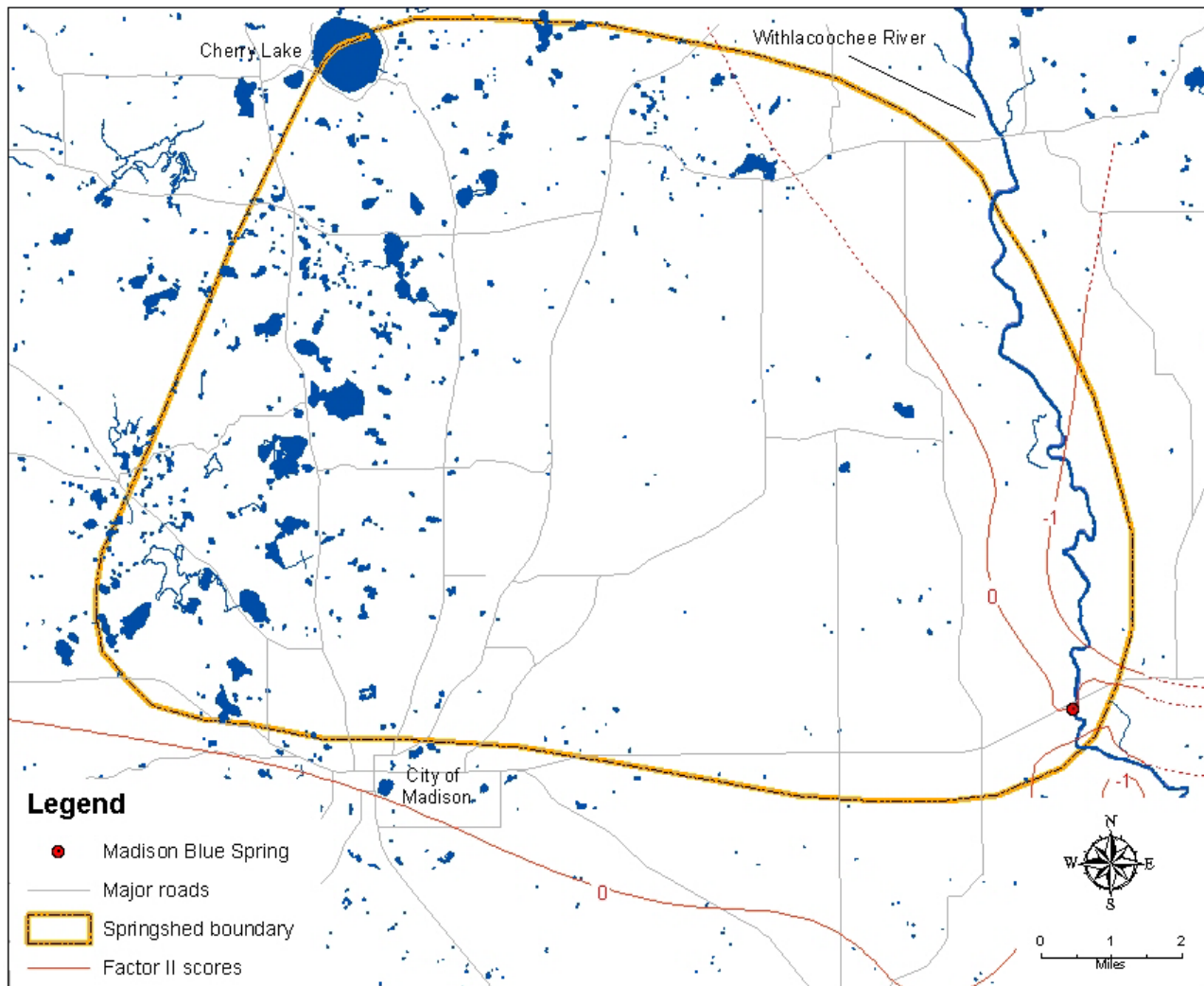


Figure 12. Factor II (TOC, potassium, -temperature, TKN, and DOC) scores in the Madison Blue Spring study area.

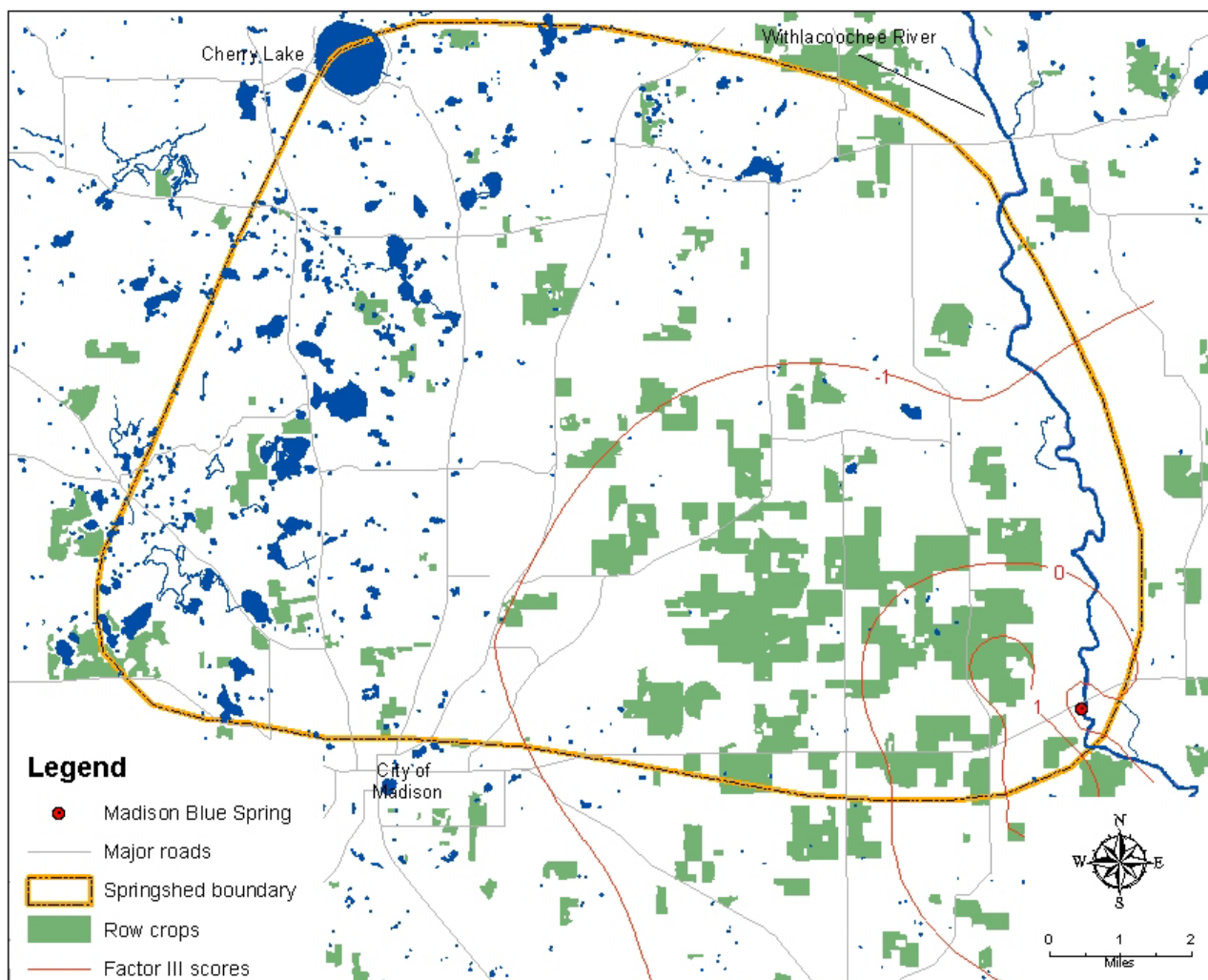


Figure 13. Factor III (chloride, nitrate, sodium, sulfate, and DO) scores in the Madison Blue Spring study area.

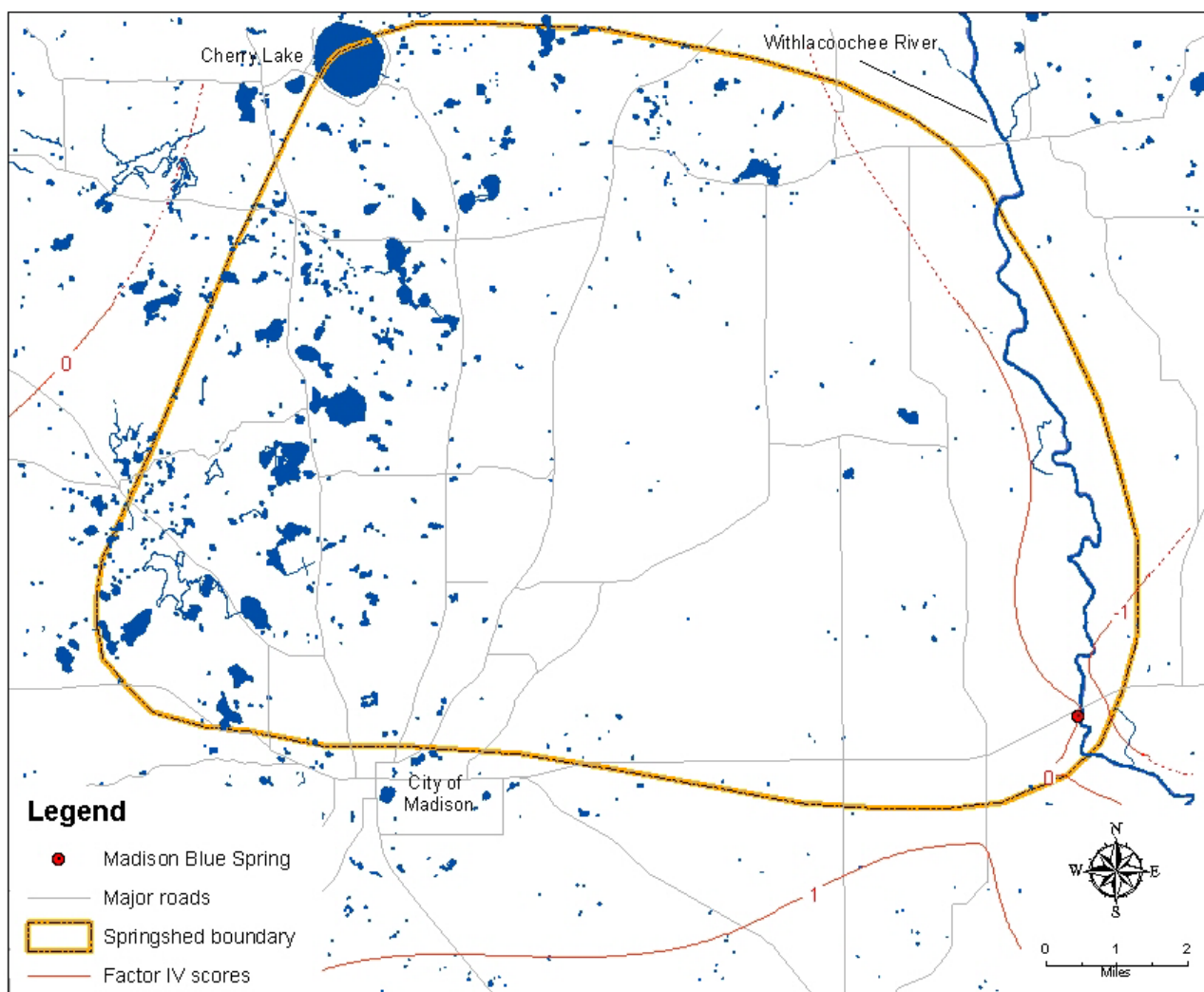


Figure 14. Factor IV (magnesium, fluoride, and -DO) scores in the Madison Blue Spring study area.

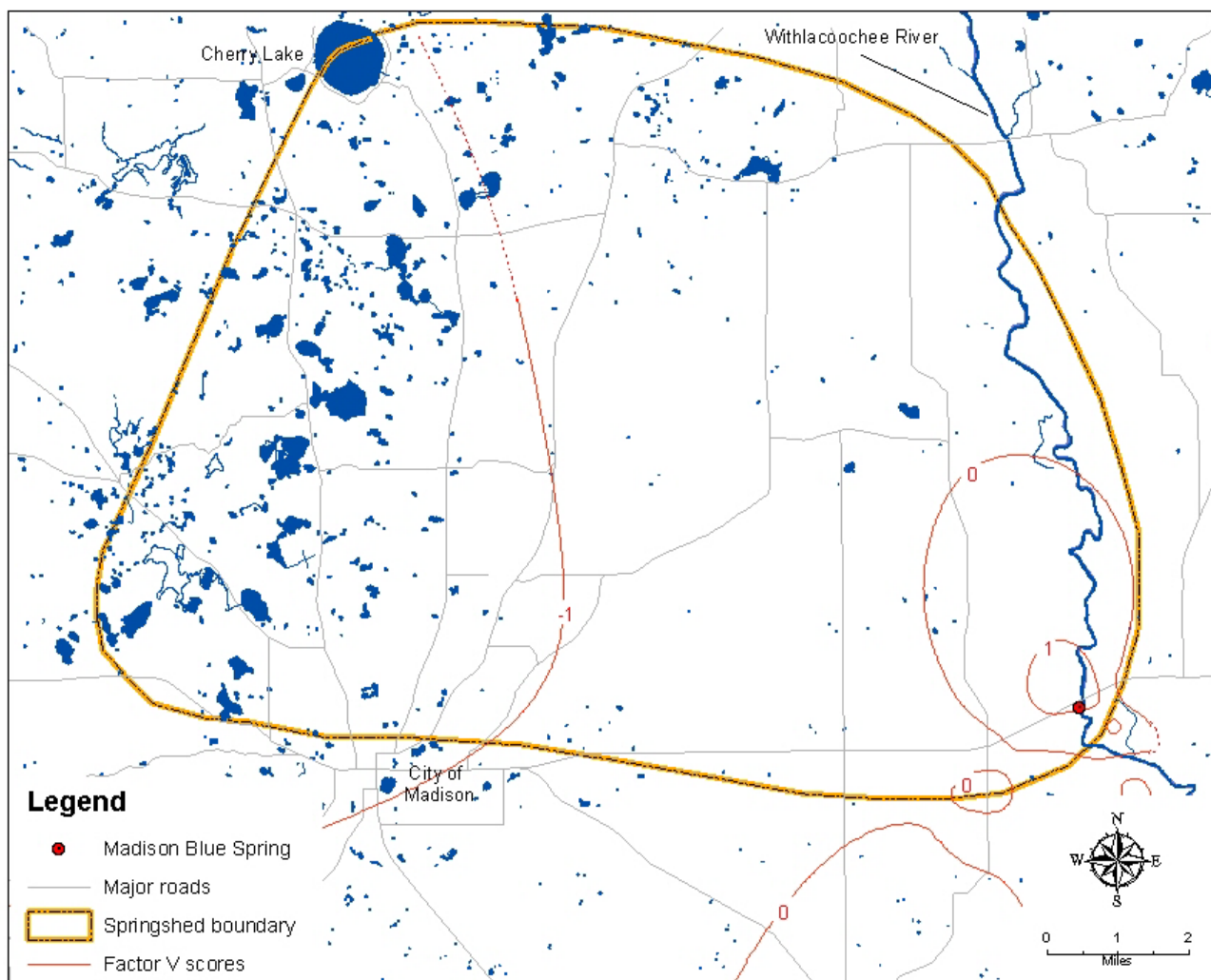


Figure 15. Factor V (iron, sulfate, turbidity, and phosphorus) scores in the Madison Blue Spring study area.

Hydrochemical Facies Analysis

Hydrochemical facies analysis (Upchurch, 1992) is an excellent way to place a series of water-quality analyses into a spatial context. The analysis depends on pattern recognition techniques. In order to place the chemical data into water-quality domains and attempt to recognize the spatial patterns of geochemical processes, a hierarchical analysis was performed using the SYSTAT[®] software. Initially, this analysis indicated that four major water-quality domains were present within the water-quality data set. Two of the domains, however, were combined due to their hierarchical similarity and spatial distribution.

Using Stanford Graphics[®] software, individual samples are plotted on “star” diagrams, which show the relative proportions of ions in the sample. Star diagrams were used in preference to other pattern-recognition methods (i.e., Stiff diagrams) because star diagrams allow use of non-standard combinations of chemicals and minor constituents can be emphasized. The analytes were selected for use in the star diagrams based on the PCA; one analyte was chosen to represent each of the five factors.

Figure 16 displays the star diagrams for each of the three major water-quality groups in the study area. It is important to remember when looking at the star diagrams in Figure 16 that the length of each axis corresponds to the *relative* concentration of a major constituent in relation to other samples, not other constituents within the same sample. The higher the concentration relative to other samples, the longer the axis. If two or more domains have similar concentrations of the major constituents, the star diagrams will be similar.

The star diagrams in Figure 16, therefore, were chosen to illustrate a representative picture of the types of patterns present within each of the water-quality domains. Table 2 provides a summary of the characteristics of each domain or water type.

The following discussion describes the process used to delineate the most significant ground-water quality domains within the study area. The establishment of water-quality domains will help demonstrate how water quality differs across the region and help identify source areas for ground water discharging from Madison Blue Spring.

Constituent	Group 1	Group 2	Group 3
	Domain I – Recharge	Domain II – Highlands	Domain III – Regional Discharge
Temp (C)	21.4	21.3	21.5
Sp. Cond (µS/cm)	311	269	448
pH (s.u.)	7.38	7.22	7.08
DO	3.3	1.4	4.4
Alkalinity	125	142	213
Calcium	43.9	41.4	80.2
Chloride	7.8	4.0	6.0
DOC	3.0	1.8	2.0
Iron	0.08	0.05	0.20
Fluoride	0.14	0.16	0.08
Potassium	0.38	0.39	0.51
Magnesium	8.9	7.3	3.0
Sodium	5.0	2.7	4.5
Nitrate+Nitrite	1.88	0.19	0.40
Phosphorus	0.06	0.05	0.14
Sulfate	11.5	3.7	9.4
TDS	174	159	240
TKN	0.11	0.11	0.16
TOC	1.23	0.97	1.37
Turbidity	0.65	0.15	5.35

Table 2. Median analyte concentrations for the four major water-quality domains in the Madison Blue Spring study area. Concentrations are in mg/l unless otherwise noted.

General Characteristics of Water-Quality Groups



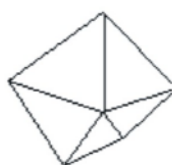
Group 1

Group 1 represents ground water that has recently recharged the aquifer. These samples typically contain relatively low concentrations of major ions and TDS. Group 1 samples typically contain elevated levels of DO and low concentrations of TKN. Group 1 samples are representative of geochemical Domain I - the Recharge Domain.



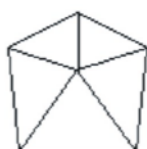
Group 2

Group 2 represents ground-water samples that are enriched in magnesium and fluoride. These constituents reflect the weathering of Hawthorn sediments fluorapatite. The samples contained in Group 2 typically display low levels of DO, sulfate, and TOC. Group 2 samples are representative of geochemical Domain II - the Highlands Domain.



Group 3

Group 3 represents ground-water samples that typically contain relatively high levels of iron, calcium, alkalinity, and TDS because of dissolution of limestone and dolostone. These constituents reflect the chemical maturity of Group 3 ground water. Group 3 samples are representative of geochemical Domain III - Regional Discharge Domain.



Madison Blue Spring

Comparing the star diagram of Madison Blue Spring to that of the star diagrams for the water-quality groups above shows that Madison Blue Spring most closely matches the water-quality pattern of Group 1. This similarity suggests that the spring source area lies in regions represented by Group 1 - the Recharge Domain.

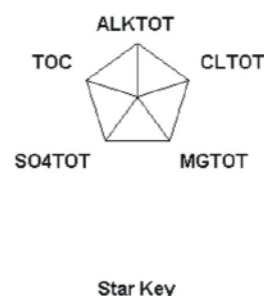


Figure 16. Star diagrams for representative water types in the Madison Blue Spring study area. The star diagram for Madison Blue Spring is also shown.

Domain I: Recharge Domain

Domain I, the Recharge Domain, covers much of the eastern half of the springshed (Figure 17), where low-permeability Hawthorn Group and Miccosukee sediments are thin to non-existent (Figure 8), sinkholes are abundant (Figure 7), and recharge to the Floridan aquifer is high (Figure 9). Geochemically, the Recharge Domain is identified by lower median concentrations of alkalinity, potassium, phosphorus, and TKN (Table 2). The Recharge Domain is also identified by higher median nitrate concentrations (1.88 mg/l), pH, and sulfate. The median nitrate concentration in this domain is significantly elevated above background concentrations of nitrate in the Floridan aquifer (<0.01 mg/l; Upchurch 1992).

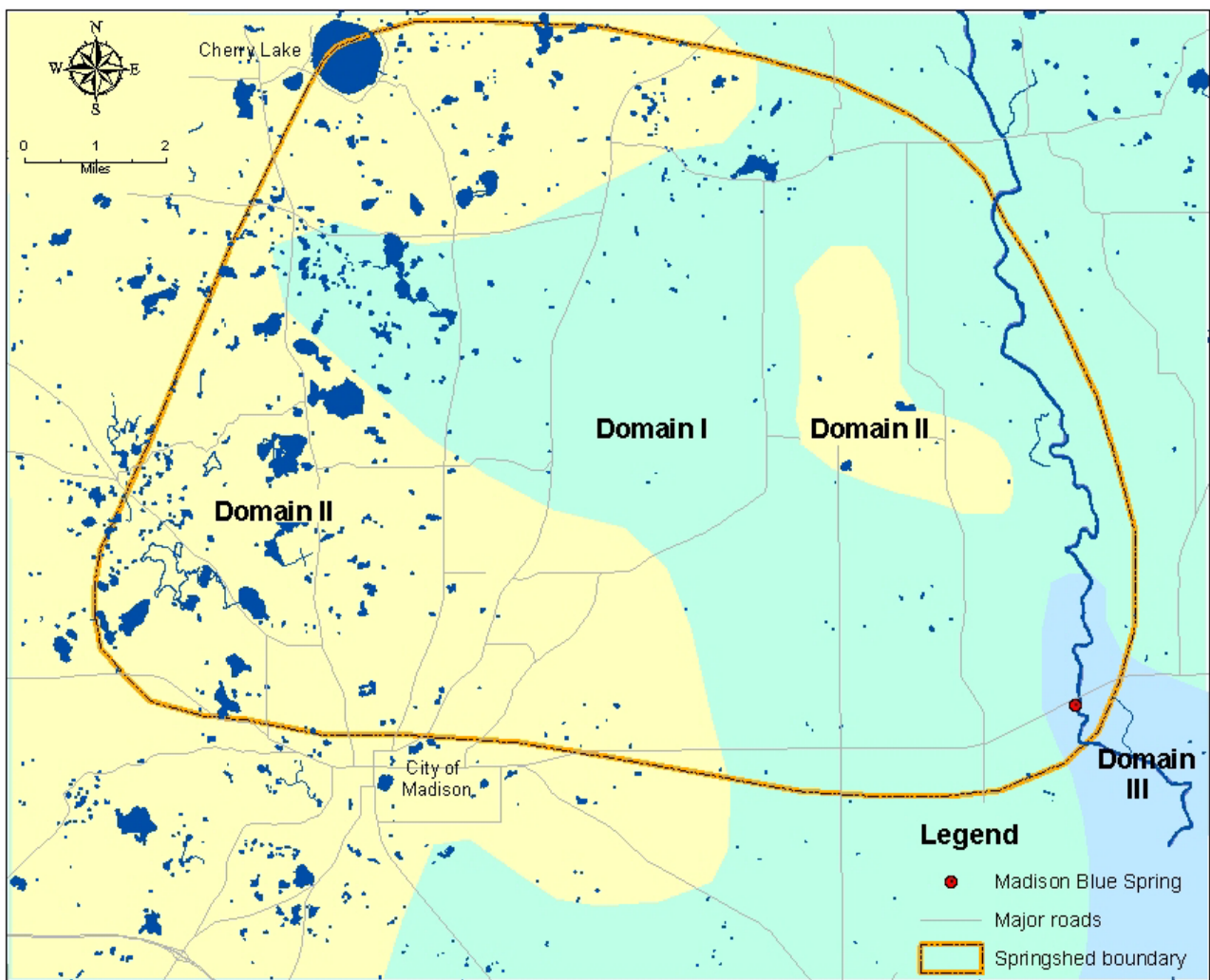


Figure 17. Spatial distribution of water-quality domains within the Madison Blue Spring study area.

Domain II: Highlands Domain

Domain II, the Highlands Domain, covers much of the western half of the springshed (Figure 17). This domain is characterized by the widespread occurrence of the Miocene Hawthorn Group and Pliocene Miccosukee Formation, which caps the highest elevations in the study area (Figure 8). Significant sinkhole features are common to this domain (Figure 7) and allow for moderate recharge to the Floridan aquifer (Figure 9). Geochemically, the Highland Domain is identified by elevated median concentrations of fluoride and magnesium (Table 2). Elevated concentrations of these constituents reflect recharge water that has come into contact with carbonate-fluorapatite and the influence of Hawthorn Group sediments on water quality in the Floridan aquifer (Lawrence and Upchurch, 1976; Upchurch, 1990). The Highlands Domain is also identified by low median concentrations of nitrate, DO, sulfate, TOC, and TDS (Table 2). Low concentrations of DO, sulfate, and nitrate suggest biologic uptake in chemically reduced ground-water recharge.

Domain III: Regional Discharge Domain

Domain III is found in the southeastern portion of the springshed along the Suwannee River and in areas near the Withlacoochee River and Madison Blue Spring (Figure 17). This domain is characterized by regional discharge of ground water. This regional discharge of ground water to the surface is identified by elevated median concentrations of TDS, iron, calcium, and alkalinity (Table 2). These constituents reflect the influence of chemically mature ground water and upward movement of ground water from deeper flow paths in the Floridan aquifer.

DELINEATION OF SPRING-WATER SOURCE AREAS

Water-quality data collected in the study area suggest that the regional ground-water system and Madison Blue Spring have very similar chemical compositions. However, there are subtle chemical differences between many of the samples that enable one to distinguish chemical patterns unique to groups of samples across the region. These patterns indicate source areas that yield chemical fingerprints that can be used to identify spring-water source areas.

Because the ground water discharging from Madison Blue Spring differs slightly from regional ground water, the chemistry of the spring water was compared to the chemistry of the three water-quality domains described above. This method was particularly useful in determining the source areas for ground water discharging from Rainbow Springs (Jones and others, 1996), Crystal Springs (Champion and DeWitt, 2000), and Ichetucknee Springs (Upchurch and Champion, 2003b). Figure 16 compares the star diagrams for the spring and the water-quality domains described above.

A comparison of the star diagrams indicates that Domain I, the Recharge Domain, is supplying most of the water to Madison Blue Spring. The high recharge rate in Domain I has produced ground water with very low total dissolved solids, TOC, and TKN. The match of Madison Blue Spring water with Domain I water is consistent with the relatively young age of water as determined by Katz and others (1999).

Using this domain strategy, the elevated levels of nitrate in Madison Blue Spring most likely originate in recharge areas to the immediate northwest of the spring. Nitrate concentrations in Domain I are elevated above background levels in the Floridan aquifer and, in several wells, exceed 3 mg/l. The levels of nitrate in the Madison Blue Spring most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the spring from adjacent areas, such as Domain II.

SUMMARY AND CONCLUSIONS

The Floridan aquifer in the study area was divided into three water-quality domains, with each possessing certain chemical characteristics that reflect different geochemical processes, water types, and hydrochemical facies within the aquifer. Differences in water quality across the region are subtle and appear to be related to the presence or absence of confining layers, sinkhole distribution, land use, and recharge to and discharge from the Floridan aquifer. Each of the three domains is summarized below.

Domain I: Recharge Domain

Domain I, the Recharge Domain, covers much of the eastern half of the springshed, where low-permeability Hawthorn Group and Miccosukee sediments are thin to non-existent, sinkholes are abundant, and recharge to the Floridan aquifer is high. Geochemically, the Recharge Domain is identified by lower median concentrations of alkalinity, potassium, phosphorus, and TKN. The Recharge Domain is also identified by higher median nitrate concentrations (1.88 mg/l), pH, and sulfate. The median nitrate concentration in this domain is significantly elevated above background concentrations of nitrate in the Floridan aquifer (<0.01 mg/l; Upchurch 1992).

Domain II: Highlands Domain

Domain II, the Highlands Domain, covers much of the western half of the springshed. This domain is characterized by the widespread distribution of the Miocene Hawthorn Group and Pliocene Miccosukee Formation, which caps the highest elevations in the study area. Significant sinkhole features are common in this domain and allow for moderate recharge to the Floridan aquifer. Geochemically, the Highlands Domain is identified by elevated median concentrations of fluoride and magnesium (Table 2). Elevated concentrations of these constituents reflect recharge that has come into contact with Hawthorn Group sediments (Lawrence and Upchurch, 1976; Upchurch, 1990). The Highlands Domain is also identified by low median concentrations of nitrate, DO, sulfate, TOC, and TDS (Table 2). Low concentrations DO, sulfate, and nitrate suggest chemically reduced ground water.

Domain III: Regional Discharge Domain

Domain III is found in the southeastern portion of the springshed along the Suwannee River and in areas near the Withlacoochee River and Madison Blue Spring. This domain is characterized by regional discharge of ground water to the rivers. This regional discharge of ground water to the surface is identified by elevated median concentrations of TDS, iron, calcium, and alkalinity (Table 2). These constituents reflect the influence of chemically mature ground water and upward movement of ground water from deeper flow paths in the Floridan aquifer.

Source of Water in Madison Blue Spring

A comparison of the star diagrams indicates that Domain I, the Recharge Domain, is supplying most of the water to Madison Blue Spring. The high recharge rate in Domain I has produced ground water with very low total dissolved solids, TOC, and TKN.

Using this domain strategy, the elevated levels of nitrate in Madison Blue Spring most likely originate in recharge areas to the immediate northwest of the spring. Nitrate concentrations in Domain I are elevated above background levels in the Floridan aquifer and, in several wells, exceeds 3 mg/l. The levels of nitrate in the Madison Blue Spring most likely result from the mixing of this high-nitrate ground water with low-nitrate ground water converging on the spring from adjacent areas, such as Domain II.

Monitoring Recommendations

Regional ground-water investigations have shown that nitrate concentrations, such as those at Madison Blue Spring, have gradually increased over the last several decades (Katz and others, 1999). The agricultural community is working with the District and other agencies to implement best management practices and reverse the upward trend in nitrate concentrations. In addition, the District is in the process of adopting minimum flow and levels (MFLs) for the Spring. The Madison Blue Spring MFL will assist in maintaining water quality and discharge from the Spring. Water-quality trends in large spring systems are slow to change.

Finally, best management practices (BMPs) should be implemented to reduce the use of fertilizer near the spring. This is particularly important given the proximity of agricultural land uses to the spring. BMPs for turf fertilization in residential and golf course areas, as well as septic and centralized sewage disposal, will need to be addressed as commercial and residential development proceeds in the springshed. indicate that long-term monitoring is needed to detect any possible changes to water quality at the spring and to follow trends in nitrate concentrations. With an estimated long-term increase of 0.01 to 0.02 mg/l per year, it is likely that many years, if not decades, will be needed to monitor long-term water-quality trends at Madison Blue Spring and other springs in the region. The springs should be sampled at least twice a year to monitor intermediate- to long-term trends in water quality. This sampling program should include analyses for nutrients (e.g., nitrate), major ions (e.g., calcium), trace constituents (e.g., iron), and periodically for nitrogen isotopes to determine the effects of changing land use and to determine the effectiveness of remedial efforts to protect water quality at the springs.

Given the region's karst geology, vulnerability to ground-water contamination, and increasing population, the siting, construction, and monitoring of waste disposal facilities, such as wastewater treatment plants and septic tanks, should be reviewed and planned carefully. Storm water should be properly stored and treated to prevent ground-water contamination. In addition, the importance of nitrate sources such as residential and golf course turf fertilization, septic-tank effluent, and sewage disposal will increase as residential and commercial development proceeds in the region.

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