



Springsheds of the Santa Fe River

Prepared for

Alachua County Board of County Commissioners
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Endorsement

This report was submitted to the Alachua County Environmental Protection Department by SDII Global Corporation under Purchase Order 071623. All work was performed under the supervision of the undersigned.

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Cover Photograph

Poe Spring, Alachua County, Florida, in November, 2006. The view is looking downstream from the spring pool toward the Santa Fe River.

EXECUTIVE SUMMARY

In 2006 Alachua County, Florida, retained SDII Global Corporation to delineate springsheds for all known springs on the Santa Fe River. The springshed delineation was undertaken in two phases. Three major tasks were undertaken as part of Phase I. These were: (1) a literature review to identify previous investigations that assist in understanding springshed extents, (2) delineation of springshed using regional potentials in the upper Floridan aquifer, and (3) use of U.S. Geological Survey and Suwannee River Water Management District groundwater flow models to estimate springsheds and capture zones. When it was determined that delineation of springsheds in the Newberry Plain area of Alachua and Gilchrist counties was problematic, Alachua County agreed to Phase II, which involved adding more groundwater monitoring points and then re-contouring the Floridan aquifer potentiometric surface at a higher resolution. The results of these two phases are combined in this report.

In Phase I, the springsheds of clusters of springs were delineated with existing potentiometric surface data. The low density of existing monitoring wells and dominance of conduit flow to the springs limited delineation of springsheds for specific springs. The springsheds generally extend from the Cody Scarp to clusters of springs in a manner that is consistent with dye tracing, fingerprinting using groundwater water-quality data, cave mapping, and other available data. The only major issue is the springshed of the springs herein called the Poe-July Spring cluster. This spring cluster appears to have an unrealistically large springshed based on the existing data.

Groundwater flow modeling with the Suwannee River Water Management District's model (Schneider et al., 2008) was successful in delineating general springsheds when the model was run to steady state. This is important information because this steady-state model is utilized by the District to evaluate proposed groundwater withdrawals for permitting.

The USGS "Megamodel" (Sepúlveda, 2002) was designed to explore the flow relationships of the Intermediate and upper Floridan aquifer. The model was not serviceable for use in characterization of springsheds or spring capture zones.

It is clear that groundwater flow modeling has limitations as far as characterization of springshed capture zones based on flow times.

Phase I included a recommendation for additional monitoring in several springsheds where data are lacking or sparse. In addition, development of a sub-regional flow groundwater model and additional dye tracing and/or water-quality fingerprinting were suggested to better delineate springsheds of concern.

Phase II included refinement of the September 2007 Floridan aquifer potentiometric surface through addition of 205 monitoring points. These monitoring points consisted primarily of domestic and monitoring wells, but stage data from selected springs and river gages on the Santa Fe River were included. Most of these data were obtained by the Alachua County Environmental Protection Department, with additional provided by the District.

Geostatistical analysis of these data indicates that the data density of this new monitoring network is sufficient for springshed delineation. A Floridan aquifer potentiometric surface map was prepared from the September 2007 data utilizing a 1-foot contour interval. The results of the analysis allow for higher resolution of major springsheds. The springs that drain the Newberry Plain generally do not have distinctive springsheds, however. This result is consistent with cave mapping, dye tracing, and other investigations that indicate complex overlaps of spring flow systems.

The final delineations suggest that springsheds for the Santa Fe Rise, Hornsby Spring, and Poe Spring can be discretized for management purposes. The springsheds for Blue, Ginnie, and other springs that drain the Newberry Plain cannot be easily differentiated, and it is recommended that the Newberry Plain be treated as a single springshed with multiple springs.

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INTRODUCTION

Alachua County has been involved for several years in developing an understanding of the springsheds¹ along the Santa Fe River (Figure 1). This is partly because of concerns about rising nutrient levels discharging from many of the springs and also because of the County's awareness of the need for protection of the springs as the county develops. Because of this concern, Alachua County retained SDII Global Corporation (SDII) to delineate springsheds along the Santa Fe River, including springsheds within and adjacent to the county.

Project Phases

This report presents the results of delineation of springsheds along the Santa Fe River system (Figure 1). The report is organized by project phase.

Phase I

Phase I, which was completed in 2007, included delineation of springsheds based on existing data. Potentiometric surface data were sparse in many areas, and the delineation resulted in broad delineation with little information for separating the details of each springshed.

Also in Phase I, two groundwater flow models were utilized to delineate springsheds by inverse particle tracking. The groundwater flow model developed by the U.S. Geological Survey (USGS; Sepúlveda, 2002) was found to be unsuitable for springshed delineation because Layer 1, the surficial aquifer layer, was constructed in the model as a constant head source of water to the underlying model layers. The Suwannee River Water Management District (District) groundwater flow model (Schneider et al., 2008) was constructed as a fully three-dimensional model with many specified springs and swallets. That model was better able to identify possible springsheds, but the swallets in the model limited the predicted extents of spring recharge areas to some extent.

When Phase I was completed, it was recommended that additional Floridan aquifer potentiometric surface data collected in Alachua and Gilchrist counties in order to develop a high-resolution potentiometric surface map for better delineation of springsheds in the Lower Santa Fe River system.

1. A springshed is the ground- and surface-water drainage area contributing groundwater to spring discharge (Copeland, 2003).

Phase II

Phase II of the study included an extensive data collection effort by Alachua County to develop the recommended, high-resolution potentiometric surface data. All totaled, Alachua County Environmental Protection Department staff obtained almost 200 data points, which included potentiometric data from wells in the Newberry Plain² as well as elsewhere in Alachua and Gilchrist counties and neighboring areas, stream stage data, and spring stage data. The District also provided data resulting in 205 data points for the high-resolution study. All data points were surveyed in and water level measurements were obtained for September, 2007, for study.

SDII utilized these data to perform a geostatistical analysis of the Floridan aquifer potentiometric data and develop a 1-foot contour map of the potentiometric surface for high-resolution delineation of the springsheds of the Santa Fe River system.

Scope of Work

Phase I

Three activities were undertaken as part of Phase I. These tasks are discussed individually below.

Task 1 – Literature Review: In order to assist in understanding how the springs function, the investigations conducted for springs on the Santa Fe through dye tracing, chemical fingerprinting, previous springshed delineations and other sources were reviewed and incorporated into the final report.

Task 2 – Delineate Springshed Extents and Capture Zones Using Existing Groundwater Flow Models: Groundwater flow models can be used with limitations to delineate springsheds and spring capture zones.² Since the existing models are finite difference models, they cannot account for conduit flow, an important process at the Santa Fe River Springs.

Two groundwater flow models were utilized with the intent of comparing them and delineating capture zones and springshed that encompass the results of both models. The models used were developed by the District (Schneider et al., 2008) and U.S. Geological

2. The Newberry Plain is that portion of the Western Valley (White, 1970) that includes the karst terrain located along the Alachua-Gilchrist County line. It extends northward from south of the town of Newberry to the Santa Fe River and from the Cody Scarp on the east to the Waccasassa Flats/Brooksville Ridge on the west (White, 1970).

Survey (Sepúlveda, 2002). Based on the two models, the areas that represent the estimated travel times to the springs were estimated to incorporate the areas delineated by the combined models.

Task 3 – Estimate Springsheds from Potentiometric Surface Maps: In addition to running the groundwater flow models to identify contribution areas to the springs, two potentiometric maps of the Upper Floridan aquifer were developed for estimation of springshed extents. The two maps represent May and September, 2000. The year 2000 was selected for analysis because

- The District's groundwater flow model (Schneider et al., 2008) was calibrated to conditions in 2000,
- 2000 was a dry year so the potentiometric surface should have maximum relief and enhance ability to identify springsheds, and
- Available Floridan aquifer potentiometric data were at a maximum.

Based on these two maps, the springsheds were delineated by identifying watershed divides within the groundwater system. A series of maps was produced to depict these springsheds and their spatial extents. Note that it was not possible to identify springsheds associated with specific springs in many cases. This is because of

- The high density of springs along the river,
- The fact that many springs share a springshed (they appear to function as large spring systems with multiple vents), and
- The relative scarcity of potentiometric data near the springs.

Where these conditions existed, the springs were treated as clusters (informal spring groups) and springsheds were delineated for the multiple springs.

Phase II

The scope of work for Phase II of this study consisted of two tasks (Tasks 4 and 5 to be consistent with Phase I terminology).

Task 4 – Potentiometric Data Collection: Task 4 included data collection for development of a high-resolution potentiometric map of the Floridan aquifer as recommended in Phase I. This task was completed by the Alachua County Environmental Protection Department and the data were transferred to SDII Global Corporation for processing.

Task 5 – Geostatistical Analysis of the High-Resolution Potentiometric Data: Task 5 included geostatistical analysis of the potentiometric data. A structural analysis was conducted to develop contouring “rules” and kriging was utilized to model the potentiometric surface and prepare uncertainty maps.

BACKGROUND HYDROGEOLOGY

It is important to understand several aspects of the regional geology before introducing the results of this study. The three most important hydrogeological concepts deal with the

- Regional physiography or landforms,
- Degree of confinement of the Upper Floridan aquifer, the principal water bearing aquifer of the area and the aquifer from which the majority of springs discharge water, and
- Regional, Upper Floridan aquifer potentiometric surface.

These are three aspects of the system are discussed below.

Regional Physiography

The study area includes nine physiographic provinces (Figure 2). The most important of these to the behavior of the Santa Fe River springs are the Gulf Coastal Lowlands, Bell Ridge and the associated Waccasassa Flats, High Springs Gap and the Brooksville Ridge, Western Valley (the Newberry Plain), and the Northern Highlands (White, 1970).

The Gulf Coastal Lowlands consist of an extensive karst plain that is characterized by numerous small sinkholes and internally drained basins. The bedrock consists of the Eocene Ocala Limestone and, locally, Oligocene Suwannee Limestone (Table 1). The Santa Fe River lies within this province from about the mouth of the Ichetucknee River westward.

Bell Ridge (Figure 2) is a dune ridge that bisects Gilchrist County from north to south. The ridge is perched on a feature known as the Waccasassa Flats. The Waccasassa Flats are underlain by sandy and clayey sediments that have significantly lower permeabilities than the surrounding limestone. As a result, Bell Ridge and the Waccasassa Flats are characterized by a perched water table and numerous swamps and wetlands.

The High Springs Gap is a low, gap between the Brooksville Ridge and the Northern Highlands within which the Santa Fe flows. The Brooksville Ridge is a complex of weathered,

sandy sediments and limestone that forms a topographic high. The Brooksville Ridge is dotted with large sinkholes and is a recharge area in many areas.

The Western Valley (Figure 2), or Newberry Plain, is a low valley that trends north to south between the Brooksville Ridge and Northern Highlands. The valley is a karst plain with sandy soils overlying limestone. Sinkholes are abundant.

Finally, the Northern Highlands (Figure 2) consist of a relatively high plateau characterized by little karst and thick sequences of low permeability, clay-rich sediments of the Miocene Hawthorn Group (Table 1). Note in Figure 3 that the Northern Highlands are also characterized by well-developed, dendritic stream systems. These streams exist because the underlying, low permeability sediments greatly retard recharge to the underlying limestone.

Table 1. Generalized lithostratigraphic column and aquifer systems in the Suwannee River Basin.

LITHOSTRATIGRAPHIC NOMENCLATURE			AQUIFER SYSTEM
SYSTEM	SERIES	FORMATION	
Quaternary	Holocene Pleistocene	Undifferentiated Sand	Surficial Aquifer
Tertiary	Pliocene	Undifferentiated Sand	Intermediate Aquifer and Confining Unit
	Miocene	Hawthorn Group St. Mark's Formation	
	Oligocene	Suwannee Limestone	Upper Floridan Aquifer
	Eocene	Ocala Limestone Avon Park Limestone Oldsmar Limestone	Mid-Floridan Confining Unit
	Paleocene	Cedar Keys Formation	Lower Floridan Aquifer

The boundary between the Northern Highlands and Western Valley/Gulf Coastal Lowlands (Figure 1) is known as the Cody Scarp (White, 1970; Upchurch and Lawrence, 1984; Upchurch, 2002, 2008). This scarp is characterized by numerous streams that sink into the subsurface by way of swallets as the streams flow off the Northern Highlands. The sinkholes of the Cody Scarp are large as a result of coalescing of smaller sinks in an area where the overlying cover is relatively thick (Upchurch, 2002, 2008). The Scarp is also an area where through-flowing streams, such as the Santa Fe River, go underground via swallets or siphons, and re-emerge through resurgences, or springs. Many of the springs of the Santa Fe System are siphon-to-resurgence systems that range in size up to the well-known Santa Fe Sink/Rise system near High Springs (Butt et al., 2007).

Degree of Confinement of the Upper Floridan Aquifer

The behavior of the upper Floridan aquifer (Table 1) is highly dependent on recharge. Where the aquifer is unconfined (Figure 3), the aquifer receives widespread recharge. In areas where the aquifer is confined, recharge is limited or insignificant. Unconfined areas are characterized by well-developed porosity and permeability as a result of initial, intergranular porosity of the limestone, fractures and karst conduits (Upchurch, 2002). Where the aquifer is well confined, the initial, intergranular, moldic, and fracture porosity exists, but the karst-related porosity is limited in extent (Upchurch, 2002; Budd and Vacher, 2004).

Within the study area, the recharge areas of the springs are limited to the unconfined or semi-confined areas depicted on Figure 3. Springsheds can be extended into the Northern Highlands where confinement is present, but the springs do not receive significant water from these regions. The water quality data from the upper Floridan aquifer strongly suggests that areas where the aquifer is confined under the Northern Highlands is old and that flow is sluggish to stagnant (Lawrence and Upchurch, 1976, 1982; Upchurch and Lawrence, 1984; Upchurch, 2002; Upchurch and Champion, 2003a,b).

Figure 4 is an example of a springshed delineated by the potentiometric surface. The Ichetucknee Spring Group springshed abuts the Cody Scarp and Northern Highlands to the north and east. The Cody Scarp is at the location where the green Upper Floridan aquifer potentiometric surface contour lines are close together along the upper and right hand side of the figure. Note that the springshed is drawn to extend into the Northern Highlands. This portion of the springshed is not part of the active flow system. For this reason, the springshed delineation lines in this report are terminated at the location where the Floridan becomes well confined and the flow system becomes significantly less dynamic.

Upper Floridan Aquifer Potentiometric Surface

Figure 5 depicts the Upper Floridan aquifer potentiometric surface as drawn by the USGS from potentiometric data from the year 2000. Contour interval is 10 feet. Note that the contour lines indicate a steep gradient under the Bell Ridge area (cf. Figure 2). The term Bell Ridge potentiometric high is used for this feature in the remainder of this report. This indicates that recharge is limited and that the permeability of the Floridan aquifer is also limited. As a result, water that was unable to recharge the aquifer runs off as streams and forms lakes and wetlands. The low permeability allows what little recharge there is to slowly drain down gradient. Springs that back up to the Bell Ridge potentiometric high receive little water from the area of the potentiometric high because of the low recharge and low permeability.

A similar situation exists on the margin of the Northern Highlands and to the west of the Suwannee River. While the gradient is not as steep, it is still steeper than in the Western Valley or Gulf Coastal Lowlands. The potentiometric-surface contour lines shown in Figures 4

and 5 illustrate the same phenomenon and reflect low recharge and low aquifer permeability relative to other areas of the study area.

Finally, note in Figure 5 the large areas in the Gulf Coastal Lowlands, Western Valley, and High Springs Gap areas where the potentiometric contours lines are widely spaced. These areas are characterized by low hydraulic gradient is low and high aquifer permeability. These conditions result in efficient draining of the aquifer after recharge. It is within these areas that springsheds are typically best developed in Florida.

PREVIOUS WORK

The Santa Fe River has been the focus of a number of studies that impact on springshed delineation. In 2006, Alachua County retained karst Environmental (Butt et al., 2006) to investigate hydrologic connections between Mill Creek Sink, near the city of Alachua, and Poe, Hornsby and Treehouse Springs. Studies, such as these, set the stage for initial attempts at springshed delineation.

Spring Characterization

At the present time, the District is undertaking a series of investigations that will lead to minimum flows and levels (MFLs) for the rivers and selected springs within the District. The basis document for the MFLs for the upper Santa Fe River³ has been completed (Water Resource Associates, 2006) and the District has adopted MFLs for the basin.

The District is also working on developing MFLs for the Lower Santa Fe River⁴ at the present time. The MFL report for the lower Santa Fe will include suggested MFLs for

- The Lower Santa Fe River,
- The Ichetucknee River,
- All first magnitude springs on the Lower Santa Fe and Ichetucknee Rivers, and
- All second magnitude springs that are on lands purchased by state and local

3. The Upper Santa Fe River basin extends upstream from the gage on the Santa Fe River at Worthington Springs.

4. The Lower Santa Fe River basin extends from the gage at Worthington Springs downstream through the Santa Fe Sink and Rise system to the mouth of the river where it flows into the Suwannee River. Olustee Creek and the Ichetucknee River and springs fall within the Lower Santa Fe River basin.

government for conservation purposes.

Therefore, MFLs will be developed for the Tree House Spring, Hornsby Spring, Blue Hole Spring, an unnamed spring designated COL 101974, Columbia Spring, Devils Ear in the Ginnie Spring group, Siphon Creek Rise, the Ichetucknee group of springs, July Spring, Poe Spring, Rum Island Spring, and the Santa Fe Rise. The process of developing MFLs for these springs will be greatly enhanced by Alachua County's springshed delineation efforts.

In addition to the studies associated with MFL development, there have been a number of site-specific investigations dealing with major springs along the Santa Fe River. These include dye studies (i.e., Karst Environmental Services, 1997; Butt, 2005) and chemical fingerprinting studies (Upchurch and Champion, 2003; Upchurch et al., 2004) associated with Ichetucknee River and springs, delineation of the Ichetucknee springshed (Upchurch and Champion, 2003), dye tracing associated with Hornsby and Poe Springs (Butt et al., 2006), and chemical fingerprinting and dye investigations associated with Ginnie Springs (Wilson and Skiles, 1988).

Kinkaid (1998) explored the sources of water in the Devil's Ear System (including July Spring) using water clarity, and ^{222}Rn , and $\delta^{18}\text{O}$ data. He concluded that as much as 62 percent of the water in the Devil's Ear system is river water, apparently related to an up-gradient swallet or siphon.

Butt et al. (2007) developed a summary of relationships of swallets and siphons in the Santa Fe River to Santa Fe basin springs. The results synthesis of cave mapping, dye tracing, and other data clearly indicate that many of the springs of the Santa Fe basin have significant surface-water sources. Those springs that are served by siphons or swallets in the river should have somewhat limited springsheds.

Upchurch et al. (2007a) investigated temporal trends in nitrate + nitrite concentrations in District springs. It was found that Santa Fe River springs reveal variable temporal trends of nitrate + nitrite concentrations as follows:

- Statistically significant trends with declining concentrations over time: 6 springs (i.e., Hornsby Spring and Poe Spring),
- Statistically significant trends of increasing concentrations with time: 2 springs (Ichetucknee Head Spring, Gilchrist Blue Spring), and
- Springs with no temporal trend in nitrate + nitrite either because of low sample size or lack of statistical significance: 9 springs.

Upchurch et al. (2007b) investigated the relationship of nitrate + nitrite to spring discharge. It was determined that the nitrate + nitrite concentrations are directly proportional to spring discharge. That is, nitrate concentrations are greatest when spring discharge is greatest. This

relationship suggested that nitrate + nitrite concentrations reflect nitrogen leaching and flushing processes in the springsheds and that MFLs that maximize flow will not assist in reducing nitrogen flux to the Santa Fe River. In order to investigate the nitrogen leaching/flushing process, Upchurch et al. (2007b) compared nitrate + nitrite concentrations to specific conductance in spring discharge. Springs where the two analytes were inversely correlated were found to reflect springsheds where a significant proportion of the groundwater was derived from surface water runoff and recharge through swallets and/or siphons in the Santa Fe River. Where the two analytes were positively correlated, the springshed was dominated by diffuse recharge and longer residence times in the aquifer. Examples of runoff-dominated springsheds include Columbia Spring, Santa Fe Spring, Poe Spring, and Hornsby Spring. Examples of diffuse recharge-dominated springsheds include Gilchrist Blue Spring, Devil's Ear Spring, Ginnie Spring, Blue Hole Spring, Devil's Eye Spring, and Grassy Hole Spring.

These investigations have all showed a close association between spring water quality and swallets and other recharge features associated with the nearby Cody Escarpment (Upchurch, 2002, 2007). The springsheds that correspond to these springs should reflect the sources of water, both in their physical locations and in terms of recharge basin size.

Springshed Delineation and Springshed Management

Springshed delineation as a management tool is just beginning in Florida. Because of the need to manage land use in order to protect water quality and flows to springs, there has been a concerted effort over the last few years to delineate springsheds and, in some cases, identify travel times of groundwater to springs. This section discusses some of these efforts.

Spring Catalogs

The first step in understanding how springs function and how to protect them is identification of the springs. This involves cataloging of springs and describing their properties.

Naming and cataloging of springs typically involves identification of any location where a significant amount of water issues from the ground. As such, some confusion has arisen as to what constitutes a spring and which springs have significant springsheds. For example, the springs of the Ichetucknee Spring Group (Ichetucknee Springs) predominantly drain groundwater from the upper Floridan aquifer. During large rainfall events and wet seasons, creeks, such as Rose and Cannon creeks, discharge to swallets and contribute to the spring discharge. In contrast, the Santa Fe Rise is a resurgence - a spring whose flow is largely surface water that has entered a cavern system in the aquifer through a swallet or siphon in a stream. Groundwater contributions to a resurgence may be minor compared to the volume of surface water that flows through the system. Copeland (2003) has discussed the different forms of "springs" in Florida and developed a nomenclature system for springs, which is followed in this report.

The first systematic description of Florida springs was by Ferguson et al. (1947). This report described selected springs throughout the state and present physical descriptions of the springs, discharge data, and water quality data. No attempt was made to identify groundwater contribution areas. Ferguson et al. (1949) discussed Poe and Ichetucknee [sic] springs and noted the presence of Blue Springs, Hornsby Springs, July Spring, Lilly Spring, and two small springs near High Springs.

Rosenau et al. (1977) revised the "Springs of Florida" and included additional springs in the statewide catalog. Spring-specific descriptions included the current status of each spring and a summary of discharge and water-quality data. Santa Fe River springs which were discussed included Hornsby, Poe, Blue, Ginnie, and the Ichetucknee Springs Group. Springs that were identified with coordinate locations included Allen, Betty, Columbia, Darby, Devil's Eye, Jamison, Jonathan, July, Lilly, Northbank, Rum Island, Wilson, and a series of small springs at High Springs.

Hornsby and Ceryak (1999) developed the most comprehensive inventory of springs on the Santa Fe. Their report includes location data, a brief discussion of the physical setting of each spring and recent flow and water quality data. In addition, an appendix summarizes much of the historical flow and water quality data for each spring and an appendix of presents available cave maps. The 26 named Santa Fe River springs that are included in Hornsby and Ceryak are Betty, Blue, Columbia, Hornsby, Darby, Deer, Devil's Ear, Devil's Eye, Dogwood, Ginnie, Ichetucknee Spring Group, Jamison, July, Lily, Little Devil, Oasis, Pickard, Poe, Rum Island, Santa Fe (COL61981), Santa Fe Rise, Sawdust, Sunbeam, Trail, Twin, and Wilson springs. Thirty five unnamed springs (ALA12971, ALA930971, ALA930972, COL928972, COL93071,

COL1012971, COL1012972, COL101974, COL428982, COL917971, COL928971, COL101971, COL101972, COL428981, COL101975, COL61982, GIL1012973, GIL729971, GIL107971, GIL107972, GIL1012971, GIL1012974, GIL99972, GIL99974, GIL917971, GIL928971, GIL101971, GIL1012972, GIL729972, GIL729973, GIL99971, GIL928972, SUW107971, SUW917971, and SUW17972) were also described. All together, 61 springs were identified in the Santa Fe River system. Many of these are small springs that cluster near larger, better known springs and should be considered part of a spring group (Figure 1).

Hornsby and Ceryak (1999) also identified five siphons (submerged swallets) in the river. These are important because they are sources for several of the springs, or resurgences.

Most recently, the Florida Springs Initiative has funded two, statewide springs assessments. The first (Scott et al., 2002) discussed first magnitude springs⁵, including Columbia, Devil's Ear, Hornsby, Ichetucknee Springs Group, Santa Fe River Rise, Siphon Creek Rise, and Treehouse Spring on the Santa Fe River system. Flow and water-quality data, detailed location maps, and photographs were included in the report. This was a preliminary document to the 2004 "Springs of Florida."

Scott et al.'s 2004 "Springs of Florida" report is an update of Bulletin 31 (revised) by Rosenau et al. (1977). It presents a detailed discussion of springshed delineation methods and reports on the current status of Florida's major springs. As with previous reports, water quality and discharge data are summarized. The Santa Fe River springs that were included include Columbia, Devil's Ear, Blue (Gilchrist Blue), Ginnie, Hornsby, Ichetucknee Springs Group, Poe, Santa Fe River Rise, Santa Fe, Siphon Creek Rise, Sun, and Treehouse springs.

The apparent growth in the number of springs identified within the Santa Fe River system over time is a result of increased awareness of the springs and their importance, development and commercialization of some springs, statutory requirements for stewardship of springs on public lands, and the effects of springs on property values. Small (third magnitude) springs are often discovered. Many of these small springs are ephemeral and develop and wane over short periods of time, primarily as a result of major rainfall events. Other springs and siphons are located within the river, so that are not normally observable. Most of these features were first discovered during the droughts of the late 1990s and mid-2000s, when the Santa Fe River was at record low stage.

5. First magnitude springs have an average discharge of 100 cubic feet per second (cfs) or more (Meinzer, 1927; Copeland, 2003). One hundred cfs equals 64.6 million gallons of water per day. Second magnitude springs discharge between 10 and 100 cfs.

Springshed Delineation

Springshed delineation is as much an art as a science. This is partly because the springsheds may vary in size with time and variations in recharge and partly because data are sparse and variations within datasets are sometimes subtle. The methods for springshed delineation are discussed in Scott et al. (2004), and include drawing spring basins from potentiometric surface maps and particle tracking with groundwater flow models.

Some examples of past springshed delineations include Jones and Upchurch (1993) at Lithia and Buckhorn springs in Hillsborough County, Florida; Jones and Upchurch (1994) at the Kings Bay springs in Citrus County, Florida; Jones et al. (1996) at Rainbow Springs in Marion County, Florida; Jones et al. (1997) at Homossassa, Chassahowitzka, Weeki Wachee, and Aripeka spring, Citrus and Hernando counties, Florida; Toth and Fortich (2002) at Wekiva Springs in Orange and Lake counties; Upchurch and Champion (2003) in the Ichetucknee Springs springshed in Suwannee and Columbia Counties; Barrios and Chelette (2004) at the Econfinia Creek springs in Washington and Bay counties, Florida; Barrios (2005) at the Choctawatchee River springs in Holmes, Walton, and Washington counties; Upchurch and Champion (2004) at four springs in the Suwannee River Water Management District; and Barrios (2006) at the St. Marks and Wakulla River springs in Leon and Wakulla counties.

Shoemaker et al. (2004) explored the use of groundwater flow models for identifying areas contributing to recharge to springs in north-central Florida. They present examples of the use of models for springshed delineation and time-based capture zones.

Water Resource Associates and SDII Global Corporation (2005) delineated the springsheds of Silver and Rainbow Springs for Marion County, Florida in order to assist in development of springs protection areas. They utilized two different flow models to identify the springshed for the two springs as areas within which groundwater could be expected to reach the springs in 10 and 100 years. These zones were identified as Spring Protection Zones for land-use planning and management.

Finally, there is an on-going effort to identify springsheds throughout the state. The Florida Geological Survey is actively pursuing this effort and is the repository for springshed delineation maps. Greenhalgh (2003) and Greenhalgh and Baker (2005) have produced statewide maps showing general springshed areas based on potentiometric surface data as a result of the Survey's efforts.

Spring Flow Path and Travel Time Mapping

Very little has been done as far as travel time and flow path mapping at springs in Florida. Modeling, chemical fingerprinting, dye tracing, and cave diving are the primary means by which flow paths and travel times can be evaluated. Much of this work has been completed relative to springs in the Santa Fe River basin. This section discusses these three methods in the context of nearby spring systems.

Modeling - Groundwater flow models have been used for many years to identify the extent of contributing areas to a spring and to delineate areas based on travel times to the spring. The method takes advantage of particle tracking, a numerical solution available in most finite-difference flow models. Particle tracking is essentially a bookkeeping process wherein a parcel of water is numerically tracked as it moves from cell to cell in the model. Particle tracking can be run forward and backward. In the forward mode, numerical “particles” are placed in a grid cells and the model is run to estimate where the parcels of water move. In the inverse mode, the particles are placed at the spring and the model is run backward to determine from whence the particles were derived. The latter mode is most commonly utilized and the model is run for specified time steps to identify where they particles would have been 2 years previously, 5 years previously, and so on in order to obtain travel times.

The problem with using flow models to predict capture zones in karst terrains is that the models cannot account for conduit flow. Therefore, the model results may greatly under estimate the capture zones associated with cavernous flow.

Shoemaker et al. (2004) utilized this method to compare springshed extents in north central Florida. The springsheds for Rainbow and Silver springs were also derived by this method (Water Resource Associates and SDII Global Corporation, 2005).

Water Resource Associates and SDII Global Corporation (2005) used two groundwater flow models to estimate the extents of areas with 10 and 100 year travel times to Silver and Rainbow springs. One model, the “Megamodel” of Sepúlveda (2002), was utilized to evaluate both springs. The St. Johns River Water Management District North-Central Model (Mutz and Dogan, 2004) was also utilized for Silver Springs travel time estimates. The Suwannee River Water Management District regional groundwater flow model (Schneider and Upchurch, 2006) was used to model travel times for Rainbow Springs. The maximum extents of the 10 and 100 year travel times as calculated by the various models were combined to obtain a maximum estimated capture zone extent for each spring.

Geochemical Fingerprinting – While geochemical fingerprinting cannot estimate travel times, it can be used in many cases to determine the spatial extent and origin of water traveling to a spring. Jones et al. (1996) used the method successfully to determine the segments of the

Rainbow Springs spring shed that were contributing water to the various spring vents within the spring group. A similar approach was utilized by Upchurch and Champion (2003) to identify source waters for the springs of the Ichetucknee Springs Group.

Chemical fingerprinting includes identification of suites of chemicals that differ from spring to spring. These suites are then matched to similar suites of analytes from groundwater in wells within the springshed.

Dye Tracing - Dye tracing involves introduction of an unique chemical to the groundwater via a well or sinkhole. Springs in the vicinity are then monitored for arrival of the tracer chemical at the spring. The time of arrival is used to estimate the travel time and concentration profile can be used to estimate the dilution and dispersion that has occurred along the flow path. Dye traces work best in conduit flow situations where dilution and dispersion are minimal and rock-water interactions are least likely to cause sorption of the dye, thus inhibiting flow through the aquifer.

Some of the best dye trace experiments in Florida have taken place within the Santa Fe River watershed. These include the traces reported by Karst Environmental Services (1997) and Butt and Murphy (2003), who proved connections between swallets and sinkholes near Lake City, Florida, with the Ichetucknee Spring Group springs. Travel times in this system were found to be up to one mile per day. Similar dye trace studies by Butt et al. (2006) have demonstrated connections between Mill Creek Sink in Alachua County and Hornsby and Treehouse Springs.

Butt (2005) has also demonstrated the utility of dye tracing to establish the connection between septic tanks within the Ichetucknee State Park to the springs, thus demonstrating a potential source of nitrate in the spring.

While dye tracing provides irrefutable evidence of a connection between springs and karst features and contaminant sources, there is no way to identify the precise route of the water from the source to the spring. Furthermore, the method deals with specific routes through the springshed. It does not allow identification of the springshed or general contribution areas.

Dye tracing provides an important contribution to understanding the behavior of springshed behavior. The travel times of tracers through conduits are often orders of magnitude faster than through rock or soil matrix. Therefore, tracer tests provide a sobering reality check to those who utilize groundwater flow models to predict capture zones and travel times in fractured and/or karst aquifers. Where rapid conduit flow is present in a spring system there is a high probability that the true capture zones will (1) extend well outside of the model-predicted capture zone and (2) have more rapid travel times than predicted by the flow model.

Cave Mapping - Cave diving has made important contributions to understanding the behaviors of springsheds through the preparation of cave maps and identifying the importance of

caverns to the flow systems. Orientations of caverns provide insight into groundwater flow directions. The summary by Butt et al. (2007) is an excellent example of the use of cave mapping to solve hydrologic problems.

Many caverns associated with the springs in the Santa Fe River system have been explored and mapped. Examples of cave maps are presented in Hornsby and Ceryak (1998). The recent report by Butt et al. (2007) summarizes the connections between swallets and resurgences in the Santa Fe River system. This report was based on diving records, dye tracing, and other lines of evidence.

Spring Protection

Based on modeling, dye tracing, and other hydrogeologic analyses, it is possible in many cases to identify locations where land use is most likely to lead to reduced water quality or flows in springs. These areas, which are often termed spring protection zones, can be identified and management strategies developed with a minimum of data.

The Florida Springs Task Force (2000) discussed the need for protection zones, and the Florida Departments of Community Affairs and Environmental Protection (2002) stress the need for identification of spring protection areas. The proposed revisions to Chapter 369 Florida Statutes would require protection zones for first and second magnitude springs, where needed. Springshed delineation and travel time estimates are the major first step to this process.

The North Central Regional Planning Council (1978) evaluated the Ichetucknee Springshed with respect to flooding as a limitation to development. The Ichetucknee Trace⁶ was the primary concern. Given the importance of the Trace to the function of the Ichetucknee Springs, this report marked an early evaluation of spring protection.

Upchurch and Champion (2002) revised the Regional Planning Council's work and attempted to identify areas where geologic hazards, such as flooding and spring contamination, might limit development or require special protection in the Ichetucknee springshed. In 2004, they attempted to delineate hypothetical spring protection areas at five, first magnitude springs, including the Ichetucknee Springs Group. Upchurch and Champion's (2004) Ichetucknee Springs delineation included Primary and Secondary Spring Protection zones and a protection zone based on the streams that empty into the swallets that have been traced to the springs. We are aware of only three springs where spring protection zones have been identified by governmental agencies. These are protection zones for Wekiva, Silver, and Rainbow Springs.

6. The Ichetucknee Trace is a low valley that connects Cannon Creek and the swallets that capture stream water near Lake City with the Ichetucknee Springs. It is thought to be an ancient stream valley and is characterized by elongated closed depressions (sinkholes) and flooding during extreme rainfall events.

Water Resource Associates and SDII Global Corporation (2005) delineated the springsheds of Silver and Rainbow Springs for Marion County, Florida in order to assist in development of spring protection areas by the county government. They utilized two different flow models to identify the springshed for the two springs as areas within which groundwater could be expected to reach the springs in 10 and 100 years. These zones were identified as protection zones for land-use planning and management.

A different approach was taken for Wekiva Springs. The protection areas are codified in Florida Statutes (Wekiva River Protection Act, Ch. 369.301-369.324 F.S., and Wekiva Parkway and Protection Act, Ch. 369.314-369.324 F.S.). The springshed was delineated by potentiometric surface contouring and modeling was involved to identify flow paths.

METHODS

This section describes the methods utilized to delineate springsheds and capture zones for springs on the Santa Fe River.

Phase I Potentiometric Surface Development and Springshed Delineation

In order to identify probable springsheds, the May and September, 2000, potentiometric surfaces were evaluated and springsheds were drawn on the maps to identify areas that, according to the potentiometric surface data, drain toward the springs. The year 2000 was selected for evaluation because

- There was a relatively high number of wells monitored in that year,
- The District's ground-water flow model is calibrated to that year,
- The year was characterized by low rainfall, so ground-water basins were likely near their maximum extents, and
- A state-wide potentiometric surface map had been previously prepared by the USGS (2000; Figure 5).

Owing to the widely spaced wells, it was not possible to delineate springsheds for each spring. Rather, the springs were separated into "clusters" within which individual springsheds could not be discerned and between which there was some evidence to allow boundaries of the combined springsheds to be identified (Figure 6).

Potentiometric surface data from monitoring wells within the Santa Fe River vicinity were obtained from the District, Alachua County, and the U.S. Geological Survey (USGS). In order to force the contouring algorithm to conform to the Suwannee, Santa Fe, and Ichetucknee

ivers, control points were obtained from the relevant U.S. Geological Survey topographic maps. The data were then contoured with Surfer® using the kriging option with zero nugget and a linear interpolator. The contour grid was 200 meters on a side and contour interval was set at 1 foot. The resulting contour maps were brought into ArcView® for development of Geographic Information System (GIS) shape files.

Simultaneously, the data were hand contoured. The final potentiometric-surface contour maps were prepared by comparing, and combining where necessary, the USGS potentiometric surface map with the hand and machine contoured maps.

The estimated locations of springsheds were drawn on the contour maps by hand and then digitized to shape files in order to produce the springshed delineations presented below. Springsheds were limited in extent to those areas where the upper Floridan aquifer is considered to be either unconfined or semi-confined.

Phase II Geostatistical Analysis

Geostatistical analysis consists of two steps (Isaaks and Srivastava, 1989; Chilès and Delfiner, 1999). First, a *structural analysis* is performed to determine the pattern of variance with distance between sample pairs. The results of this analysis assist in determining the maximum distance between samples (water-level measurements) before they are no longer correlated and beyond which contour lines can no longer be drawn. In addition, the structural analysis allows one to establish "rules" for estimating the uncertainty, in terms of standard deviations, of interpolations between correlated data points.

Once the structural analysis is completed and the "rules" of uncertainty estimation are completed, the second step, *kriging*, is initiated. Two maps are prepared as part of the kriging phase. The first is the traditional contour map showing the distribution of the property being contoured. The second map is an uncertainty map, which illustrates the areas where one cannot interpolate or extrapolate because the data points are too far apart and the magnitudes of uncertainty, in standard deviations, between correlated points are too high. This map is used to select additional monitoring locations, if needed, and to evaluate the uncertainties associated with the contour map.

Structural analysis of water level data was performed using the U.S.E.P.A. code Geo-Eas (Englund and Sparks, 1991). The kriged maps were contoured utilizing Surfer® (Golden Software, 2002).

Groundwater Flow Modeling

There are two groundwater flow models available for use in delineating the springsheds and travel times associated with groundwater leading to springs along the Santa Fe River. These

are (1) a model developed by the Suwannee River Water Management District (Schneider et al., 2008) and the USGS “Megamodel” (Sepúlveda , 2002) which covers all of north Florida. Both models are regional in nature and neither was designed to assist in characterizing springsheds. Even so, these models have been successfully utilized for springshed delineation in Marion County, Florida (Water Resource Associates, 2006).

The Suwannee River Water Management District groundwater flow model (District model) is a fully 3-dimensional model with layers to represent the surficial aquifer, the intermediate confining system, and the upper, middle, and lower Upper Floridan aquifers. The model is based on a 5,000 x 5,000 foot grid and extends from south Georgia to the southern part of Marion County and the Tallahassee area to the Atlantic Ocean. Recharge is based on rainfall during the calibration period in 2000. The model is also calibrated to spring and river discharge, lake levels, and groundwater levels in over 1,000 wells throughout the area. All first and second magnitude springs and some third magnitude springs are included in the model and known swallets and siphons are included as wells in order to balance the water budget for downstream springs.

Similarly, the USGS Megamodel is a 3-dimensional model with active layers to represent the intermediate aquifer and/or confining beds and the upper and lower Floridan aquifer. The uppermost layer (the surficial aquifer) uses specified heads to act as a source/sink for the flux of water to the underlying aquifers. The grid sizes are similar to the District model and calibration is to groundwater levels and selected springs. The Megamodel extends from the Atlantic Ocean to the western part of the Suwannee River Water Management District and from south Georgia to south central Florida. Few springs are included in the model.

The District model was developed in GMS[®], a proprietary graphical interface coupled with the U.S. Geological Survey’s MODFLOW. The Megamodel was developed in MODFLOW and converted by SDII to the GMS model interface.

The models were run to steady state using the particle tracking option to identify the projected springsheds. Particle tracking was also run to identify the 5, 10, 25, and 100 year capture zones.

Note that the models do not incorporate conduit flow, so they best replicate flow systems that integrate intergranular and conduit flow. As such, caverns are not identified by the models. The District model includes most of the springs of concern and some swallets, however. Also, the model grid sizes (5,000 x 5,000 feet) are large relative to the short-term capture zones of many springs. For these, one can only conclude that the short-term capture zones are within 5,000 feet of the springs.

Phase II Springshed Delineation

Index Period

The index period for the Phase II potentiometric surface map was September, 2007, to coincide with District and USGS semi-annual data collection efforts.

Data Collection

The Alachua County Environmental Protection Department (EPD) identified 185 monitoring points, the majority of which were wells in the western part of Alachua County and eastern Gilchrist County (the Newberry Plain area). Other data points included stage data from the Santa Fe River and springs and data from the St. Johns River Water Management District and the Southwest Florida Water Management District. Additional data from Alachua and Gilchrist counties were obtained from the Suwannee River Water Management District. Some of the District datasets consisted of daily measurements. Daily measurements for September, 2007, were averaged to obtain the single value used in the geostatistical analysis. Figure 6 depicts the locations of the monitoring points and site-specific index numbers. Appendix A provides a key to the index numbers, site coordinates, and elevation data.

All new monitoring points were surveyed to the National Geodetic Vertical Datum (NGVD) by Alachua County EPD, and the potentiometric surface data were transferred to SDII for geostatistical analysis.

RESULTS

Phase I Springshed Delineation

Phase I resulted in identification of eight springsheds. Because of the inability of the potentiometric surface data to capture small elevation differences that might indicate individual springsheds, the springs were clustered (Figure 7) to assist in defining springshed boundaries. Figure 8 presents the results of the springshed delineation.

Note that the springsheds are truncated on Figure 8 where the upper Floridan aquifer becomes well confined. Conceptually, the springsheds can be extended to the crests of the potentiometric surface highs under the Northern Highlands, but the groundwater in these areas is not considered to be active springshed.

Considering the uncertainties associated with the lower resolution of the Phase I potentiometric data in this study, the Ichetucknee Springs Group springshed (Figure 8, Area A) is consistent with the District's high resolution springshed delineation (Figure 4). The springshed includes Rose Creek and Cannon Creek, both of which are known to supply water to the springs through recharge to swallets.

Area B (Figure 8) is the springshed for the Betty Spring cluster of springs. The segment of the springshed to the south, towards the Bell Ridge potentiometric high, is not considered to be an important source of water to these springs because of the lower permeability of the aquifer strata in that area.

Area C (Figure 8) is a small springshed associated with the Betty Spring cluster (Figure 7) that could be separated from the main cluster. The segment of the springshed to the south, towards the Bell Ridge potentiometric high, is not considered to be an important source of water to these springs because of the lower permeability of the aquifer strata in that area.

Area D (Figure 8) includes both the Sunbeam and Wilson Spring clusters because of an indistinct boundary between the two. The majority of the water discharging to these springs is apparently from the north. The segment of the springshed to the southwest, towards the Bell Ridge potentiometric high, is not considered to be an important source of water to these springs because of the lower permeability of the aquifer strata in that area.

Area E (Figure 8) is the springshed for the Ginnie Springs cluster of springs. There appears to be a major influx of water discharging to these springs from the north. This is consistent with the evaluations of water sources by Wilson and Skiles (1988) and Kinkaid (1998) who noted water sources from the north at springs in the Ginnie Springs. The northernmost segment of the springshed to the west, towards the Bell Ridge potentiometric high, is not considered to be an important source of water to these springs because of the lower permeability of the aquifer strata in that area. The southern portion of the springshed that converges on the Bell Ridge potentiometric high is thought to be a significant source of water because the springshed is larger and streams flowing off of the Waccasassa Flats enter the aquifer in this area via swallets and other conduits.

Area F (Figure 8) is the apparent springshed for the Poe-Rum Island Springs cluster. Water discharging from this springshed apparently comes from both north and south of the river. Note that the southern part of the springshed includes most of the Western Valley (Newberry Plain). There is a general "rule of thumb" that average discharge of a spring is roughly equal to 1 cfs/mi.² of springshed (Faulkner, 1973). If this is the case, then the portion of the Poe-Rum Island springshed south of the river is too large for the magnitude of the springs in this cluster. Either some of this water is finding its way to the Ginnie Group of springs and other, undocumented seeps, or it is flowing under the Waccasassa Flats to the springs on the Suwannee River. The potentiometric surface does not provide information as to this issue.

Springshed G (Figure 8) is the springshed for the Hornsby-Columbia Spring cluster. The springshed terminates against the Northern Highlands in Alachua and Columbia Counties and includes such swallets as Mill Creek Sink.

Finally, springshed H appears as a narrow capture zone (Figure 8) associated with the Santa Fe River Rise. This springshed area appears small relative to the findings of Martin and Scream (2001). They concluded that only 4% of the water discharging from the River Rise was contributed at the River Sink at low river flow. Ninety-six percent of the water discharging from the sink was thought to be derived from other sources. The largest source of discharging water was thought to be the Old Bellamy Cave conduit system that extends to the east. They further concluded that this eastern conduit system received little surface water, so most of the discharge was from diffuse recharge. At intermediate discharge from the Rise, about 73% of the discharge was from the River Sink and the remaining 27% was from other sources.

Phase II Springshed Delineation

The Phase I springshed delineation was based on the USGS 2000 potentiometric surface map, which was somewhat generalized. Because of inability to adequately characterize the Poe-July springsheds, apparent under representation of the springshed of the Santa Fe River Rise, and other issues, Phase I recommended addition of more monitoring points and use of geostatistical analysis to evaluate the need for better monitoring, prepare a better map for springshed delineation, and attempt to identify details of the Floridan aquifer potentiometric surface that might allow for differentiation of individual springsheds. This section presents the results of this effort.

Structural Analysis

Structural analysis of the potentiometric surface data resulted in a semivariogram exhibiting a Gaussian curve with a nugget of 15 ft². The sill was determined to be 800 ft.² with a range of 350,000 ft. (Figure 9).

Note that the semivariance and sill are rather high, with a maximum of 800 ft.². This is because water levels are highly variable within the unconfined portions of the study area. Figure 10 illustrates a hydrograph of a Floridan aquifer well in Gilchrist County. Note that water levels can vary as much as 15 feet within a year. The data collected for the Phase II study were obtained over a period of one month at the end of the rainy season. As a result, there is a high degree of local variability. Furthermore, because of the potentiometric surface highs to the east and west of the study area, de-trending the data in order to minimize the accumulation of variance with distance between points was not advantageous. Therefore, the variogram was constructed without de-trending and the accumulation of variance over great distances between data pairs is high. This results in some localized uncertainty in the potentiometric surface highs, but not in the unconfined areas of the Newberry Plain.

Kriging Results

Figure 11 illustrates a contour map of the regional Floridan aquifer potentiometric surface based on raw, un-kriged data. Note the potentiometric highs in eastern Alachua County and in west central Gilchrist County. The potentiometric surface high to the east lies under the Northern Highlands and to the west under the Brooksville Ridge and Waccasassa Flats (Figure 2) where the Floridan is relatively confined. The large, low area in the central part of the study area is the Western Valley or Newberry Plain, where the Floridan aquifer is unconfined. Note also the cone of depression developed in central Alachua County. This reflects the effects of pumpage for water supply to Gainesville.

Figure 12 presents the same area using modeled potentiometric data. Note that the overall pattern of potentiometric highs and lows is similar to that shown in Figure 11. The cone of depression near Gainesville is not shown on the map. Rather, the effects of the Gainesville Regional Utilities (GRU) wellfield are represented by a re-entrant in the potentiometric surface.

In order to depict the potentiometric contours in the Western Valley/Newberry Plain in detail, the regional maps shown in Figures 11 and 12 were used to control the kriged maps and new maps were prepared that zoom in on eastern and central Gilchrist County and central and western Alachua County. These maps, which utilize 1-foot contour intervals, were used to evaluate Alachua County's monitoring network and draw springshed boundaries.

Figure 13 depicts a contour map of raw potentiometric surface data in the Newberry Plain and surrounding areas. The potentiometric highs under Bell Ridge and the Northern Highlands are well depicted. The relatively flat potentiometric surface under the Newberry Plain is shown as a broad region with a gentle hydraulic gradient from the southeast corner of Alachua County northwest to the Santa Fe River. Note that the cone of depression at the GRU wellfield lies within the potentiometric high under the Northern Highlands. This cone of depression appears to be reducing the gradient to the west and a small saddle is depicted in the hydrologic divide that separates the GRU cone of depression from the low potential areas of the Newberry Plain.

Figure 14 presents the same area utilizing the modeled potentiometric elevations (K^* values) derived by kriging. As noted above the GRU cone of depression is represented by a re-entrant rather than an internally drained area.

The kriged standard deviation (K_{SD}^7) map (Figure 15) is used to evaluate and identify spatial gaps in data where additional data points are needed. For most of the study area the K_{SD} values are between 4 and 5 feet. This minimum K_{SD} reflects the uncertainty in aquifer potentials as distance between monitoring wells increases. The K_{SD} is as high as it is because

7. The kriged standard deviation is the square root of the semivariance values shown in Figure 9.

of local variability in aquifer water levels created by local drawdown by pumpage and temporal variations in water levels over the index period (September, 2007). Additional of additional sampling points is unlikely to reduce this uncertainty. It appears that only synoptic sampling to minimize day-to-day variability will further reduce the uncertainty. In other words, the monitoring plan is appropriate in the Newberry Plain area and does not need additional sampling points. The area shown in red on Figure 15 is very high uncertainty. The area represents one well data point and may reflect surveying or measurement error.

Figure 16 shows another way of evaluating the kriged data points. This figure depicts residuals⁸ for the Newberry Plain Floridan aquifer data. Blue areas indicate that the modeled elevations under estimated the aquifer potentials, and yellow areas indicate where the modeled data over estimated the raw data. The yellow (over estimated) areas on the western side of the study area reflect wells on the Bell Ridge potentiometric high. The blue area in Alachua County represents the GRU wellfield cone of depression. Residuals are typically less than 2 feet in the Newberry Plain area. Again, these data suggest that kriging successfully modeled the Floridan aquifer potentiometric surface data, which indicates an appropriate monitoring network.

Springshed Delineation

Most of the Santa Fe River springsheds can be better delineated using the 1-foot contour map based on the high-resolution monitoring of the study area. Figure 17 depicts these springsheds. The following paragraphs discuss each springshed, beginning at the western side of the study area and progressing to the east.

The area west of the Bell Ridge potentiometric high is not well constrained by the Alachua County Monitoring Network. As a result, one can only conclude that water flowing from the potentiometric high westward ultimately reaches the Suwannee River through springs, such as Hart Springs, and diffuse flux to the river.

The Sunbeam – Wilson Springshed as shown on Figure 17 includes Wilson, Sunbeam, and several other small springs. The springshed well delineated on both sides of the Santa Fe River. There appear to be clear groundwater divides in all directions. Springsheds of individual springs within the mapped springshed cannot be identified at the current resolution.

The study area only includes the southern end of the springshed of the Ichetucknee River and Springs. This springshed was previously delineated by Upchurch and Champion (2003) utilizing high-resolution monitoring. The springshed is depicted in Figure 4.

8 . Residuals are by calculating $\text{Residual}_X = X_{\text{obs}} - X_{\text{calc}}$ for each data point (X). Positive residuals indicate that the kriged estimates under estimate the measured data and negative residuals indicate over estimation of the data by the kriged values.

The Ginnie Springshed includes Ginnie, Devil's Ear, Devil's Eye, July, Dogwood, and other springs. As noted by Wilson and Skiles (1988) and Kinkaid (1998) the individual springs exhibit complex inter-relationships and have variable sources of water from the river and groundwater flow from north and south of the river. The springshed is well defined south of the river. The only significant uncertainty is on the southeast part of the springshed where the groundwater divide used to define the eastern springshed boundary broadens. North of the river, there is considerable uncertainty as to the springshed boundary. There is a well-defined hydrologic divide between the Ginnie and Sunbeam-Wilson and Ichetucknee springsheds, but the eastern boundary is indistinct, largely because of lack of monitoring points. The southeastern portion of the springshed appears to be a source for other springs upstream.

The Rum Island – Gilchrist Blue Springshed is defined on the west by a locally apparent divide, but much of the boundary is drawn through areas where the potentiometric surface is broad and divides are ill-defined, if present. The boundary with the Poe Springshed is equally indistinct and a well-defined divide only exists under the Cody Scarp and the Northern Highlands. There is probably a source of water on the north side of the river, as well. The extent of the springshed north of the river cannot be estimated based on existing data. Note that the drainage basin, as drawn, is much too large for the volumes of water discharging from the springs. The potentiometric surface map indicates that water is flowing to the river in the vicinity of the Ginnie and Rum Island – Gilchrist Blue reaches, but the data do allow for certain springshed delineation.

The Poe Springshed is well-constrained in some segments and ill defined in others. Again, the lack of well-defined hydraulic divides adds uncertainty to the springshed delineation. Well developed divides exist under the Cody Scarp and Northern Highlands, partly as a result of interactions with the cone of depression created by the Gainesville wellfield (GRU Capture Zone, Figure 17).

The Hornsby – Treehouse Springshed has known sources related to swallets (Butt et al, 2006) and siphons in the river (Butt et al., 2007). Based on the high-resolution springshed map, the springshed appears to be relatively broad in extent with moderately to poorly defined hydraulic divides to the north and south.

Finally, the Santa Fe Rise Springshed is known to be dominated by riverine water derived from the swallet (Santa Fe Sink) at O'Leno State Park (Martin and Screatton, 2001; Butt et al., 2007). The Old Bellamy Cave System is thought to derive water from the northeast, as well. The springshed appears to support these conclusions. It is relatively small and is skewed to the northeast from the Sink-Rise system.

Interpretation of the Phase II Springshed Delineations

Overall, the springshed delineation has added much to the level of detail obtained in the Phase I springshed delineation (Figure 8). Clearly, discharge from the springs upstream of the Sunbeam – Wilson Springshed is dominated by source areas south of the river. All of these springsheds have headwaters that are distributed along the Cody Scarp and/or the Bell Ridge potentiometric high. In both situations, surface water draining off the confined areas recharges the Floridan aquifer through swallets. In addition, there is enhanced recharge through large sinkholes (uvalas and poljes; Upchurch, 2002, 2007). It is problematic in many cases as to which spring this water migrates. Additional dye tracing may assist in identifying source-to-sink relationships.

Some general features of the overall pattern of springsheds are of importance, however. First, the lack of distinct divides between springsheds in many cases leads to remaining uncertainty. Second, the apparent springshed areas are not necessarily proportionate to the discharge from the springs associated with the springsheds. Both of these features are indicators of complex karst-conduit flow.

The well-documented instances where (1) conduits that discharge at springs on the Santa Fe cross each other in the vertical dimension and (2) adjacent springs have different sources of water (Wilson and Skiles, 1988; Kinkaid, 1998; Martin and Scream, 2001; Butt et al., 2007; etc.) support the complexity of the karst-conduit flow systems in the Santa Fe springsheds. Therefore, given (1) the known complexity of near-field flow to the springs, (2) the presence of indistinct groundwater divides in many springsheds, and (3) the lack of proportionality of springshed areas to spring discharge, the Newberry Plain should be considered as a single springshed for management purposes. Trying to attribute specific locations in the far-field flow systems of the springsheds to specific springs may lead to management difficulties and disputes.

Modeling Capture Zones with Groundwater Flow Models

As noted above, groundwater flow models can be utilized to confirm springshed extents and identify rough travel times of groundwater to springs. The travel times and recharge area extents (springsheds) as estimated by the models are limited by the inability to incorporate conduit flow in the regional, finite difference models and by the complexity of swallet and siphon to spring flow known to exist in the Santa Fe River basin.

Springshed Delineation and Capture Zones Identified by the Megamodel

Figure 18 depicts the areas identified by particle tracking using Sepúlveda's (2002) "Megamodel." The area shown in yellow represents the springsheds identified by running the model to steady-state. There are significant areas for the Ichetucknee and Sunbeam clusters, and a very small area related to Poe and July springs. Otherwise, there was no regional

dispersion of particles in the model. The shorter term capture zones (5, 10, 25, and 100 year particle track areas) are limited in extent and not representative of the known capture zones (see the literature and springshed delineations discussed above).

The inability of the model to depict reasonable capture zones is not surprising. Some of the reasons for this inability to document larger capture zones are

- The 5,000-foot grid size is too large to capture detail of flow near a spring.
- Many of the springs were not represented in the model, so particle tracking was from the cell within which the spring(s) fell. This causes uncertainty in the particle tracking results.
- The model cannot account for fracture and cavern flow, which is a major pathway for water to the Santa Fe River springs.
- Many of the springs are actually resurgences, which should have small capture zones.

Clearly, the Megamodel is not adequate to approximate capture zones and travel times to the springs.

Springshed Delineation and Capture Zones Identified by the District Model

Figure 19 depicts the areas identified by particle tracking using the District's model (Schneider et al., 2008). The District model has a fully active layer one (the surficial aquifer or unconfined upper Floridan aquifer, where appropriate) and included all first and second magnitude springs and many of the known siphon-resurgence systems (Butt et al., 2007). As such, it represents a better approximation of the springsheds than the Megamodel, but the short-term travel times are clearly under estimated.

The area shown in yellow represents the springsheds identified by running the model to steady-state. There are significant springshed areas shown on the capture zone map (Figure 19). The larger springs have large, steady-state capture zones or modeled springsheds, as one would expect. Springs that do not have large capture zones include resurgences (i.e., Santa Fe Rise) and some of the smaller springs just upstream from the mouth of the Ichetucknee River (the Sunbeam Spring cluster, Figure 7; Sunbeam – Wilson Springshed, Figure 17).

The shorter term capture zones (5, 10, 25, and 100 year particle track areas) are limited in extent to the immediate vicinities of the cells within which the springs are located. These are clearly not representative of the known capture zones of these springs (see above).

The inability of the model to depict reasonable capture zones is not surprising. The reasons are as discussed in the previous section and include:

- The 5,000-foot grid size is too large to capture the detail and complexity of flow near a spring;
- The model cannot account for fracture and cavern flow, which is a major pathway for water to the Santa Fe River springs;
- Many of the springs are actually resurgences, which have small capture zones; and
- The siphons in the river are, in some cases, within the same cells as the springs, so they supply water to nearby springs in the model.

Clearly, the District's model is somewhat suitable to identify rough springsheds, but it is inadequate to approximate short-term capture zones and travel times to the springs.

DISCUSSION

This section discusses the results of previous investigations and compares these findings to the results of this investigation. The springs are grouped in clusters as shown in Figure 2. The order of the discussion is from the most upstream spring cluster, Santa Fe Rise, downstream to the mouth of the Santa Fe River and the Betty Spring Cluster.

Santa Fe Rise

The Santa Fe Rise is considered a first magnitude spring (Ferguson et al., 1947; Rosenau et al., 1977; Hornsby and Ceryak, 1998; Scott et al., 2002, 2004). It is a resurgence of the Santa Fe River, which goes underground through a swallet (Santa Fe Sink) in O'Leno State Park, near High Springs, Florida.

Scientists at the University of Florida have traced the water from sink to resurgence and investigated the processes that affect recharge water that enters the Santa Fe River Sink and discharge from the Santa Fe Rise (detailed list of these publications is included in Section 6). Special focus of this research has been on the mixing of river water with aquifer water underground. Some of the important findings of these investigations are discussed below.

A dye tracer test found that the River Sink is connected with Sweetwater Lake (a small lake between the Sink and Rise) and several karst windows. The tracer was not, however, detected at the Rise (Hisert, 1994). A second dye trace beginning at Sweetwater Lake was detected at the River Rise (Hisert, 1994), thus establishing the connection and demonstrating that dilution and/or dispersion may be important processes for reducing concentrations of the dye to less than detection limits. The Hisert investigation was undertaken when the river stage was moderately high (44.3 ft. above msl). Hisert (1994) also estimated that the rate of travel from Sink to Rise was 2.7 miles per day.

Dean (1999) and Martin and Dean (1999, 2001) utilized temperature measurements to show that flow rates vary with river stage. At high stage (44.3 ft. above sea level), travel time was estimated to be less than 6 hours. During low stage (34.3 ft.), the travel time was over 7 hours. At “exceptionally low stage” in 2001, the entire flow of the river was captured by a small sink upstream from the River Sink (Smith et al., 2002). After several precipitation events, during which stage rose, discharge pulses moved through the Sink/Rise system. The data obtained indicated the possibility of a complex “plumbing” system controlled by differing elevations of conduits.

Martin and Screaton (2001) used the Sink/Rise system to characterize exchange and mixing of diffuse and conduit flow water. They concluded that only 4% of the water discharging from the River Rise was contributed at the River Sink at low river flow. while, 96% of the water discharging from the sink was thought to be derived from other sources. The largest source of discharging water was thought to be a conduit system that had been mapped by cave divers to extend to the east. They further concluded that this eastern conduit system received little surface water inflow, and most of the discharge was from diffuse flow. At intermediate discharge from the Rise, about 73% of the discharge was from the Sink and the remaining 27% was from other sources.

The Santa Fe Sink/Rise complex is, therefore, a complex system with significant recharge at the Sink and other conduits within the main stem of the Santa Fe River during moderate to high flow conditions. During droughts, when the river is low, the discharge from the Rise is sustained by movement of water out of the aquifer matrix into the conduit system.

Butt et al. (2007) briefly described the Santa Fe Rise cave system, which is called the Old Bellamy Cave System, and concluded that the groundwater contribution came from the east, following this cavern system. This is consistent with the springshed delineation (Figure 7).

The springshed maps (Figures 8 and 17) clearly show the potential for flow from the Santa Fe Sink area and flow from the east. The northwestern boundary of the springshed also suggests that there may be some contribution from as far away as the lower reaches of Olustee Creek.

The groundwater flow models (Figures 18 and 19) fail to delineate capture zones that are distant from the Santa Fe Rise. This is a result of the construction of the models, which indicate that the water discharging from the Rise is derived within 5,000 feet of the spring. This is, of course, not consistent with the dye tracing and other evidence that implicate the Sink and sources to the east and northeast.

Hornsby–Columbia Spring Cluster

The Hornsby-Columbia Spring Cluster includes Hornsby, Columbia, and ALA112971, or Treehouse, Springs, all first magnitude springs. In addition, Darby Spring, which is located near Hornsby Spring, and an unnamed spring (COL428981) are located within the cluster. In the Phase II springshed delineation, the springshed was named the Hornsby – Treehouse Springshed because the high resolution data seems to tie Treehouse into the springshed more than Columbia Spring, a resurgence.

There are several siphons within this reach of the Santa Fe River. Butt et al. (2007) have characterized the interactions of these siphons with the springs.

Butt et al. (2005) conducted dye traces from Mill Creek Sink and Lee Sink, the swallet that captures flow from Cellon Creek, in Alachua County to Hornsby Spring. They were able to demonstrate direct connections with the spring with travel times of 12-13 days from Mill Creek Sink, which is located approximately 6 miles southeast of Hornsby Spring and 28 to 31 days from Lee Sink, which is approximately 9 miles from the spring. The spring has a cavern system that has been explored to the east (Butt et al., 2007).

Treehouse Spring is a first magnitude spring located on the Alachua County side of the Santa Fe River. It is a double resurgence (Butt et al., 2007) associated with three siphons, two of which are located in the river and one in the Hornsby Spring Run.

Columbia Spring, a first magnitude spring on the Columbia County side of the river, is thought to be a resurgence (Butt et al., 2007). It is associated with two siphons that are located on the east and west sides of the river, respectively, just downstream from the US 441 bridge (Butt et al., 2007).

Darby Spring, which is near the mouth of the Hornsby Spring Run, was also found to be connected to mill Creek Sink. The travel time from the sink, which is over 6 miles from the spring was 28 to 31 days.

Therefore, two of the largest springs in this cluster (Columbia and Treehouse) are more closely associated with river flow than groundwater. Only Hornsby and Darby appear to have dominant groundwater components. The springshed maps for this spring cluster (Area G, Figure 8 and the Hornsby – Treehouse Springshed, Figure 17) suggest a source area that extends to the east, toward Mill and Lee sinks. The SRWMD groundwater flow model (Figure 19) also shows a groundwater component that flow from the east and the vicinity of Mill and Cellon Creeks.

Poe, Rum Island, Gilchrist Blue, and Ginnie Springs Clusters

The literature review failed to identify any evidence of cave mapping in the Poe Spring system. Butt et al. (2006) screened Poe Springs during the Mill Creek Sink dye trace, but no dye was detected. The Phase I springshed map (Figure 8) and high resolution springshed map (Figure 17) indicate that the springshed is predominantly to the northeast. Poe Spring is served by recharge through one or more swallets and sinkholes along the Cody Scarp. The District model (Figure 19) suggests that the source for Poe may be to the south and east, toward the Cody Scarp in Alachua County.

The Rum Island – Gilchrist Blue Springshed (Figure 17) was lumped with Poe Spring in the Phase I delineation (Figure 8). These springs, which are located on the north and south sides of the river, respectively, have sources to the southeast (Figure 17) and, apparently, northeast (Figure 8, Area F). The District model shows water flowing to both springs from the southeast.

The Ginnie Springs cluster and springshed includes springs of the Ginnie Springs Group, July Spring, Devils Ear and Devils Eye springs, and others. The springshed indicate sources of water on both north and south sides of the river. The springshed appears to terminate on the Bell Ridge potentiometric high. The District flow model indicates springsheds for these springs are located within the Newberry Plain (Figure 19).

Dye tracing by Wilson and Skiles (1988) on the south side of the river at Ginnie Springs (Figure 7, Area E) suggested that there is no cross over between July and Ginnie Springs flow systems. The water flowing to the Ginnie system did not indicate that July was interconnected to the Ginnie flow system. Mapping of the Devils Ear system indicated that caverns extend to the north of the river as well as under it. Dye injected in wells south of the Ginnie system migrated to the Ginnie and Devils Eye systems, however. Based on cavern orientations and the work of Wilson and Skiles (1988), there is some suggestion that the springshed north of the river may be dominated by the Devils Ear system, including July Spring, while flow from the south appears to go predominantly to the Ginnie system. The District groundwater flow model (Figure 19) suggests this phenomenon with the steady-state capture zones being contiguous and extending well south in the Western Valley (Newberry Plain). Note, however, that there is a minimal capture zone north of the river.

Therefore, one must conclude that the flow systems of the Poe, Rum Island – Gilchrist Blue, and Ginnie Spring springsheds are complex and cavern-dominated. Water enters the systems from north and south of the river. The sizes of the springsheds mapped by potentiometric surface data (Figure 8 and 17) and the model results (Figure 19) strongly suggest that most discharge from the springs within the spring clusters is from the south, however. The data also suggest that these springsheds should be considered as one for management purposes.

Siphon Creek, Wilson, and Sunbeam Clusters

The Siphon Creek cluster (Figure 2) is a siphon/resurgence system (Butt et al., 2007). It could not be differentiated from the Wilson and Sunbeam clusters (Wilson – Sunbeam Springshed) based on potentiometric data (Figures 8 and 17) or the District flow model (Figure 19), which did not indicate a capture zone owing to the presence of siphon and resurgence in close proximity.

The Wilson and Sunbeam clusters could not be separated from each other on the basis of potentiometric data (Figures 8, Area D, and 17). The capture zone as indicated by the potentiometric data is limited, which explains the low magnitude of springs in this area. It is interesting that the steady-state run of the District flow model indicated that water from near the Santa Fe Rise might contribute to the Area D springs. This is not corroborated by any other data, however.

For the purpose of springshed delineation and management, the springsheds of the two spring clusters should be considered as one.

Betty Spring Cluster

The Betty Spring Cluster (Figure 8) could be subdivided into two springsheds based on the low-resolution potentiometric surface (Figure 8, Areas B and C). The springshed was not delineated as part of the Phase II delineation because of low data density. Both springsheds from the Phase I investigation indicate source areas to the north of the springs. The groundwater flow model (Figure 19) also indicated a capture zone north of Betty Springs. The smaller, unnamed springs within the cluster resulted in small to non-existent capture zones.

Ichetucknee Spring Group Cluster

The Ichetucknee Springs Group includes six named springs. The spring group is part of a state park. As a result of their importance, these springs have been extensively studied, including many studies that provide information relevant to the Ichetucknee springshed.

Lawrence and Upchurch (1976) investigated groundwater quality in the area near Lake City, the headwaters of the Ichetucknee springshed, and found that water draining from Alligator Lake, a sinkhole lake that periodically drained into the Floridan aquifer, migrated toward the springs.

Cannon Creek, Clay Hole Creek, Rose Creek, and several other small streams that flow off the Northern Highlands were known to drain to sinkholes at the foot of the Cody Scarp. Karst Environmental (1997) established the best evidence of connections of these swallets to the Ichetucknee Spring Group through dye tracing. Dye was injected into Rose Sink, a swallet that captures Rose Creek and that is located near Columbia City, about half way between the park and Lake City. The dye appeared in several springs and transport rates up to

approximately 1 mile per day were observed. The pattern of the dye detections appeared to indicate flow to the east of the spring, with significant dye arrivals at Mission and Blue Springs.

A second dye trace from Black and Dyal Sinks, which are located in the Clay Hole Creek sinkhole complex just southwest of Lake City, completed the connection of flow from the swallets to the Ichetucknee Spring Group. This study by Butt and Murphy (2003) first detected dye at Rose Sink, the site of injection of dye in the 1997 study. Dye was also detected at Mission, Blue Hole, and Devil's Eye Springs. Therefore, there is a clear groundwater flow system from Alligator Lake and the Clay Hole Sink complex near Lake City to the Ichetucknee Spring Group. It took from 65 to 125 days for the dye to reach the springs from the distal margin of the springshed.

Upchurch and Champion (2002) developed a preliminary springshed for the Ichetucknee Springs Group in order to consider development potential of the springshed. The map developed by Upchurch and Champion was general and conceptual in nature.

In 2003, Upchurch and Champion (2003a) developed an assessment of the source areas of the Ichetucknee Spring Group based on water-quality data. By matching groundwater quality with the quality of water discharging from the springs, they were able to show that the water that flows from the north migrates to the east and discharges at Blue Hole, Mission and other springs. There was a component of groundwater flow from the east to the southern most of the springs in the group.

Also in 2003, Upchurch and Champion (2003b) utilized a high resolution monitoring network established by the District to identify the springshed extent. By contouring the groundwater potentials at a 1-foot interval, the springshed became evident. Figure 4 in this report is the springshed delineation developed by Upchurch and Champion.

The springshed delineated in Phase I of this report (Figure 8) is similar to the Upchurch and Champion springshed (Figure 4). It lacks the details of the earlier study, however, because of lower monitoring-well density. The capture zones predicted by the District groundwater flow model terminates at Rose sink and does not extend as far north as Dyal and Black sinks or the toe of the Cody Escarpment.

CONCLUSIONS AND RECOMMENDATIONS

In summary, this springshed delineation project resulted in some important findings relative to our understanding of the springs of the Santa Fe River. The following presents general conclusions and recommendations that derive from this study.

1. The springsheds of clusters of springs can be delineated with existing potentiometric surface data. The low density of existing monitoring wells and dominance of conduit flow to the springs limit delineation of springsheds for specific springs.

2. High resolution monitoring yields much better springshed delineation than the existing monitoring network, however.
3. Springsheds of most springs cannot be individually delineated. In order to identify springsheds based on low- or high-resolution potentiometric data the springs will have to be grouped.
4. Springsheds in the Newberry Plain are broad and do not have well-defined hydrologic divides. Therefore, the springshed boundaries have associated uncertainty.
5. While potentiometric evidence was found in the high-resolution potentiometric surface data to allow for springshed boundary delineation, the springshed areas appear to be disproportionate to the discharge of the associated springs.
6. It is recommended that the Newberry Plain springsheds (Poe, Run Island – Gilchrist Blue, and Ginnie) be considered as one springshed for springshed management purposes because of uncertainties in springshed delineation.
7. The springsheds (Figures 8 and 17) generally extend from the Cody Scarp or Bell Ridge potentiometric high to the springs in a manner that is consistent with dye tracing, fingerprinting using water-quality data, cave mapping, and other available data.
8. In this report, the springsheds were truncated under regions where the upper Floridan aquifer is confined (Figures 8 and 17). Traditional springshed maps, including the Ichetucknee Springs Group map (Figure 4), extend the springshed to the nearest up-gradient groundwater divide. This results in unrealistically large springsheds and conveys the generally incorrect impression that the portions of the “springsheds” that lie under well-confined conditions may be vulnerable to contamination from the land surface.
9. Geostatistical analysis of the high-resolution monitoring data indicates that there are no statistically significant gaps in the monitoring network. Increasing the resolution by adding more sampling points would require a large, expensive network.
10. The nugget, or initial variability of data between well pairs, is high because of the one-month time span over which potentiometric data were collected. Shortening the index period would reduce this level of uncertainty, but be impractical.
11. Groundwater flow modeling with the District's model was successful in delineating general springsheds when the model was run to steady state. This is important information because the steady-state model run is utilized by the District to evaluate proposed groundwater withdrawals for permitting.
12. While the District model includes both springs and siphons and swallets, capture zone delineation of springs with significant surface-water contributions was generally not successful. This is because of the inability of the model to account for conduit flow.
13. The steady-state capture zones of springs with significant groundwater flow

components were generally well defined and in general agreement with the springshed delineations.

14. Short-term travel-time or capture zones were generally not identified by the groundwater flow model. This is because of the dominance of conduit flow near the springs and the large (5,000 x 5,000 ft.) model grid size.
15. The USGS Megamodel was designed to explore the flow relationships of the Intermediate and upper Floridan aquifer. Layer 1, the surficial aquifer, was set up as a constant head boundary in the model and few of the springs in Santa Fe River system were included in the model. The model grid size has the same limitation as the District model. The model was not serviceable for use in characterization of springsheds or capture zones.
16. It is clear that groundwater flow modeling has limitations as far as characterization of springshed flow times in the Santa Fe Basin. The inability of the models to incorporate the effects of conduit flow is especially important at the scale of the springsheds. This inability resulted in predicted springsheds based on steady-state flow that are often smaller than predicted by dye tracing and other means.
17. The siphon to resurgence relationships of many of the springs were generally adequately characterized by the District model, which includes major siphons and all first and second magnitude springs as well as important third magnitude springs. If there are springsheds associated with the resurgences, they are not revealed by the model, however.
18. Several recommendations are clear from this investigation. These are based on apparent based on the assumption that the area and water demands will increase. The un-prioritized recommendations follow.
 - Additional dye tracing in the vicinity of Poe, Rum Island – Gilchrist Blue, Ginnie Springs, and perhaps the Ichetucknee Springs Group would be useful for understanding patterns of flow to the Santa Fe River springs.
 - Groundwater chemical fingerprinting, such as was done at Ichetucknee Springs, would also be useful in understanding flow through the Western Valley to the springs on the Santa Fe River and sources of water for specific springs or spring groups.
 - The monitoring network developed by Alachua County and existing networks by Coca-Cola/Danone at High Springs and the District should be maintained to understand flow dynamics to the springs and assist in springs protection and management.
 - It is recommended that a transient, sub-regional, groundwater flow model be developed for the Santa Fe River watershed. This would allow for a smaller grid size, incorporation of temporal variation in spring behavior, and potential for

incorporation of some conduit flow in the model. Optimally, an integrated, surface water/groundwater model could be used to better understand and manage the effects of growth in the Lake City and Alachua County areas as well as the floods and droughts that affect the region

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Appendix A – Index and list of monitoring points utilized for the high-resolution, Phase II springshed delineation.

Index	Site ID	Northing (feet)	Easting (feet)	Latitude (Deg. North)	Longitude (Deg. West)	Elevation (feet, NGVD)
1	-111811001	1166849	10726939	29.547306	-82.489972	41.71
2	-101722001	1130129	10748567	29.605434	-82.606389	38.2
3	-101516017	1063361	10751555	29.610944	-82.816611	7.98
4	-91607001	1086209	10792554	29.724639	-82.746667	42.5
5	-81926001	1199931	10803265	29.758334	-82.388806	40.16
6	-81703001	1133867	10828088	29.824243	-82.598083	31.35
7	-51428004	1030366	10901307	30.021194	-82.928306	16.39
8	-51201007	984285	10925390	30.085187	-83.075250	16.07
9	-41827002	1167401	10931490	30.109817	-82.496583	45.97
10	-41625001	1112015	10935334	30.118278	-82.671917	33.48
11	-41329001	994300	10933560	30.108139	-83.044056	20.18
12	-31105006	933890	10985828	30.248694	-83.238278	22.41
13	-21711003	1140308	11010618	30.326389	-82.585750	47.53
14	-12029001	1220971	11029443	30.381000	-82.330778	44.66
15	-11727001	1134129	11030394	30.380526	-82.606222	45.85
16	-11534001	1073098	11022714	30.356889	-82.799361	46.5
17	11316001	985372	11070233	30.483389	-83.080194	33.18
18	11422007	1039565	11066558	30.475914	-82.908000	38.44
19	21125001	957041	11091342	30.539945	-83.171389	41.01
20	21432001	1029162	11087662	30.533444	-82.942167	34.2
21	A 0068 USGS UFA CE 1A NR NEWBERRY	1130393	10748609	29.605560	-82.605560	38.16
22	A 0071 HAWTHORNE TOWER UFA	1298739	10744312	29.599090	-82.075650	71.5
23	A 0135 ROD REESE UFA NR KEYSTONE HEIGHTS	1287653	10809386	29.777780	-82.112500	68.73
24	A 0420 LYBASS AS PHIFER	1262389	10734293	29.570560	-82.189720	63.05
25	A 0421 Lochloosa Well at Hawthorne	1290074	10721360	29.535739	-82.102233	63.85
26	A 0693 ALACHUA CO FAIRGROUNDS UFA	1231772	10776129	29.684720	-82.287500	40.63

27	A 0725 UFA LK LOCHLOOSA CR 325	1282013	10700161	29.477220	-82.126940	53.08
28	Al Hodge	1106068	10793107	29.726969	-82.684135	30.66
29	Alcorn	1177325	10770579	29.667680	-82.458750	42.77
30	Aline Hall Manship	1114972	10848407	29.879380	-82.658589	30.37
31	Asbell	1150080	10702923	29.480660	-82.541710	43.19
32	Batey	1157199	10719157	29.525560	-82.520000	41.52
33	Bickmeyer	1296102	10746438	29.604870	-82.084010	72.8
34	Bill Main	1117306	10835929	29.845162	-82.650661	25.95
35	Bliss	1206197	10820218	29.805160	-82.369690	42.28
36	Blue Springs Staff Gauge	1106958	10830546	29.829950	-82.683050	24.01
37	Braley Sink	1128006	10798347	29.742238	-82.615253	31.74
38	Broadway	1201237	10844284	29.871180	-82.386240	42.77
39	C 0120 Brooklyn Lake	1312099	10818052	29.802241	-82.035675	74.84
40	C 0123 Sungarden Tower	1410379	10830249	29.837855	-81.725983	63.93
41	C 0128 Penney Farms Tower	1345789	10882758	29.981000	-81.931083	64.11
42	C 0436 Lake Geneva #1	1319069	10806213	29.769850	-82.013369	74.47
43	C 0442 Chester Moody	1317476	10814160	29.791669	-82.018611	73.95
44	C 0453 Gold Head State Park #1	1337118	10824323	29.820083	-81.956944	72.74
45	C 0495 Thunderbolt Elementary School	1411904	10919648	30.083777	-81.722944	25.57
46	C 0579 Bayard Point at Green Cove Springs	1445597	10874150	29.959172	-81.615616	27.27
47	C 0583 Yellow Water Creek at Middleburg	1344204	10946839	30.157208	-81.937747	47.45
48	C 0592 Tynes Elementary School	1372349	10932332	30.117916	-81.848333	43.41
49	C 0599 Canvasback RD at Middleburg	1331537	10924164	30.094555	-81.977222	52.63
50	C 0607 State Road 16 at Penney Farms	1367327	10881494	29.977986	-81.863010	64.93
51	C 1011 Camp Blanding at CR315 at Keystone Heights	1346796	10845119	29.877500	-81.926944	69.87
52	C 1014 Camp Blanding at SR16	1320640	10883617	29.982777	-82.010555	59.35
53	C 1017 Camp Blanding at North Rd at Lawtey	1314266	10910055	30.055333	-82.031444	53.09
54	C 1063 Lake Asbury Wells	1376706	10911431	30.060518	-81.834070	50.01
55	Camp Kulaqua River Ranch Well	1138018	10837430	29.850090	-82.585400	31.78
56	Cary Beth Hines	1098737	10773432	29.672575	-82.706315	38.93
57	CCDA G 2	1098652	10825716	29.816333	-82.709017	23.29

58	CCDA S 3	1105497	10826761	29.819483	-82.687483	24.98
59	Charlotte Fleming	1119275	10841787	29.861348	-82.644716	26.55
60	Chris Brown	1095649	10859770	29.909845	-82.720090	25.6
61	Church of God by Faith G 13	1241684	10773701	29.678340	-82.256200	53.17
62	City of Waldo G 34	1269641	10814211	29.790560	-82.169440	63.37
63	Clara Stavely	1091029	10792985	29.726023	-82.731505	40.24
64	Copeland Park G 5	1245570	10773371	29.677550	-82.243950	54.94
65	Crapo Hetzel	1241051	10705503	29.490760	-82.255870	51.42
66	Dave and Mary Ann Smith	1109385	10833052	29.836938	-82.675511	23.62
67	DICK SURRENCY WELL	1259230	10753413	29.623056	-82.200278	74.15
68	Dollar General	1154276	10807232	29.767654	-82.532851	33.37
69	Don Alexander	1094439	10827146	29.820092	-82.722367	25.27
70	DOT FL 15	1236687	10790598	29.724660	-82.272520	50.3
71	DOT FL 28	1234875	10782836	29.703260	-82.277960	43.02
72	Erwin and Connie Wood	1154199	10781397	29.696609	-82.532017	36.5
73	Fahning Taylor	1271045	10703152	29.485150	-82.161510	52.41
74	FHP Station G 26	1210643	10786130	29.711560	-82.354410	49.52
75	Garrett	1208599	10770733	29.669150	-82.360280	44.07
76	George Brady	1104686	10859275	29.908853	-82.691546	27.27
77	Gilchrist Co NE Recycling Center	1088902	10811918	29.777994	-82.739101	39.6
78	Gilchrist NE	1088521	10823079	29.808665	-82.740833	31.01
79	Gilchrist SE	1104025	10760707	29.637799	-82.689082	40.13
80	Ginnie Springs	1101522	10832838	29.836033	-82.700300	22.47
81	Gorenberg	1185644	10756548	29.629380	-82.432010	41.55
82	Greg and Cindy Jones	1142799	10808549	29.770853	-82.569079	32.42
83	Gresham	1156492	10769949	29.665210	-82.524320	37.44
84	Grimes Wilkes	1242973	10791296	29.726770	-82.252740	56.14
85	High Springs Sprayfield	1125320	10817109	29.793726	-82.624549	29.43
86	Hines	1144508	10769181	29.662660	-82.562020	37.26
87	Hogle	1166086	10778231	29.688330	-82.494450	39.61
88	Holliman	1187423	10709833	29.500970	-82.424610	43.69
89	Jeff Pratt	1102137	10809008	29.770534	-82.697253	28.75

90	Joan Pocklington	1154967	10849188	29.883050	-82.532430	31.95
91	Jones	1116543	10744548	29.593860	-82.648960	41
92	Julie Pocklington	1138958	10794892	29.733154	-82.580598	32.98
93	Karst Environmental	1097867	10825143	29.814727	-82.711465	24.98
94	Laurie Hodson	1106268	10841063	29.858840	-82.685712	22.37
95	LeClaire	1057050	10818854	29.795707	-82.839835	25.44
96	Leon Daniel Douglas	1082849	10861394	29.913778	-82.760562	22.8
97	Loncala North	1109589	10821716	29.805775	-82.674349	26.8
98	Loncala Office	1127976	10809221	29.772138	-82.615829	31.07
99	Loncala Ranch	1116284	10797459	29.739342	-82.652147	33.66
100	Loncala South	1109271	10797310	29.738654	-82.674237	31.72
101	M 0013 Moss Bluff	1358168	10555878	29.082147	-81.884138	49.34
102	M 0021 Salt Run FA	1422013	10638948	29.311833	-81.685725	14.8
103	M 0025 CE54 Gores Landing	1340700	10633908	29.296416	-81.940794	43.42
104	M 0026 CE47 at Silver Springs	1311227	10596671	29.193308	-82.032247	41.22
105	M 0031 CE36 at Pedro	1282517	10521406	28.985560	-82.119999	44.54
106	M 0052 FORT MCCOY FIRE TOWER UFA	1308874	10660224	29.368060	-82.041390	47.28
107	M 0367 Huff UFA McIntosh	1251735	10686731	29.439444	-82.221667	48.06
108	M 0441 G&M RANCH NR ORANGE SPRINGS	1335628	10707861	29.499720	-81.958610	51.3
109	M 0443 CITRA RANCH NR ISLAND GROVE	1302185	10683509	29.431940	-82.063060	51.3
110	M 0445 Tiger Den Replacement at Ocklawaha	1340499	10547948	29.059958	-81.939269	46.97
111	M 0463 Ft. McCoy Elementary School 6	1330778	10666597	29.386110	-81.972780	49.17
112	M 0465 Belleview Elementary School at Belleview	1303241	10545248	29.051666	-82.055833	44.33
113	M 0467 Lake Weir Middle School at Lady Lake	1326149	10525561	28.998055	-81.983611	46
114	M 0471 FOREST RD 75 WELL	1367948	10681757	29.428610	-81.856390	20.21
115	M 0483 Blue House at Starkes Ferry	1373353	10523998	28.994754	-81.835882	50.32
116	MAHAFFEY UFA	1213963	10692802	29.455000	-82.340560	50.9
117	Majors	1182990	10761075	29.641740	-82.440540	41.63
118	Mark Clark	1159608	10790875	29.722867	-82.515371	35.74
119	Mark Lander	1133250	10819811	29.801461	-82.599667	31.65
120	McDilda	1127369	10763515	29.646434	-82.615729	36.16

121	McGurn Investments HRS G 06	1223379	10770177	29.668090	-82.313720	43.32
122	Mike Mcalhaney	1129558	10849322	29.882467	-82.612610	32.22
123	Milne	1140193	10841841	29.862300	-82.578730	31.69
124	Milton Stevenson	1087315	10846681	29.873511	-82.745763	17.24
125	MW 1 F	1227422	10808871	29.774630	-82.302360	52.97
126	MW 2 F	1223190	10799377	29.748390	-82.315360	41.68
127	MW 3 F	1223617	10792242	29.728780	-82.313760	29.58
128	MW 5 F	1275430	10767387	29.661940	-82.149720	71.32
129	MW FL 13	1241278	10790162	29.723600	-82.258040	54.41
130	NE 2D G 24	1245872	10787054	29.715190	-82.243460	57.74
131	Newberry Cemetary	1126860	10760106	29.637039	-82.617183	37.38
132	Newmans	1232682	10795435	29.737840	-82.285310	48.08
133	Olsen	1291137	10808494	29.775420	-82.101490	73.79
134	P 0001 Swan Lake Drainage	1320979	10787763	29.719150	-82.006841	77.28
135	P 0123 DHQ FA	1420051	10767042	29.664158	-81.694275	27.08
136	P 0132 Greenways at Rodman	1376375	10722475	29.540779	-81.830823	29.88
137	P 0164 San Mateo at San Mateo	1457541	10739825	29.589856	-81.575781	15.39
138	P 0166 Camp Kateri at Orange Spg	1333619	10714441	29.517772	-81.965099	58.39
139	P 0172 Orange Mill	1458146	10765019	29.659166	-81.574266	17.13
140	P 0246 Thunderbird Airport at Lake Como	1459317	10697865	29.474455	-81.569547	30.06
141	P 0408 Fruitland	1439274	10701120	29.483125	-81.632608	17.45
142	P 0427 Frontier Dance Hall FA	1406004	10674984	29.410694	-81.736683	9.92
143	P 0510 Hollister Work Center at Hollister	1387359	10753231	29.625591	-81.796936	47.24
144	P 0696 Silver Pond	1473009	10662962	29.378619	-81.526011	25.52
145	P 0705 Niles Rd Wells	1464634	10672671	29.405222	-81.552458	27.47
146	P 0735 Middle Rd L FA	1455515	10654661	29.355556	-81.580824	11.13
147	P 0736 Middle Rd U FA	1455515	10654661	29.355556	-81.580824	8
148	P 0772 Lake Grandin at Lake Grandin	1360156	10769551	29.669938	-81.882963	70.22
149	P 0776 Marvin Jones Rd	1443690	10675790	29.413513	-81.618302	23
150	P 0817 at Lake Broward	1453606	10719984	29.535224	-81.587848	24.18
151	P 0891 E. H. Miller School at Palatka	1420898	10755291	29.631850	-81.691388	26.87
152	P 2037 Stella Lake at Crescent City	1476954	10682329	29.431944	-81.513888	21.78

153	P 4043 Murphy Island at Satsuma	1433262	10732242	29.568644	-81.652055	25.18
154	P 4083 Etonia Buck Spg Rd at Bardin	1384339	10817321	29.801819	-81.807847	66.78
155	P 4086 Etonia East V Rd at Baywood	1379489	10788619	29.722777	-81.822500	68.44
156	Pamela July	1120446	10861426	29.915394	-82.641904	31.43
157	Pete Butt	1098536	10835800	29.844056	-82.709855	21.92
158	Poe Springs Lodge	1116309	10828939	29.825904	-82.653490	25.67
159	Poe Springs Production	1116274	10827790	29.822743	-82.653549	25.72
160	Poe Springs Staff Gauge	1117734	10828783	29.825530	-82.648990	25.83
161	PUGH Kerr	1149872	10817574	29.795930	-82.547170	32.07
162	Raulerson	1087359	10817859	29.794266	-82.744250	28.94
163	Robert Alford	1113592	10862883	29.919130	-82.663605	34.26
164	ROMP 124 D 8	1089998	10541089	29.033330	-82.723056	2.22
165	ROMP 125 D 6	1100515	10543970	29.041670	-82.690278	1.89
166	ROMP 134 6 UFA NR WILLISTON	1176762	10686885	29.437500	-82.457220	43.15
167	Ronald Weiss	1080758	10855048	29.896241	-82.766855	13.98
168	Santa Fe River at Fort White	1089041	10843545	29.864960	-82.740170	20.98
169	Santa Fe River at High Springs	1130685	10838583	29.852980	-82.608580	31.23
170	Santa Fe River at Hildreth	1051285	10861142	29.911720	-82.860160	6.27
171	SMITH BROTHERS NR RALEIGH	1196446	10698866	29.471110	-82.395830	52.25
172	SRWMD NE of Newberry	1131596	10773630	29.674410	-82.602863	34.75
173	Stahmer	1197926	10764438	29.651490	-82.393650	50.68
174	Sulek	1101181	10861459	29.914715	-82.702708	27.67
175	Tipton	1159441	10728622	29.551670	-82.513340	40.75
176	TREEO Center	1191019	10753137	29.620180	-82.414960	45.67
177	Tricia Vito Rauseo	1069236	10854015	29.892910	-82.803160	53.95
178	Truluck	1143380	10755541	29.625110	-82.564990	38.34
179	UF Lake Alice MW 3D G 31	1207366	10758530	29.635550	-82.363710	47.13
180	United Methodist Church	1220287	10765525	29.655200	-82.323290	43.5
181	Unk 1	1063362	10751553	29.610940	-82.816610	8.06
182	Unk 10	1166853	10726937	29.547300	-82.489960	41.65
183	Unk 11	1086211	10792551	29.724630	-82.746660	42.53
184	Unk 12	1189267	10865096	29.928010	-82.424820	46.8

185	Unk 13	1203381	10938293	30.129770	-82.383050	49.5
186	Unk 14	1233556	10860011	29.915460	-82.284820	52.8
187	Unk 15	1269723	10891786	30.003910	-82.171670	52.82
188	Unk 16	1254269	10835601	29.848950	-82.218620	56.74
189	Unk 17	1297642	10847330	29.882400	-82.082130	76.78
190	Unk 2	1084950	10886418	29.982670	-82.755140	23.91
191	Unk 3	1087357	10898340	30.015550	-82.748110	27.07
192	Unk 4	1095975	10908965	30.045120	-82.721390	28.96
193	Unk 5	1133865	10828087	29.824240	-82.598090	31.33
194	Unk 6	1131196	10863109	29.920440	-82.608050	31.41
195	Unk 7	1150840	10829274	29.828140	-82.544610	31.75
196	Unk 8	1148100	10906045	30.039140	-82.556530	38.36
197	Unk 9	1199929	10803264	29.758330	-82.388810	40.13
198	VISA #1	1169418	10778374	29.688840	-82.483960	39.78
199	VISA #2	1191336	10772863	29.674440	-82.414720	43.39
200	VISA #3	1184507	10771227	29.669710	-82.436160	43.41
201	VISA #4	1198816	10758108	29.634110	-82.390610	48
202	Waters G 17	1224795	10816693	29.796060	-82.310920	53.92
203	Willis	1186391	10862583	29.921000	-82.433800	44.26
204	WUFT Transmission Tower G 30	1194871	10788075	29.716390	-82.404170	44.38
205	Yates	1156251	10799091	29.745340	-82.526290	34.05

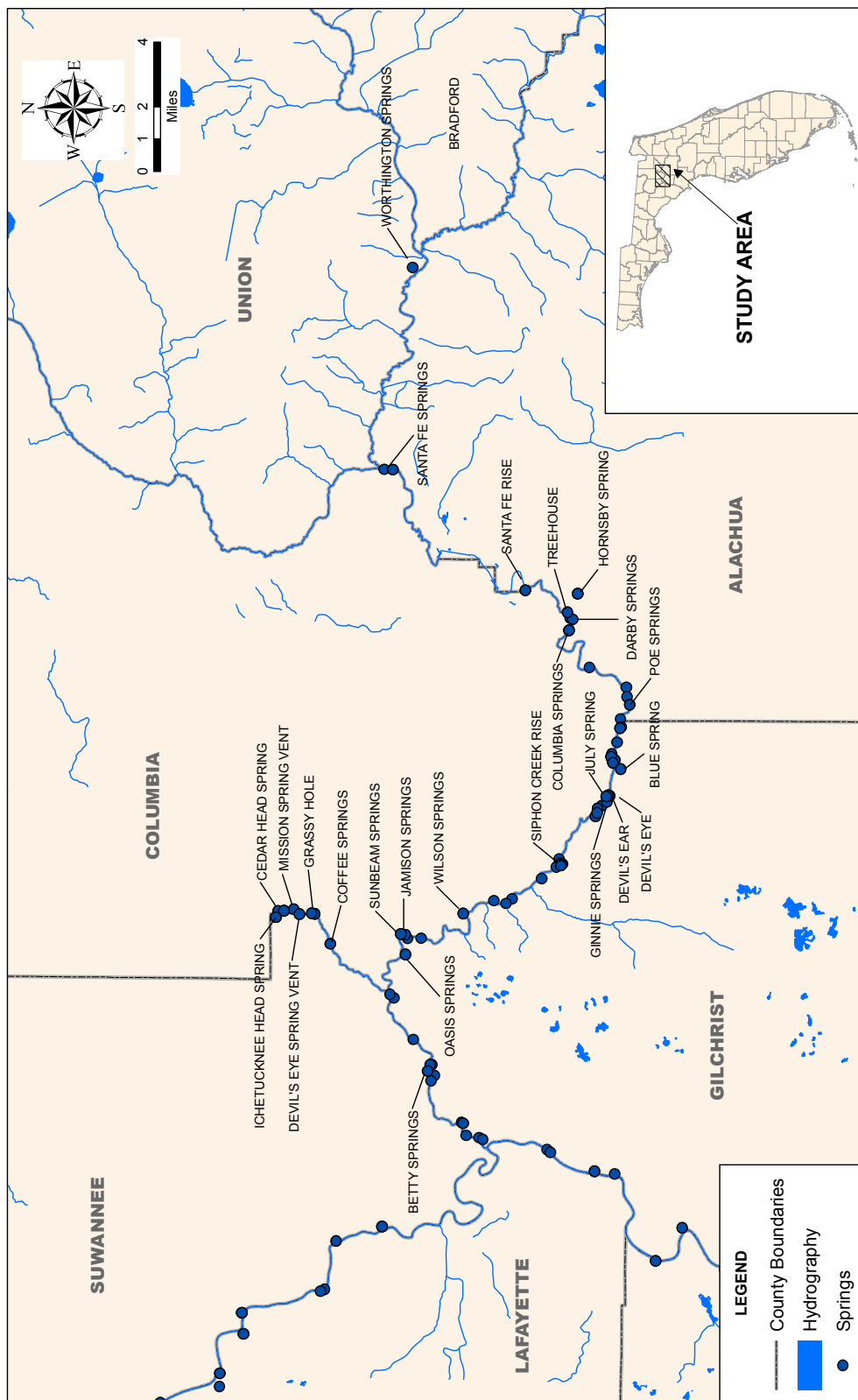


Figure 1 - Study area showing the springs along the Suwannee and Santa Fe Rivers of Florida.

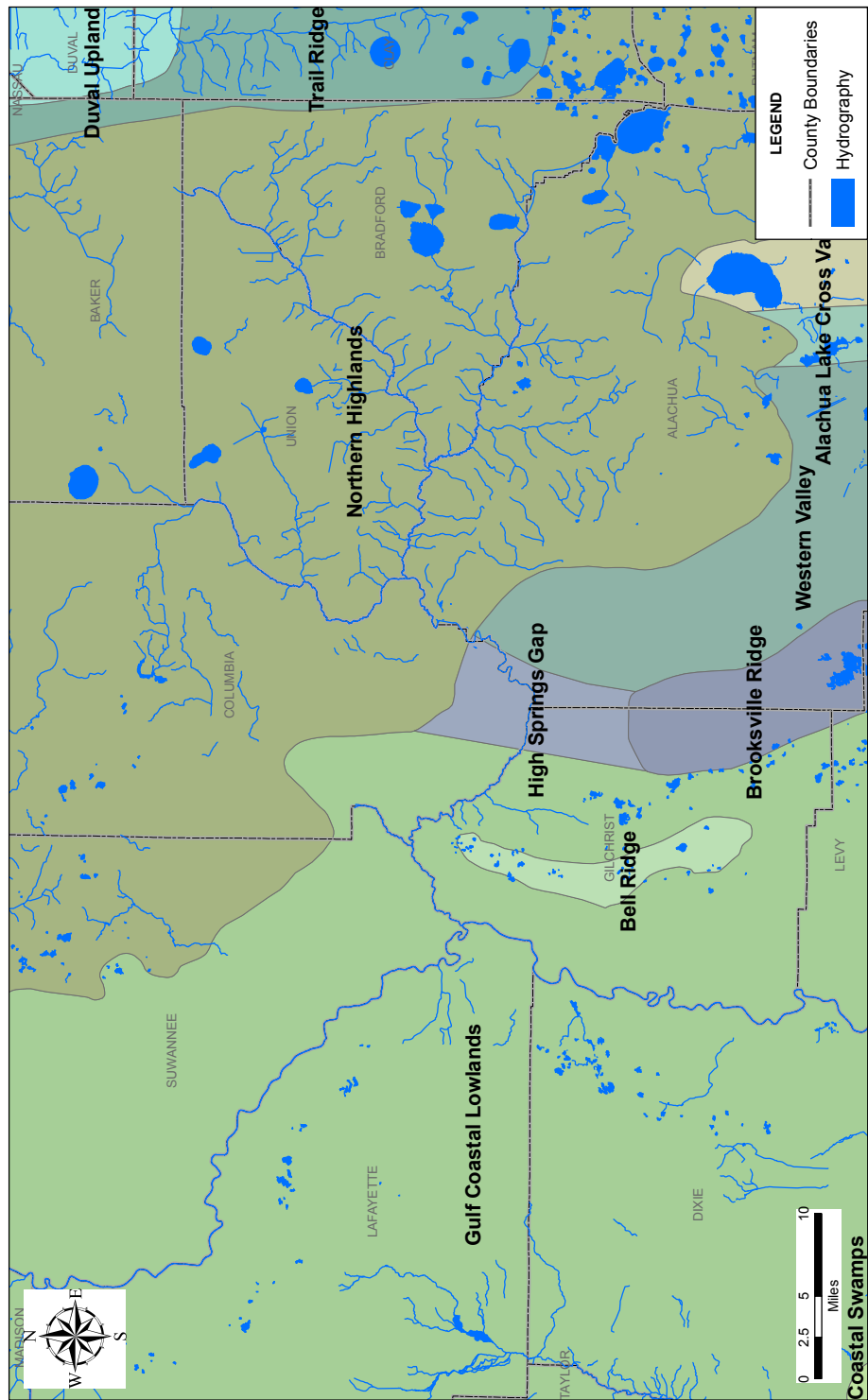


Figure 2 - Physiographic provinces within the study area. From White (1970).

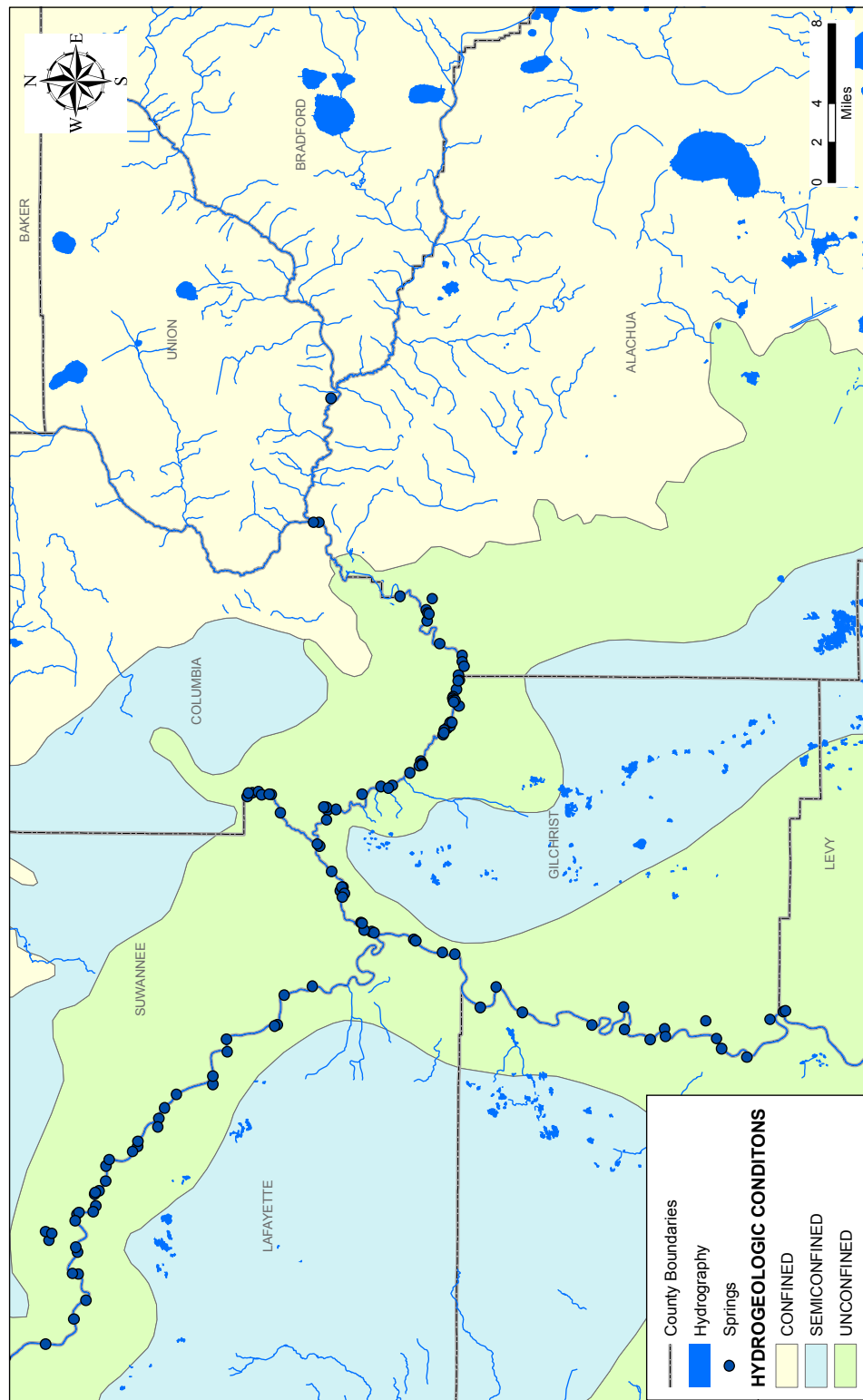


Figure 3 - Confinement of the Floridan aquifer within the study area. Data from the Suwannee River Water Management District (1980).

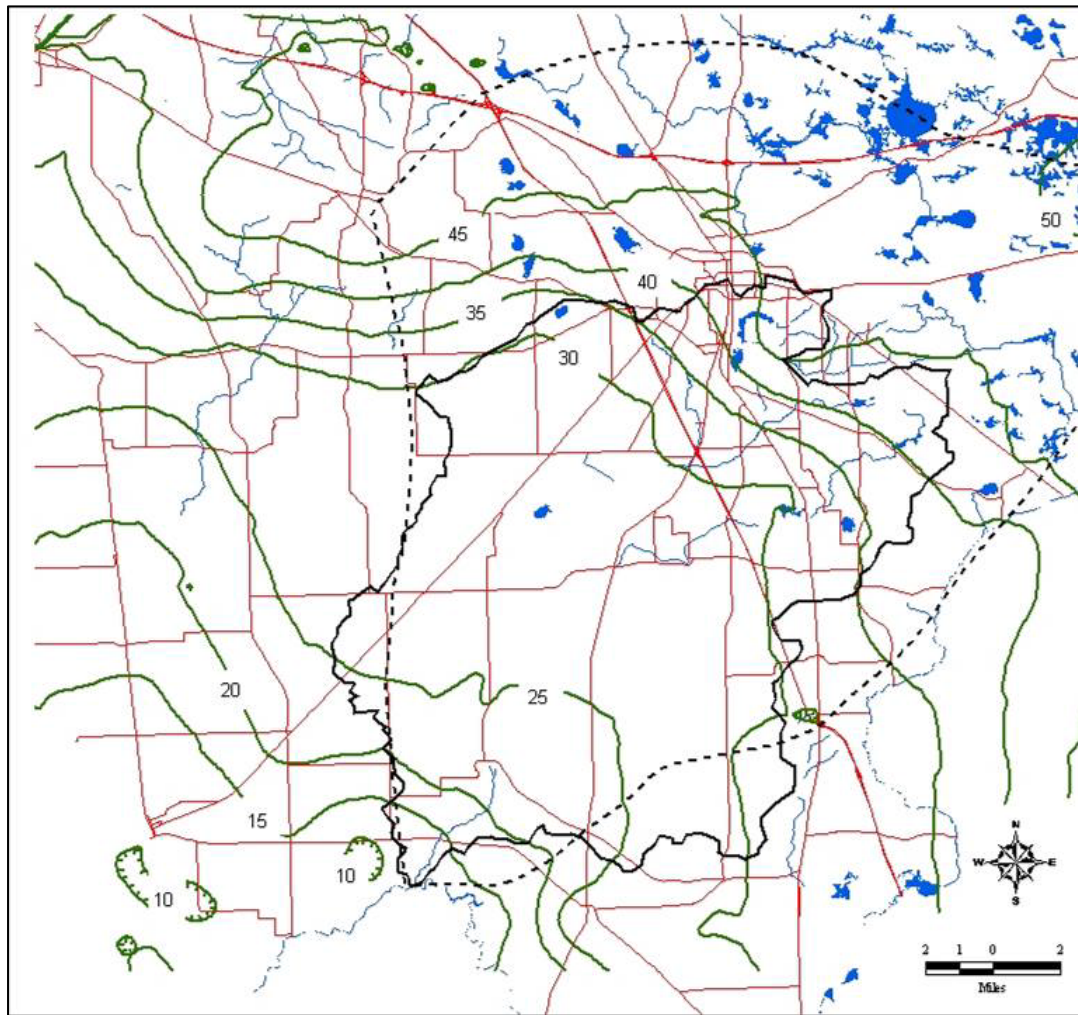


Figure 4 - Springshed delineation of the Ichetucknee Springs Group (dashed line) with upper Floridan aquifer potentiometric surface contours (green lines). From Upchurch and Champion (2003).

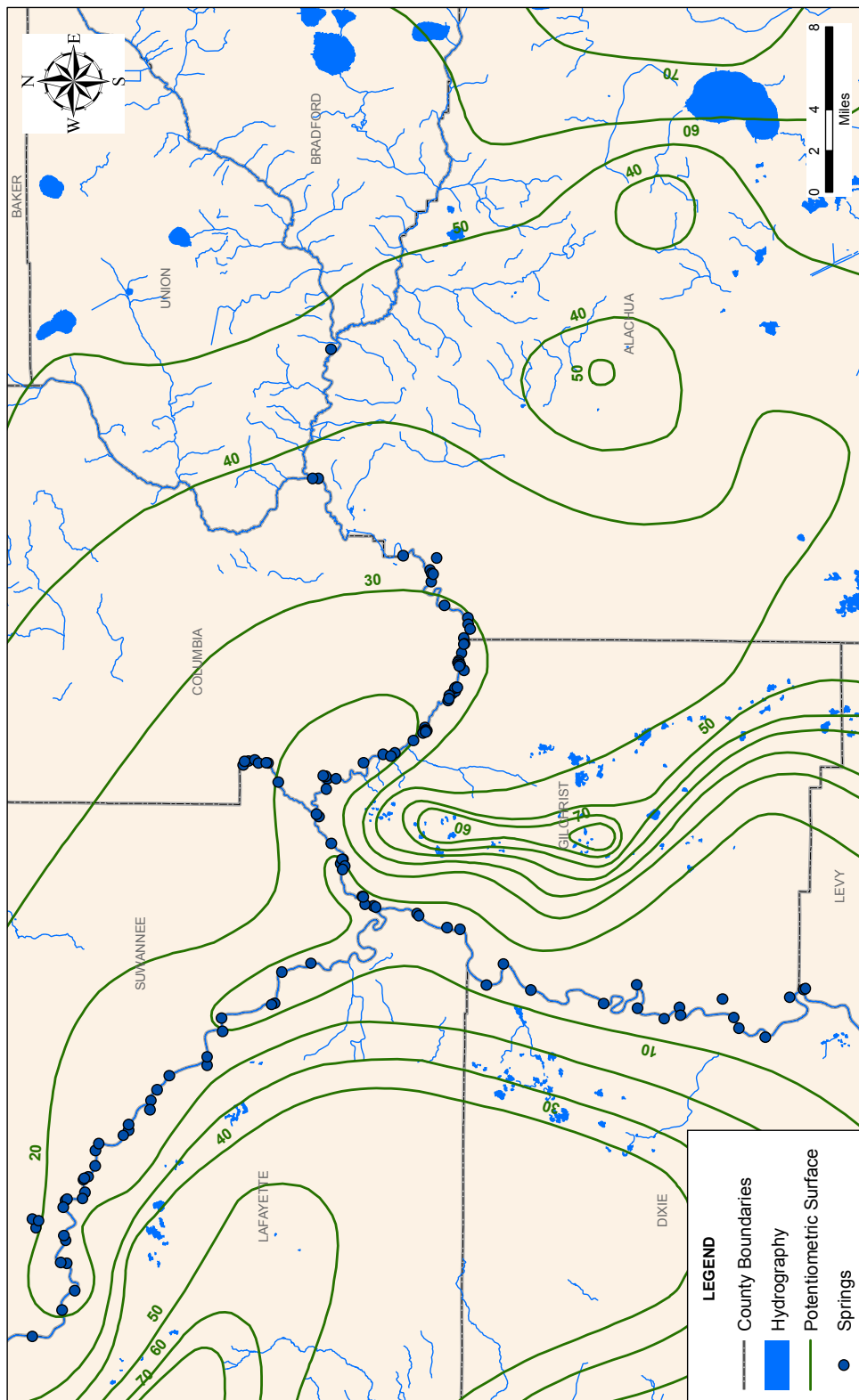


Figure 5 - Potentiometric surface of the upper Floridan aquifer in 2000. Data from the USGS.

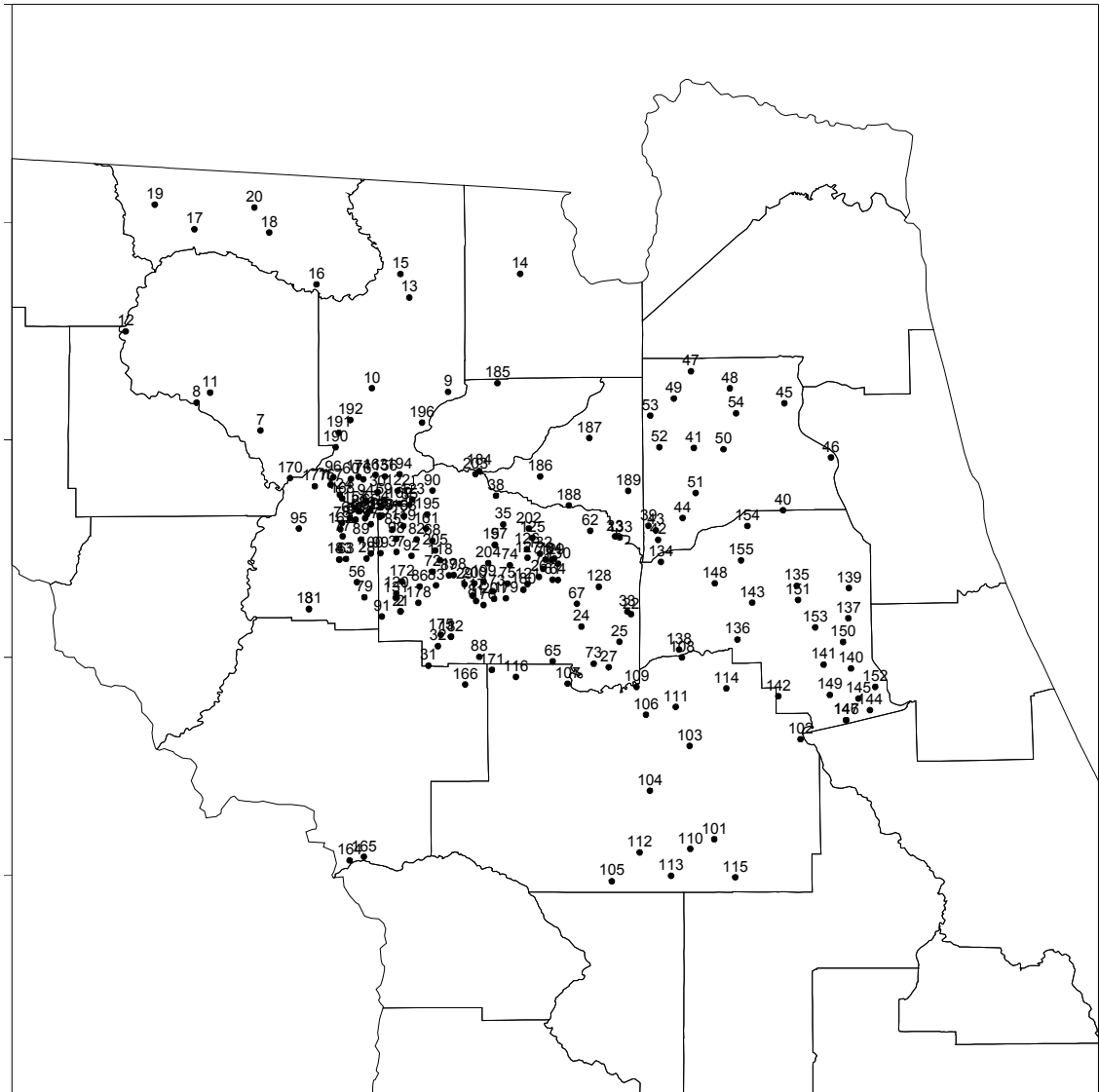


Figure 6 – Monitoring points utilized in the geostatistical analysis of the Floridan aquifer potentiometric surface. Appendix A provides a key to the index numbers.

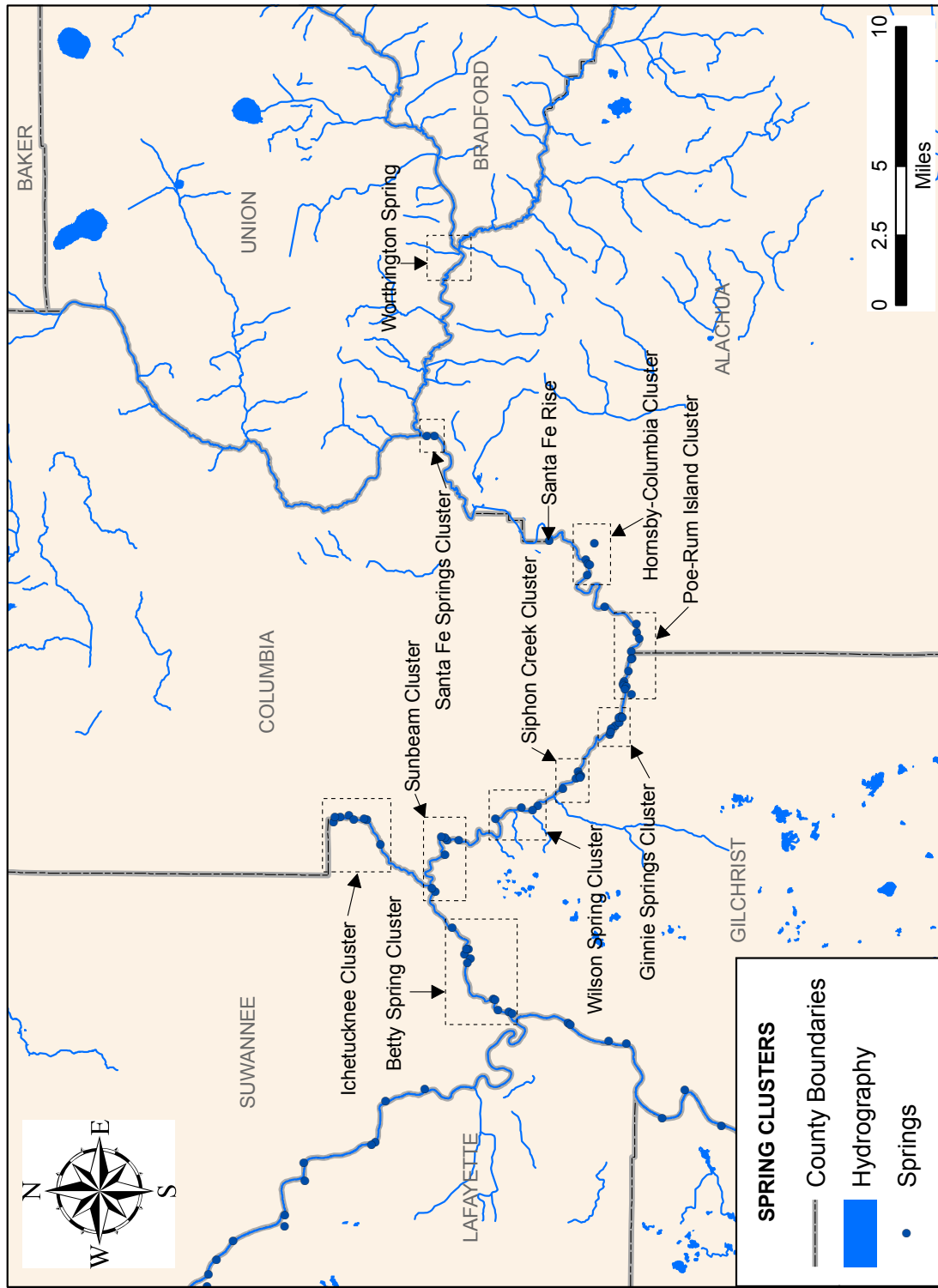


Figure 7 - Springs of the Santa Fe River divided into spring "clusters for the purpose of springshed delineation."

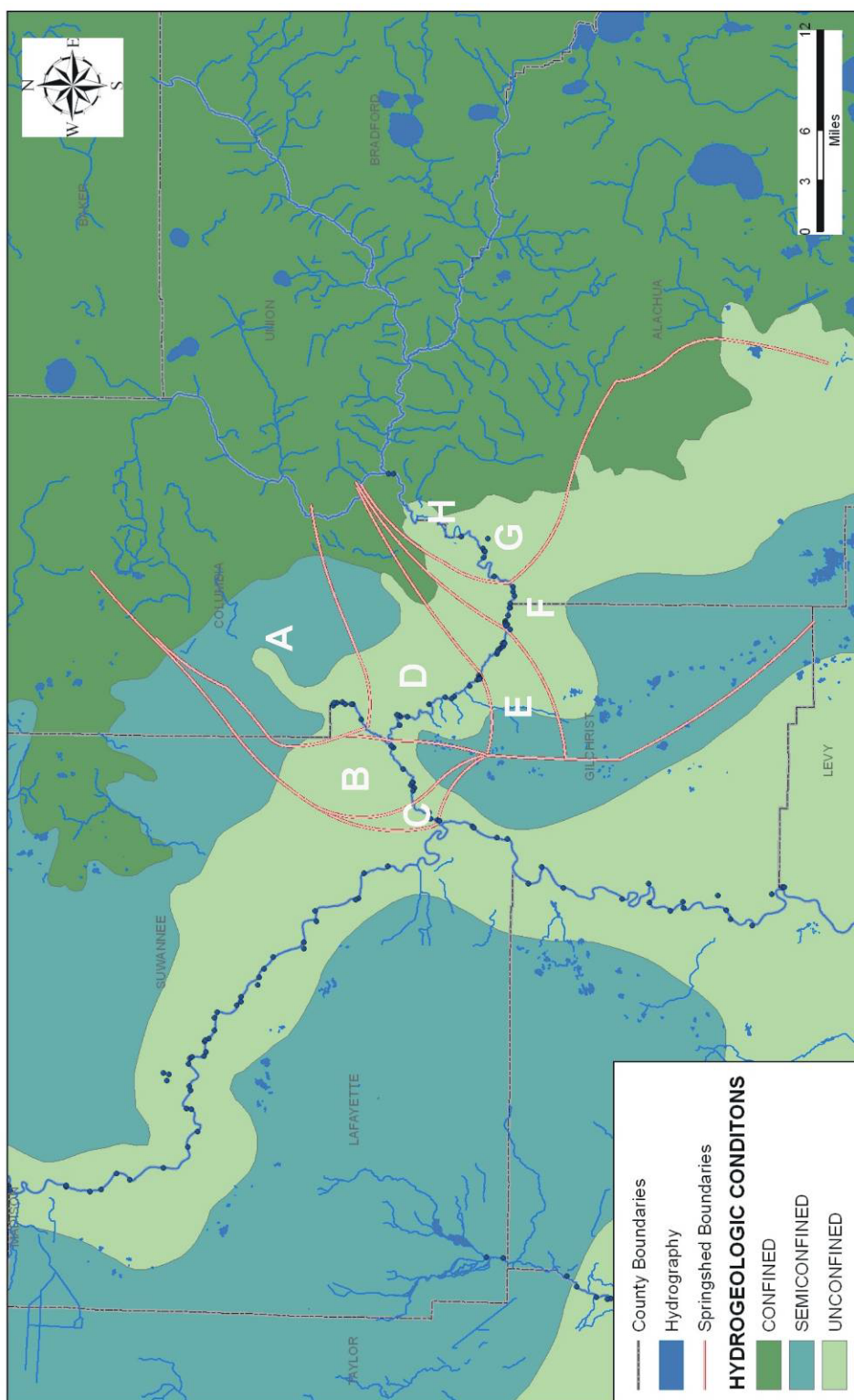


Figure 8 - Springsheds drawn from the 2000 potentiometric surface modified as discussed in the text. Springsheds were terminated at the point where the upper Floridan aquifer becomes well confined. Springsheds are as follows: A. Ichetucknee Springs Group, B. Betty Spring cluster (north), C. Betty Spring cluster (south), D. Sunbeam and Wilson Spring clusters, E. Ginnie Springs cluster, F. Poe-Rum Island Springs cluster, G. Hornsby-Columbia Springs cluster, and H. Santa Fe Rise.

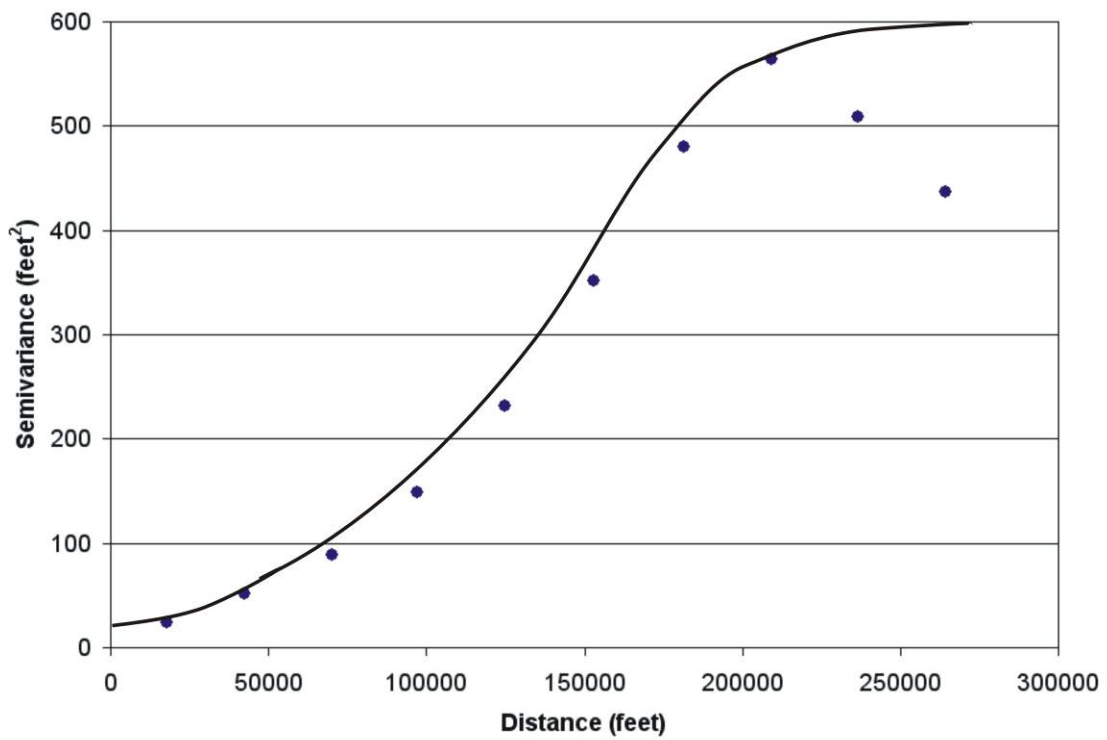


Figure 9 – Semivariogram illustrating the results of the structural analysis of the September, 2007, Floridan aquifer potentiometric surface data.

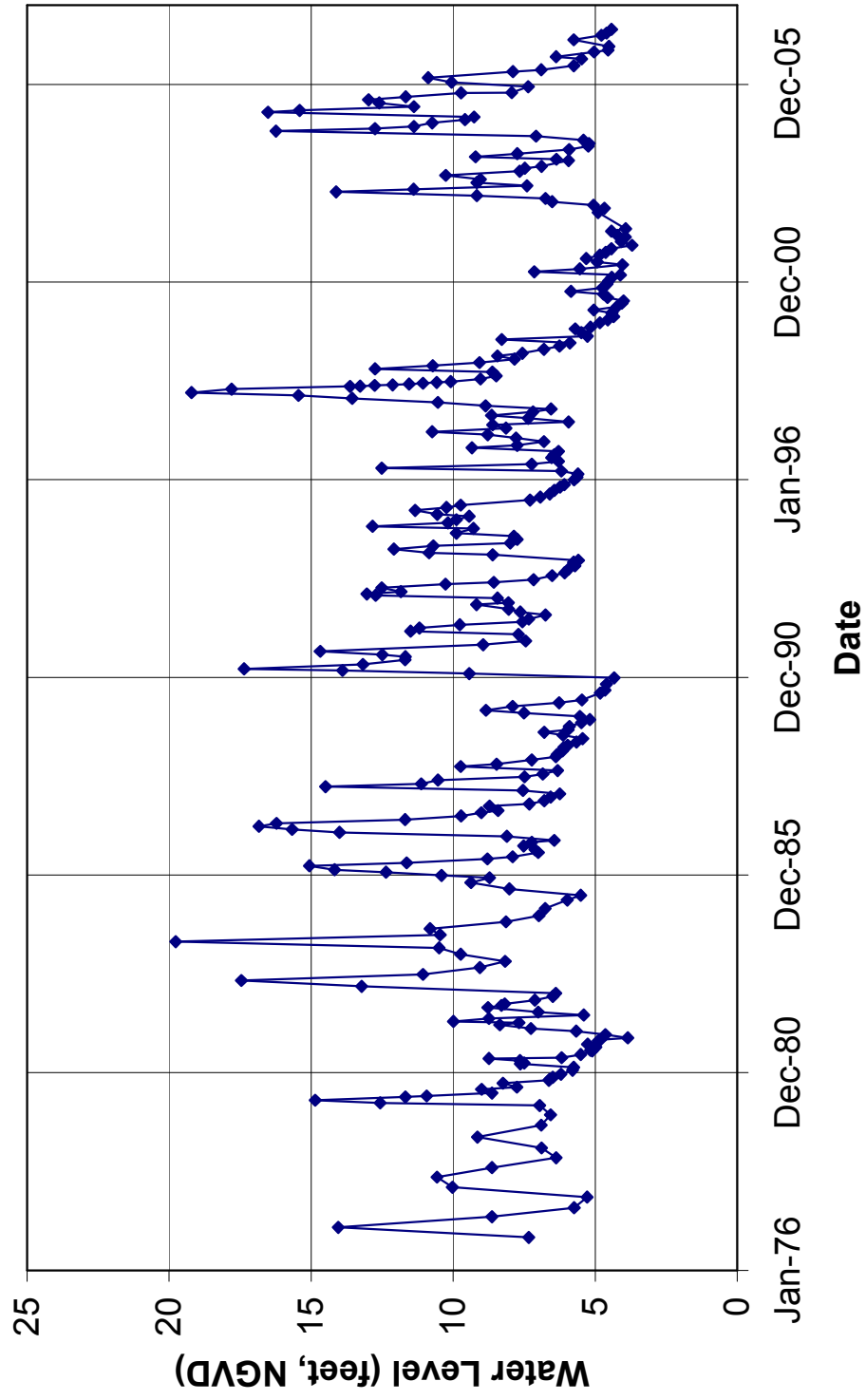


Figure 10 – Hydrograph of Floridan aquifer water levels in Well -091420001, Gilchrist County.

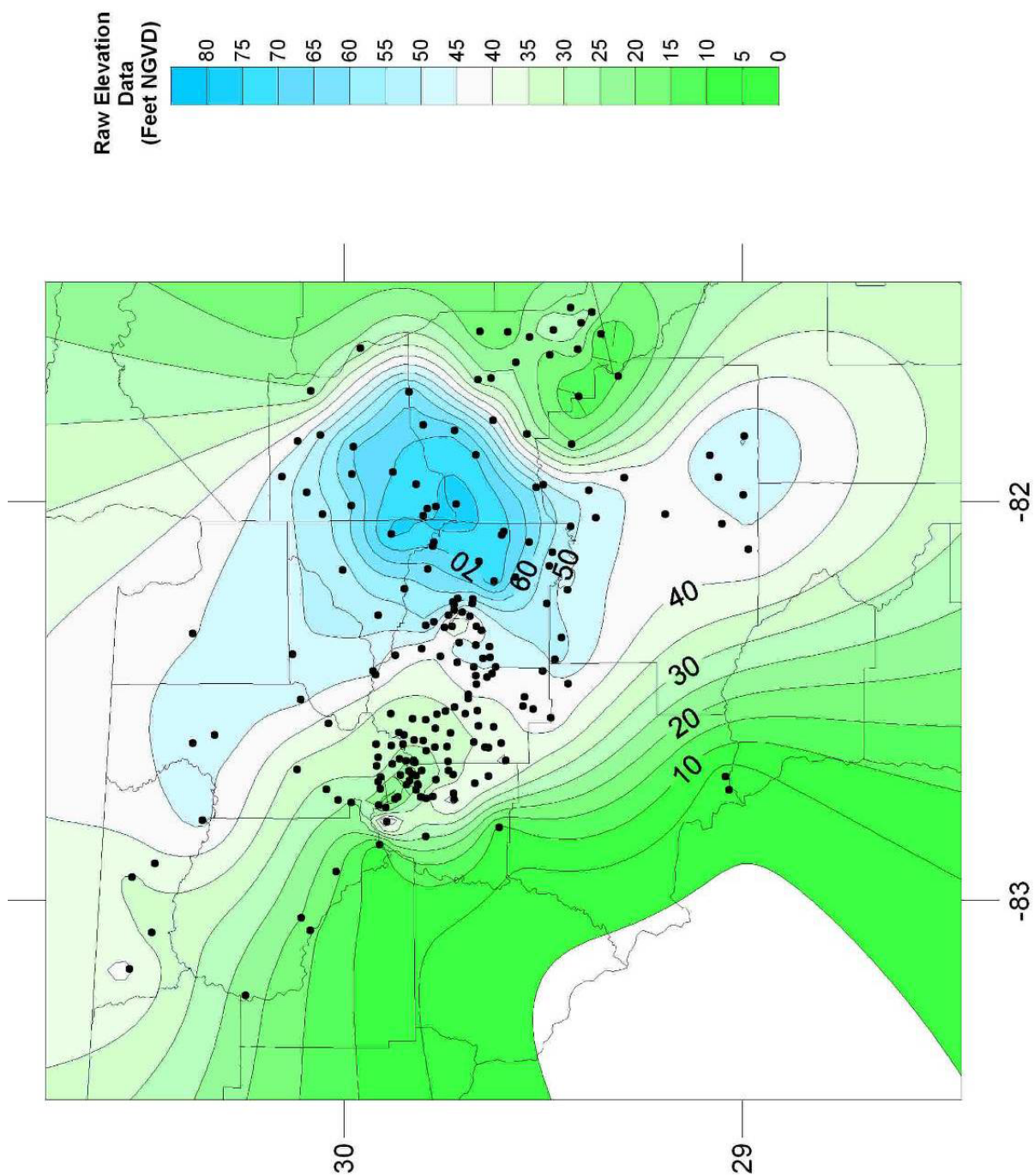


Figure 11 – Contoured regional, raw potentiometric surface data.

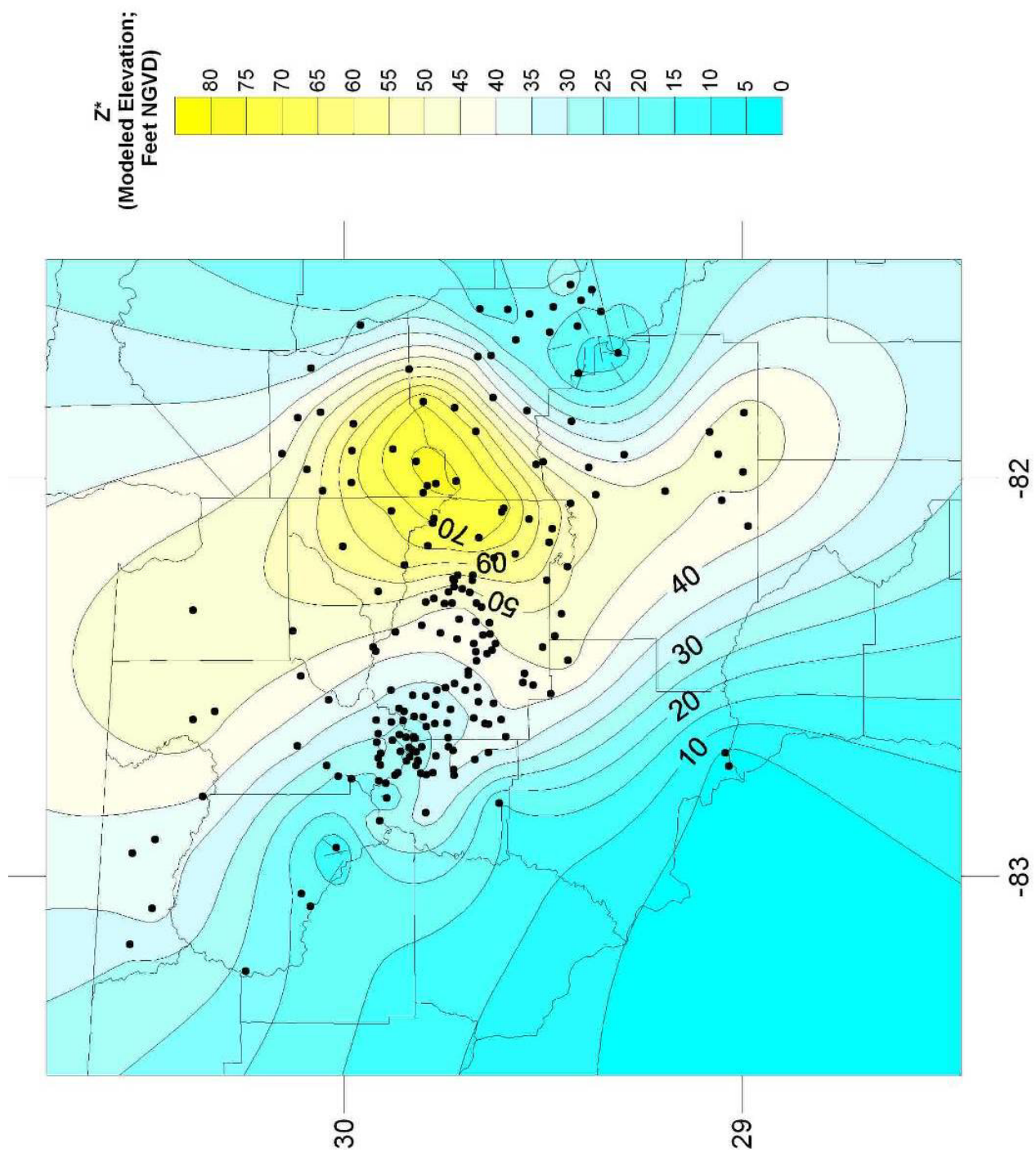


Figure 12 – Kriged regional Floridan aquifer potentiometric data (Z* output).

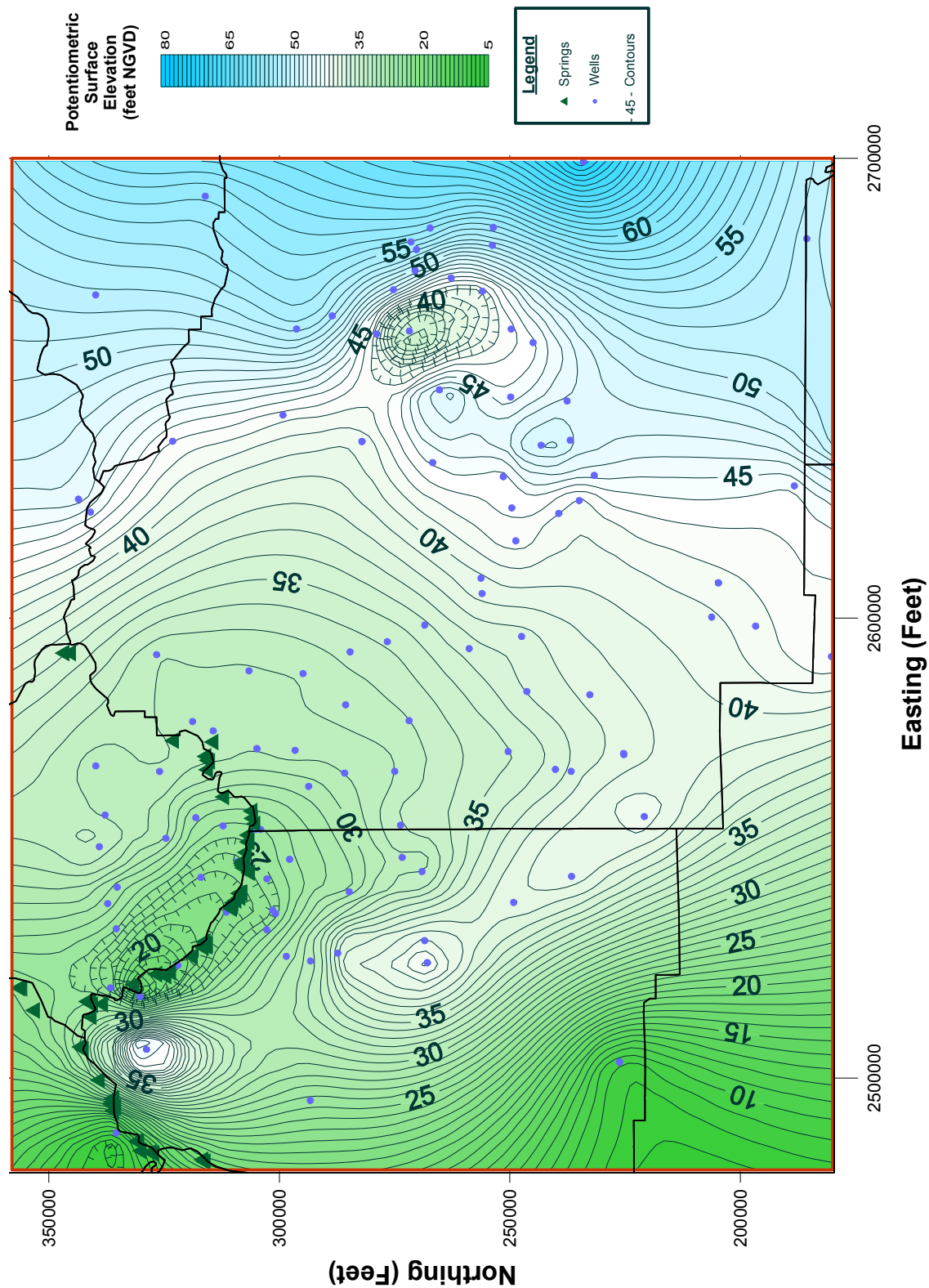


Figure 13 – One-foot contour map of raw potentiometric surface data in the Newberry Plain vicinity. Springs and monitoring wells are depicted on the map.

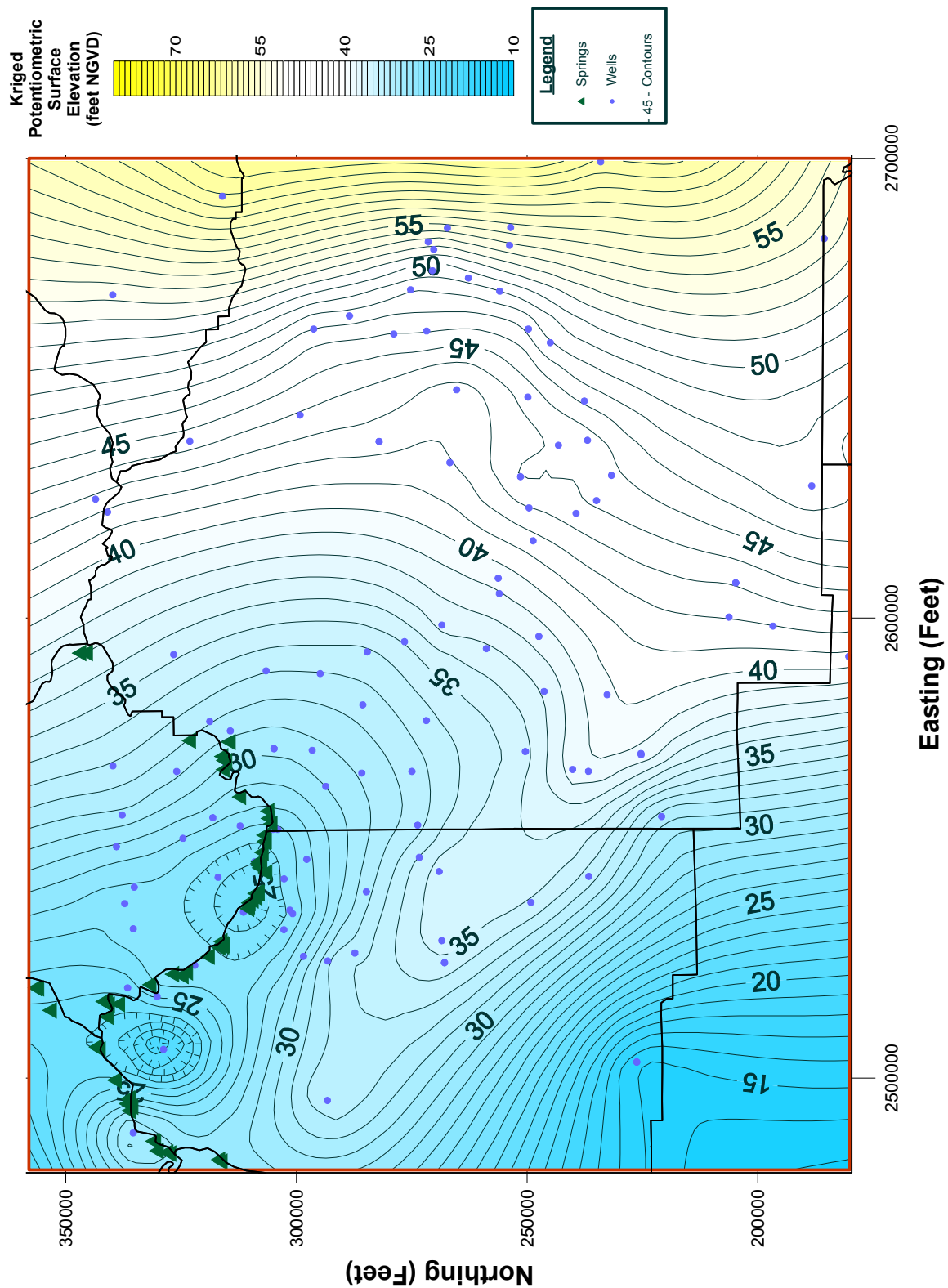


Figure 14 – Kriged potentiometric surface data (Z*) in the Newberry Plain vicinity.

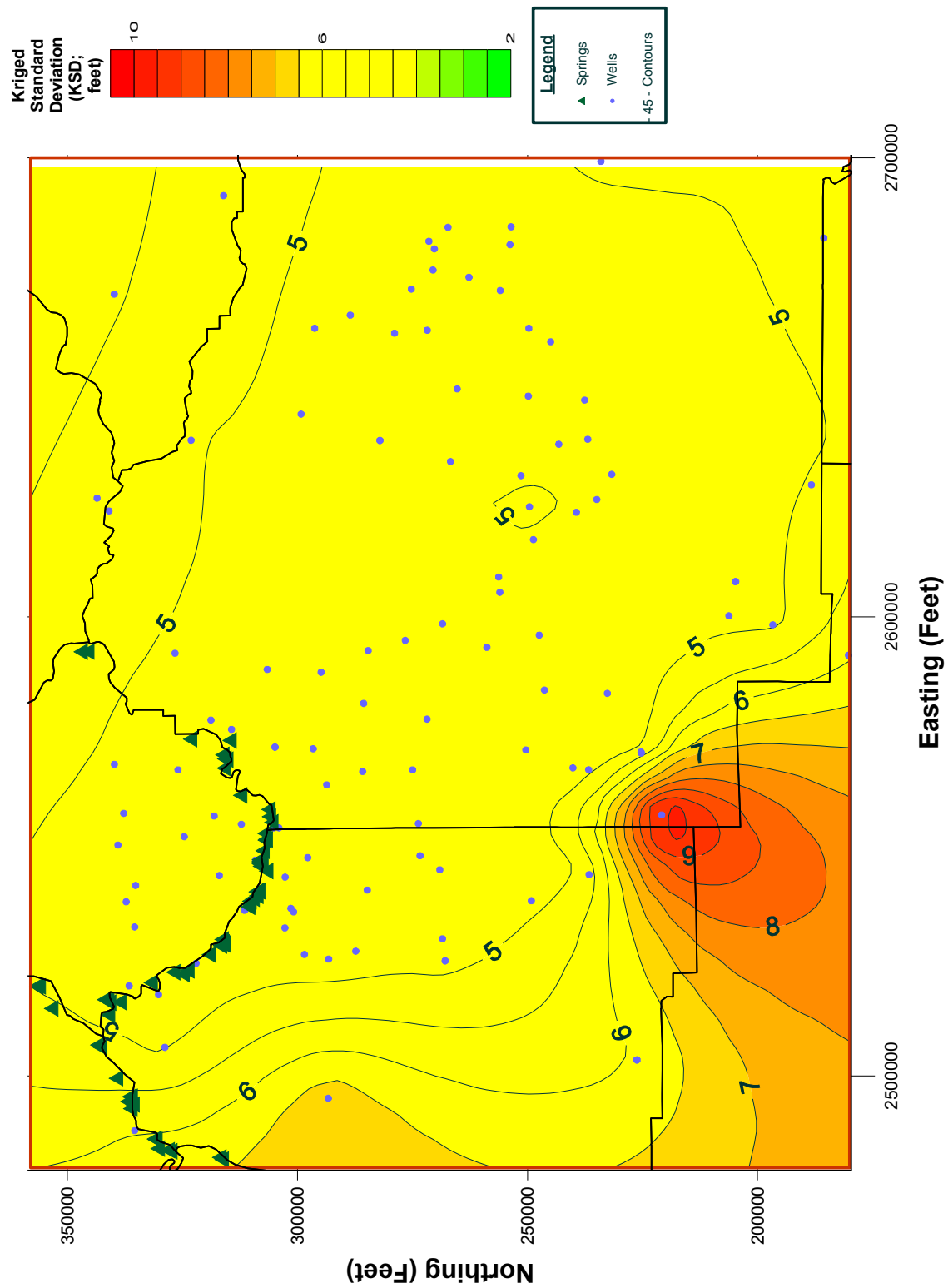


Figure 15 – Uncertainty map showing the kriged standard deviation (K_{SD}) of groundwater levels in the Newberry Plain vicinity.

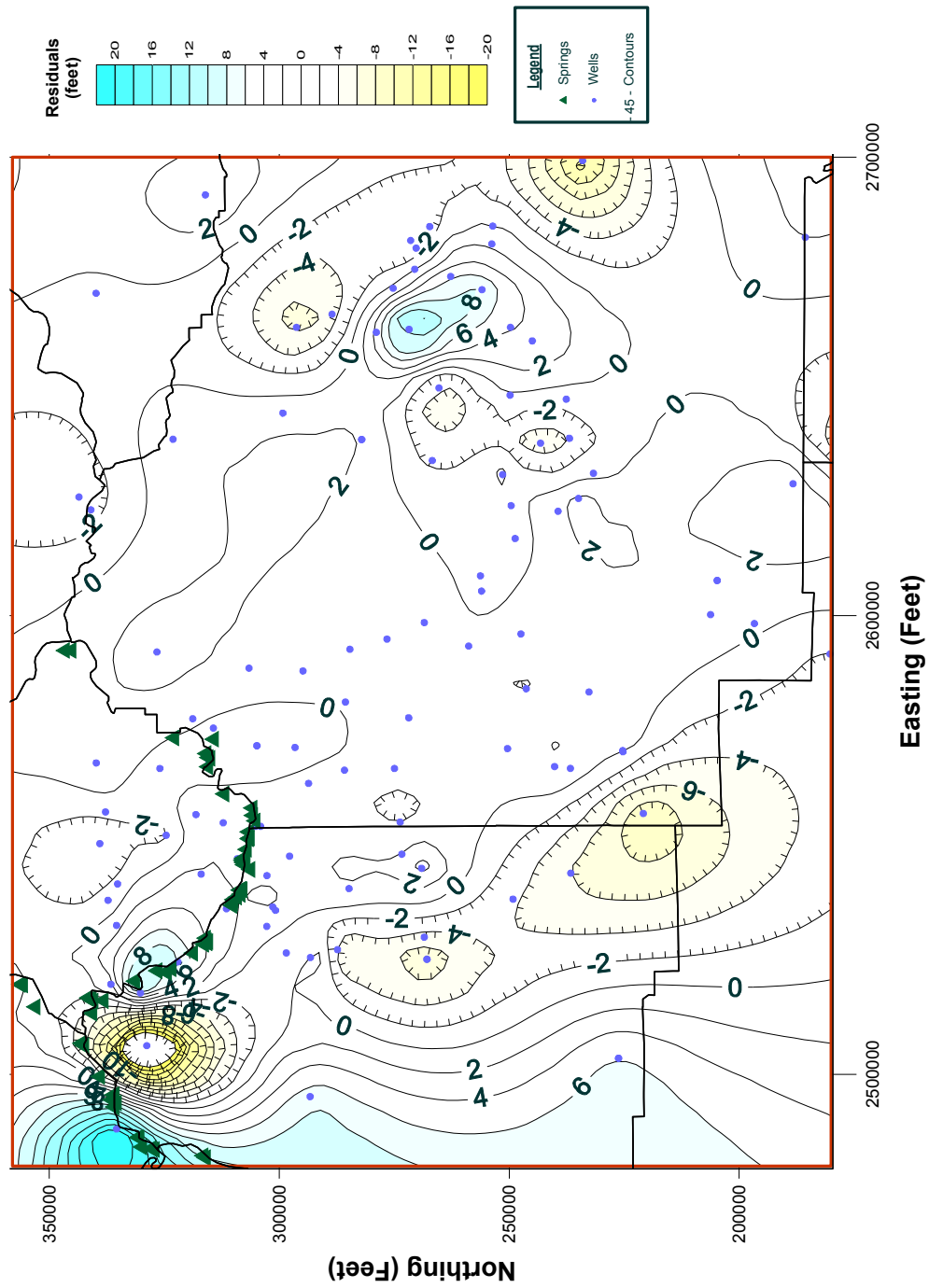


Figure 16 – Residuals from raw and kriged potentiometric data in the Newberry Plain vicinity.

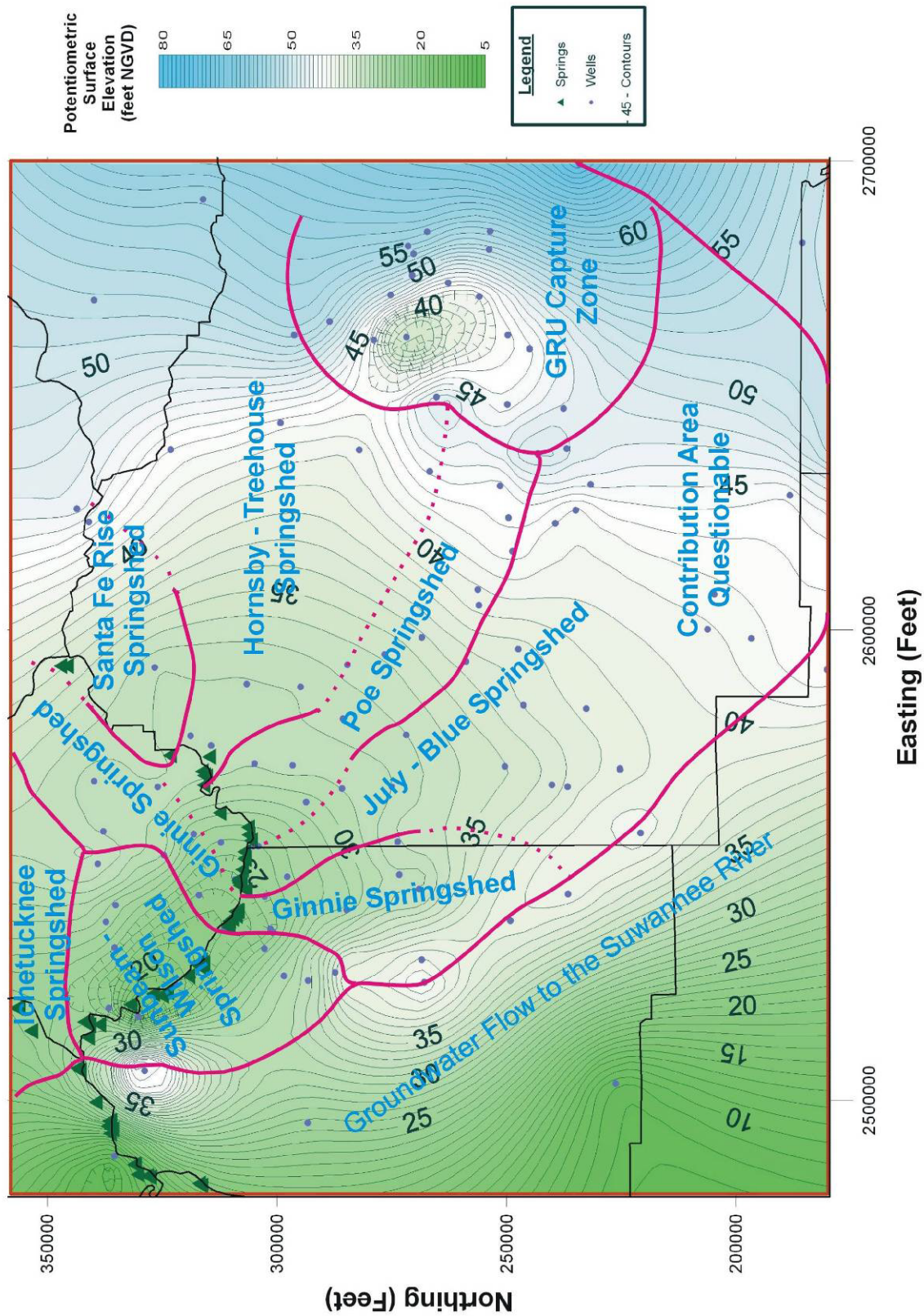


Figure 17 – Springsheds in the vicinity of the Newberry Plain delineated on the basis of the high-resolution potentiometric surface data.

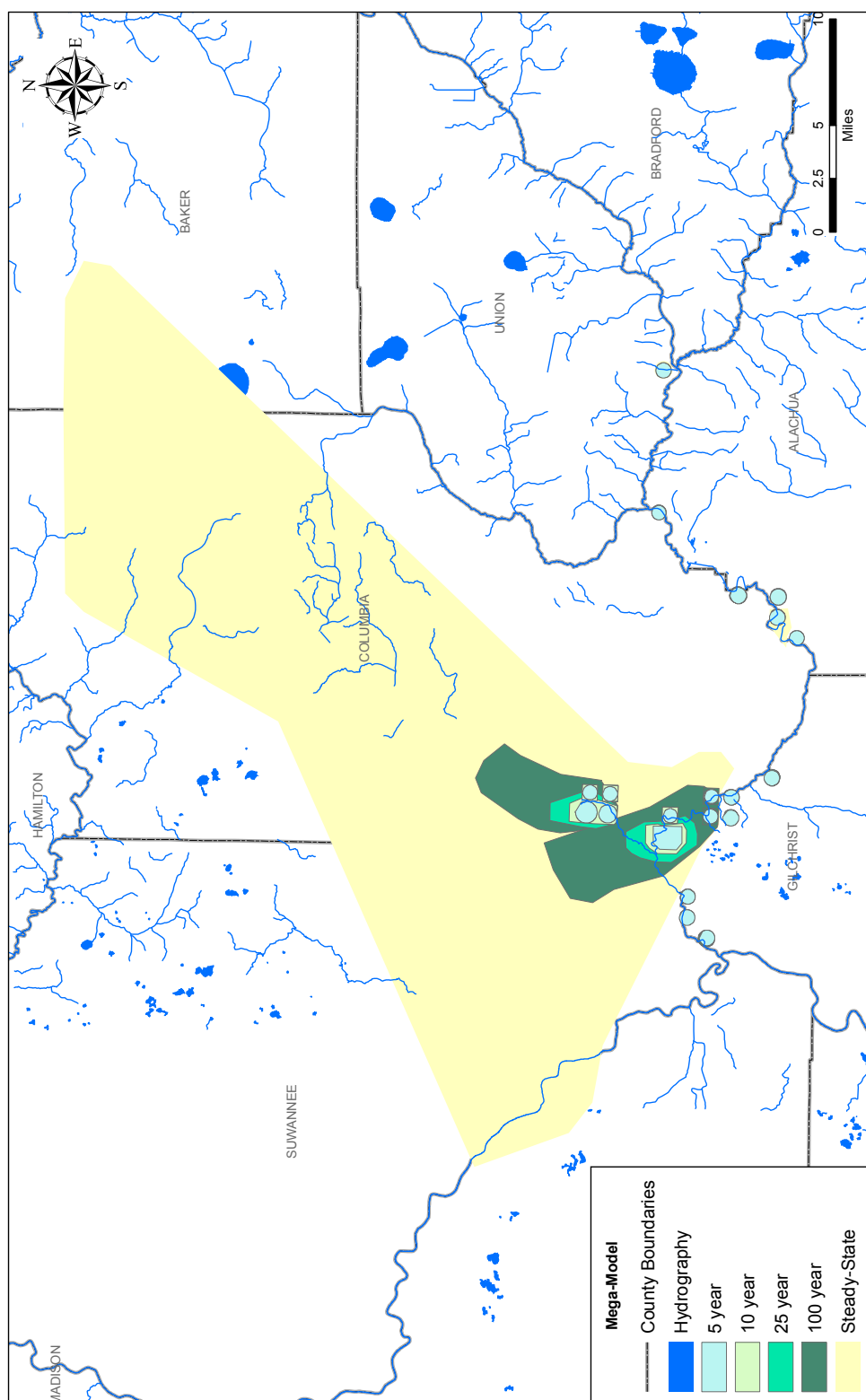


Figure 18 - Travel times for groundwater to springs of the Santa Fe. Travel times were estimated by particle tracking utilizing the USGS Megamodel (Sepúlveda, 2002)

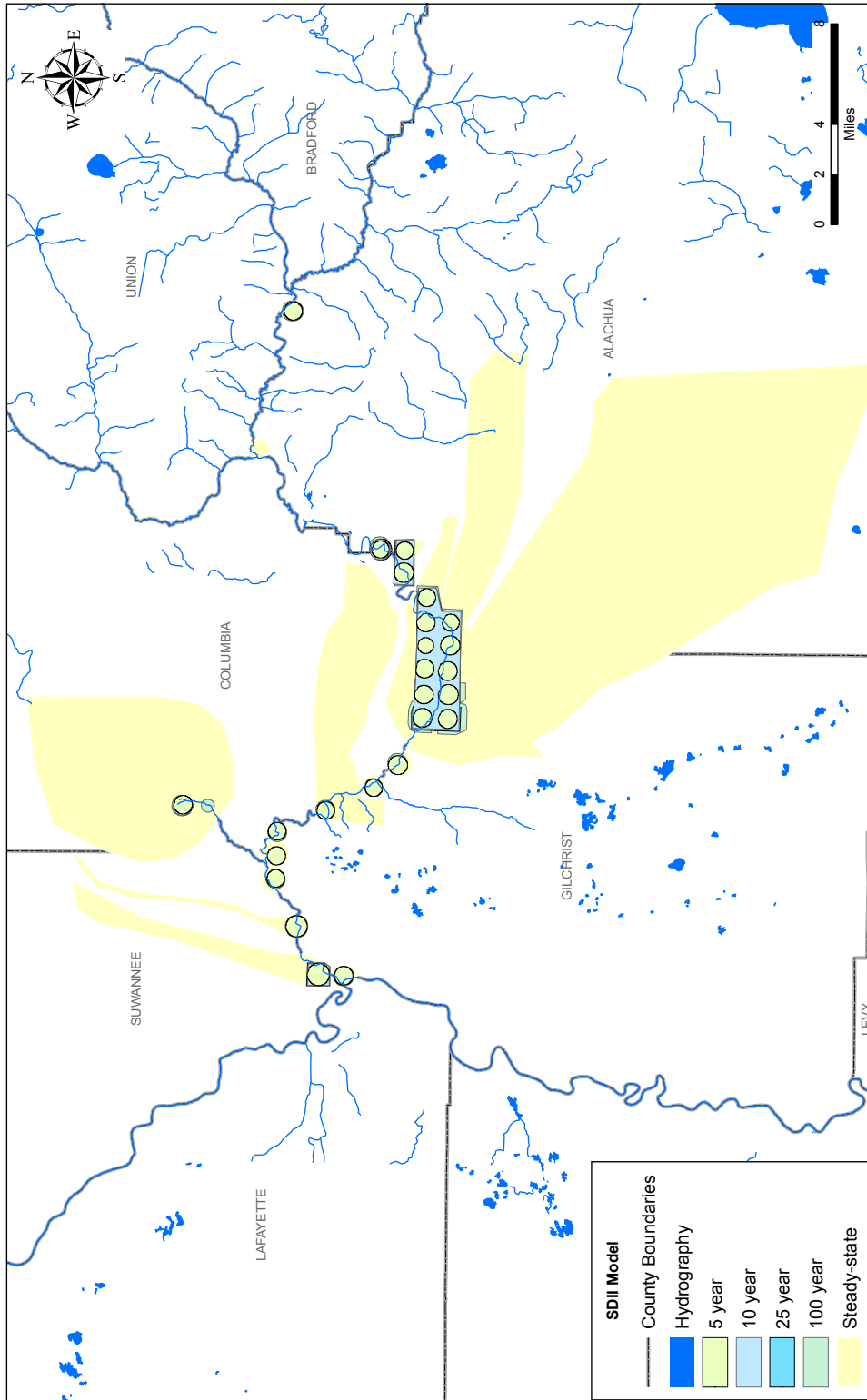


Figure 19 - Travel times for groundwater to springs of the Santa Fe. Travel times were estimated by particle tracking utilizing the Suwannee River Water Management District model (Schneider and Upchurch, 2006)

