RAS FF-6

## Hearing Docket

**From:** Emily Casey [ecasey21@hotmail.com]
**Sent:** Tuesday, June 09, 2009 11:26 PM
**To:** Docket, Hearing; Wright, Megan
**Subject:** limited appearance for Levy 1 &2

Office of Secretary of NRC,

I, Emily Casey have submitted documents via express mail, pertaining to the proposed Levy 1 and 2 nuclear power plants. They are to be considered as "limited appearance" documents.

Thank You,
Emily Casey

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Template = SECY-038

DS-03

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with Microsoft SMTPSVC(6.0.3790.3959); Tue, 9 Jun 2009 20:26:14 -0700
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From: Emily Casey <ecasey21@hotmail.com>
To: <hearingdocket@nrc.gov>, <megan.wright@nrc.gov>
Subject: limited appearance for Levy 1 &2
Date: Tue, 9 Jun 2009 23:26:14 -0400
Importance: Normal
MIME-Version: 1.0
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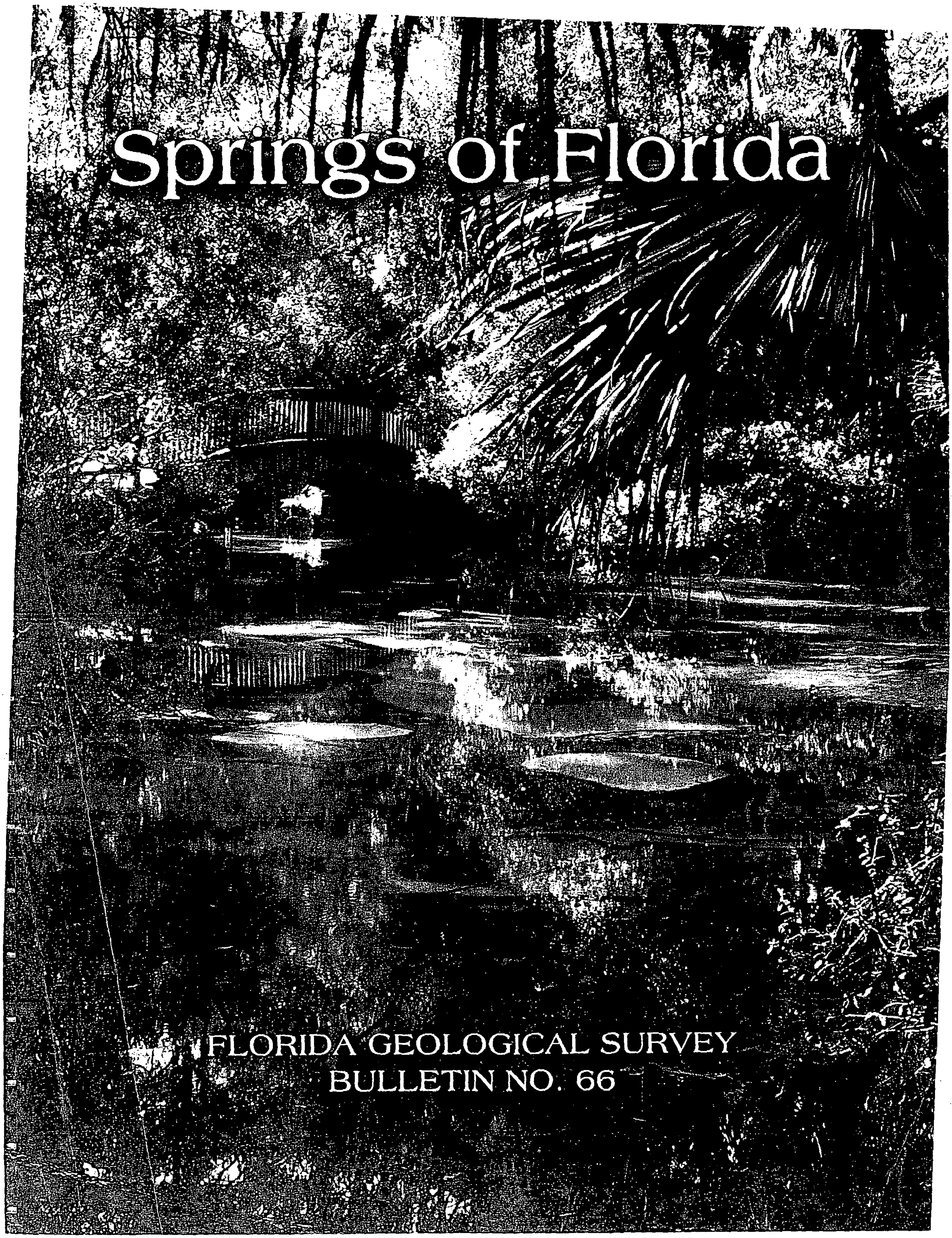
# Springs of Florida



FLORIDA GEOLOGICAL SURVEY
BULLETIN NO. 66

tion of the spring vent. The pool bottom is almost completely covered with algae and aquatic vegetation is present. The water is tinted green. The 350 ft (106.7 m) long spring run is completely covered by aquatic vegetation. The banks rise 4 ft (1.2 m) above the surface of the spring into mixed hardwood forest. The spring is located within Fanning Springs State Recreation Area, a popular swimming area with picnic pavilions, restrooms, and concessions. The larger Fanning Springs, the focal point of this recreation area, is located 400 ft (121.9 m) to the north. Discharge on August 18, 1997 measured 14.25 $ft^3$/sec[4].

### Little King Spring

**Figure 162. Little King Spring (photo by Springs Fever).**

***Location*** – Lat. 29° 06' 39.05" N., Long. 82° 38' 52.14" W. (NW¼ NE¼ NW¼ sec. 12, T. 16 S., R. 16 E.). Little King Spring is located within a dense hardwood swamp on the western side of Caruth Camp, a Sherriff's Youth Ranch. The property is on the west side of US 19/98 approximately 5 miles (8.1 km) north of Inglis. Permission to visit this spring must be obtained from the camp office.

***Description*** – Little King Spring sits in a low banked bowl-shaped depression surrounded by a wooden boardwalk. The spring pool is approximately 35 ft (10.7 m) in diameter. There are two vents, one east and one on the west side of the pool with estimated depths of 15 to 20 ft (4.6 to 6.1 m). Limestone is present near each of the vents. The spring was tannic during the August 2003 visit but is reported to flow clear during drier times. The run averages 2 ft (0.6 m) deep and 10 ft (3.1 m) wide and flows west through the swamp, eventually reaching the Gulf of Mexico in or near Withlacoochee Bay. Wooden bleachers are built on the east side of the spring for presentations. This spring is also known as Caruth Spring or Little Spring. The spring is surrounded by the Florida Sheriff's Youth Ranch.

# Little King Spring

Levy County

**Summary of Features**

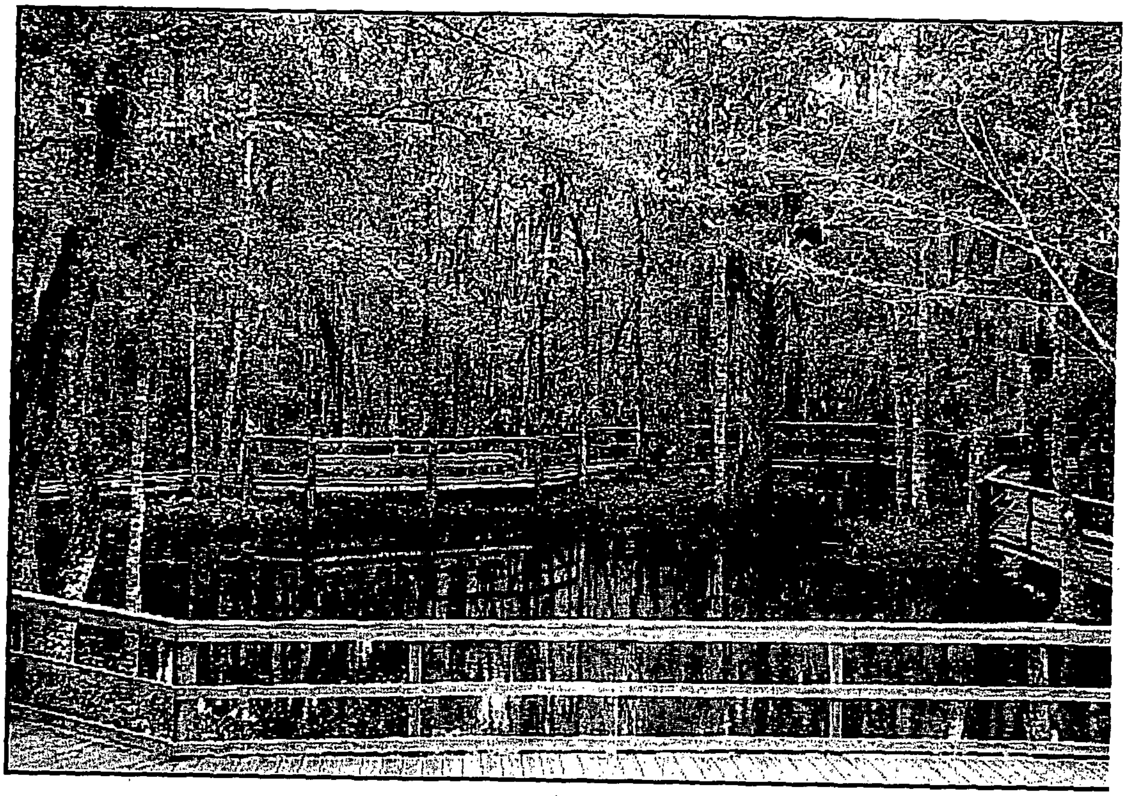
- Scale - 3rd magnitude (estimated)

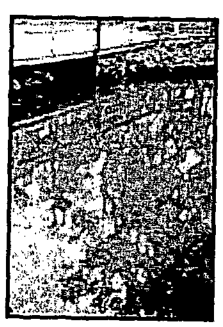
Scenery - fine
How Pristine? - boardwalk around spring, some clearing near spring

Swimming - unknown
Protection - fine
Crowds - used by Youth Ranch participants

Access - restricted
Facilities - fine nearby

Safety - very good
Scuba - no





**Reverse view of spring pool** **Spring Vent** **Spring run**

**Directions**
For maps, latitude/longitude data, driving directions, satellite imagery, and topographic representations as well as weather conditions at this spring, go to Greg Johnson's informative "Florida Springs Database" web site at the following address:
http://www.ThisWaytothe.Net/springs/floridasprings.htm#Florida

From Inglis in Levy County, drive seven miles north on U.S. 19 and turn left/west at entrance to the Florida Sheriffs Youth Ranches Caruth Camp. Drive to end of main road (goes from paved to dirt) to spring on the right, about 0.6 miles.

**Spring Description**
The spring forms a circular pool about 35 feet in diameter in an area that is a border between dense subtropical forest and a developed area with buildings. Water in the pool is fairly clear, but the canopy over the pool made it impossible to visually determine the depth and all possible flow points. Some water flowed from a limestone opening in the SE end of the pool at a depth of about 4 feet. This opening was about a foot in length. The northern and eastern ends of the pool are shallow. The bottom appears to drop away to an indeterminate depth in the western end of the pool, which is likely another flow point and the primary flow point for the spring. Water exits the pool at the NW end and flows NW toward the Gulf of Mexico about 8 miles away. (The run may empty into a nearby lake to the SW. A boardwalk has been constructed around the pool.

SEE NEXT Page

**Use/Access**

- The spring is located in the Florida Sheriffs Youth Ranches Caruth Camp, which features campsites, trails, a lake, a ropes course, multi-purpose buildings, and a pool used by the Youth Ranches program.
- There does not appear to be any formal use of the spring.

**Local Springiana**

- The 182-acre site was donated to the Florida Sheriffs Youth Ranches program by Mr. and Mrs. W.W. Caruth, Jr.. Georgia-Pacific donated an additional 60 acres.

**Personal Impressions**
The spring is small, attractive, and in a mostly natural condition. The boardwalk serves to protect the spring's banks from erosion.

**Nearby Springs**

- Rainbow Springs
- Levy Blue Springs
- Manatee Springs
- Vogt Spring

**Other Nearby Natural Features**
Rainbow Springs State Park
Manatee Springs State Park
Goethe State Forest

This shows the many ways water flows in the area.

S.E. opening indicated a North ward Flow - up From the area Progress Energy has proposed to build Levy 1 : 2.

Western Flow point and a North Western Flow exit - Shows that some water goes toword the Gulf straight From this area and some Flows on North word - (maybe toward Cow Creek -?) to Feed into the Wacassasa Before going into the Gulf

# THE HYDROGEOLOGY AND PROBLEMS OF PENINSULAR FLORIDA'S WATER RESOURCES

Gerald G. Parker, C. P. G.[1]

## THE FLORIDAN AQUIFER AND THE WATER CROP

One of the world's largest (213,200 $km^2$ or 82,000 $mi^2$) and most prolifically-yielding ground-water reservoirs, the Floridan Aquifer, underlies all of Florida and extends northward into Alabama, Georgia and South Carolina (14). Some wells pumping from this aquifer yield upward of 8,000 gallons per minute, but yields of 1,000 to 2,000 gpm are more common. The Floridan Aquifer is composed chiefly of limestone and dolostone (Fig. 1), with increasing quantities of evaporites (gypsum, anhydrite and halite) toward the base, and is the source of about 90% of the water withdrawn for human use in the Florida Peninsula north of Lake Okeechobee. The Floridan Aquifer is deeply buried, to depths of 600 to 800 feet (183 to 244 m) along Florida's Gold Coast south of that lake, and contains only saline water. In fact, most of the tier of eastern counties lying along the Atlantic Coast north of Lake Okeechobee to Jacksonville and beyond is also underlain by non-potable salty water in the Floridan Aquifer (5).

The Floridan Aquifer either contains or is underlain by brackish to salty water everywhere at some depth, the deeper parts of it consisting of brines many times saltier than the ocean. Such brackish water is only sparsely used at present but may be utilized in the future through desalination processes to produce potable water. Techniques are known and currently utilized in about a dozen Florida localities to produce potable water from the brackish ground water of the Floridan Aquifer. Economics will determine the future extent of such desalination projects. It is cheaper to desalinate brackish ground water in some areas even now than it is to develop fresh water many miles distant and import it through lengthy pipelines. Currently, either fresh or brackish ground water can be developed at the well head or pump orifice for less than 10 cents per 1000 gallons but to desalinate brackish water costs an additional 50 cents to $1.00 per 1000 gallons, depending chiefly upon the salinity and the process used.

The aquifer ranges in thickness from about 500 feet (152 m) in Citrus and Levy Counties to about 2,000 feet (610 m) in Duval County. Leve (9) indicated that the aquifer is deeper than 2,200 feet (671 m) in Nassau County with a fresh-water thickness of about 1,600 feet (488 m). The Floridan Aquifer extends to depths of 2,000 feet (671 m) or more in Central Florida (15) and may be filled with fresh water to about 2,500 feet (762 m) in some areas (Fig. 2). Kohout (6,7) indicated that the Floridan is about 2,500 feet (762 m) thick in the Miami area where he included the "Boulder Zone", a cavernous, caving (when drilled) dolostone containing salt water, in the Floridan Aquifer.

Recharge to the Floridan Aquifer ranges from about 250,000 gpd/$mi^2$ (gallons per day per square mile) to more than 1 mgd/$mi^2$ (million gallons per day per square mile) in the areas where recharge takes place. No recharge occurs in all of those areas of the state where the potentiometric surface of the Floridan Aquifer is higher than the land surface. The rate of recharge is largely dependent upon the permeability of geologic materials overlying the Floridan Aquifer, whether it is at or very close to the land surface or is buried more or less deeply.

Direct recharge from precipitation averages about 12 to 13 inches (30 to 33 cm) per square mile, or about 572,000 to 619,700 gpd/$mi^2$, in the west-central Gulf Coastal area where precipitation (P) averages about 52 inches (132 cm) a year. An average measured runoff (R) of 14 inches (34.5 cm) per year, plus an estimated 1 inch (2.5 cm) of ground-water discharge directly to the Gulf of Mexico (2), leaves only 2 to 3 inches (5.0 to 7.6 cm) of direct, overland runoff contributing to stream flow. Thus,

[1]Certified Professional Geologist 691, Consulting Geologist and Hydrologist, P. E. La Moreaux and Associates, Tampa.

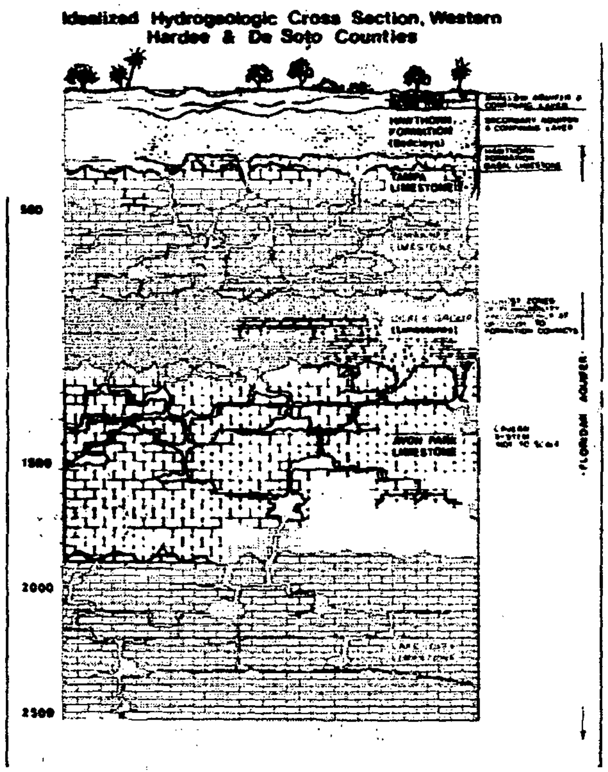



Fig. 2. Idealized hydrogeologic cross section in western Hardee and De Soto Counties, Florida.

The top of the Biscayne Aquifer is generally at or very close to the land surface with very little soil cover in Dade County, but a thickening cover of permeable sand mantles the aquifer to the north. Thus, recharge from precipitation is direct and the water table rises quickly in response to recharge from rains. Parker *et al.* (14) have shown that about 38 inches (97 cm) of an average of 60 inches (153 cm) annual average precipitation in the Miami area actually recharges the aquifer annually, thus 22 inches (56 cm) is lost to ET before reaching the water table. But 25 inches (64 cm) is discharged from the aquifer by seepage into canals and Biscayne Bay, thus 13 inches (33 cm) is discharged to ET directly from the water table. A total ET loss of 35 inches (89 cm) results by adding the 22-inch (56-cm) loss of rain not reaching the water table to the 13-inch (33-cm) loss to ET from the water table. Thirty-five to 40 inches (89 to 102 cm) of P actually reach the water table in other areas, such as Kendall and Homestead, which is not greatly different from that at Miami. About 15 to 20 inches (38 to 51 cm) of this amount is lost by ground-water discharge to canals and Biscayne Bay, while 20 to 25 inches (51 to 64 cm) is directly lost to ET from the water table. Thus, total ET losses in the Kendall and Homestead areas run about 40 to 45 inches (102 to 114 cm) a year.

In terms of the potential water crop, these figures result in about 25 inches (64 cm) per mi$^2$ per year [60 inches (153 cm) P – 35 inches (89 cm) ET] for the Miami area; 20 inches (51 cm) per year per mi$^2$ [60 inches (153 cm) P – 40 inches (102 cm) ET] for the Kendall area; and 15 inches (38 cm) per year per mi$^2$ [60 inches (153 cm) P – 45 inches (115 cm) ET] for the Homestead area. These values translate to 1,191,781 gpd/mi$^2$ for the Miami area; 1,000,096 for Kendall; and 715,068 for Homestead. They are generally higher than or equal to those of the Tampa Bay region, where the potential water crop is about 715,000 gpd/mi$^2$ (13).

The available water crop of the Gold Coast area is generally higher than that of the Floridan Aquifer in Central Florida. This is because of the normally much more rapid and greater direct recharge to the Biscayne Aquifer, the additional water transmitted from the Everglades by the controlled canals and the 3 huge water-conservation areas owned and operated by the CSFFCD (Central and South Florida Flood Control District) (8). The Hialeah-Miami Springs Well Field, for example, now obtains, at times, up to 90% of its water by seepage out of the sides and bottom of the Miami Canal. This canal in turn derives most of its water from storage in CSFFCD's Conservation Area No. 3.

The tremendous storage available in the 3 big conservation areas, the large amounts of ground-water seepage eastward from them into the Biscayne Aquifer, the well-regulated system of canals and huge, high-capacity pumps that are capable of moving tremendous quantities of water from places of excess to places of deficit results in water management in the Gold Coast being much simpler and more effective than elsewhere in Florida. Problems of water supply still occur there, but these problems are more related to management problems, which are rapidly being overcome, than to a dearth of available water in the KLOE (Kissimmee-Lake Okeechobee-Everglades) system (11). Thus, the current paper will delve no further into the Gold Coast as an area of critical water problems. Such problems exist mostly in the SWFWMD (Southwest Florida Water Management District) and in the adjoining, temporary RLGCWMD (Ridge and Lower Gulf Coast Water Management District).

## CRITICAL WATER—PROBLEM AREAS OF SWFWMD

There are currently defined 3 principal water-problem areas: 1) The coastal strip of salt-water encroachment (Fig. 3), 2) the big well fields of the Tampa Bay area (Fig. 3) and 3) the areas of large drawdown of the aquifer water levels as shown in Fig. 4 by the hachured contours. Each of these 3 problem areas is distressed either by over-

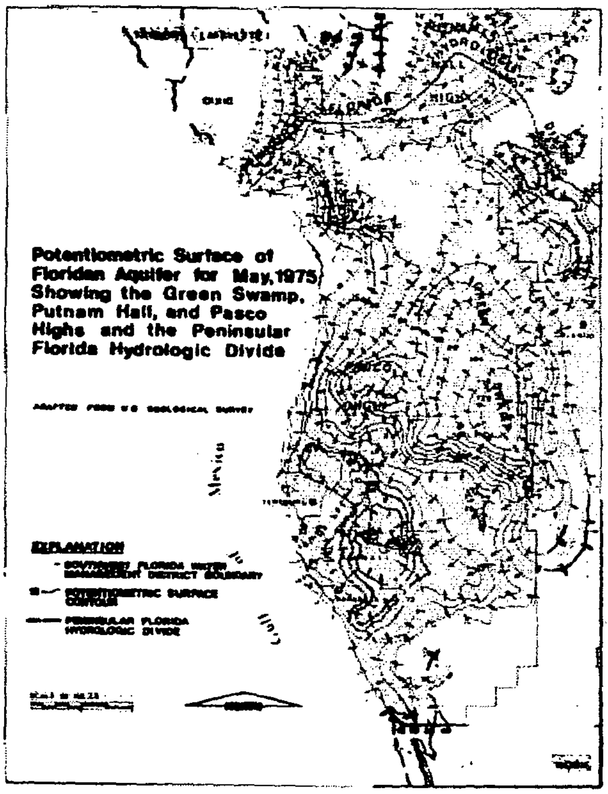



Fig. 4. Potentiometric map of Southwest Florida Water Management District and surrounding lands for May, 1975. Features shown include: Potentiometric contours; the 3 principal artesian highs; regional direction of ground-water flow through the Floridan Aquifer; and the Peninsular Florida Hydrologic Divide. Hachured lines are closed contours outlining areas of internal flow.

development of the water resources for water-supply uses or a combination of large water-supply development with tidal canals and ditches which result in salt-water encroachment.

## COASTAL STRIP OF SALT–WATER ENCROACHMENT

A coastal strip of varying width containing an encroaching wedge of salt water extends along the Gulf Coast from Lee County northward. The northern part of this strip, from Tampa northward to Citrus County, has been mapped by the U. S. Geological Survey (2,16). A part of this mapping which will give an idea of the width and general inland extent of the salt-water wedge from the Gulf shore is shown in Fig. 3. The inland edge of the encroaching salt-water wedge is marked by a heavy dashed line indicating the place at which salt-water of 250 mg/1 (milligrams per liter) occurred at a depth of 100 feet (30.5 m) below msl (mean sea level) in 1969. The chloride content increases steadily below this depth. It likewise increases seaward until chloride in the ground water at or close to the shoreline, even at very shallow depths, equals that of the waters of the Gulf of Mexico, about 20,000 mg/1.

The U. S. Geological Survey has not completed its mapping of the encroaching wedge of salt water southward from Tampa, but complaints of residents in the coastal strip of western Hillsborough, Manatee and Sarasota Counties indicate that wells formerly producing fresh water have now become salty.

The phenomenon of salt-water encroachment, its causes and controls are too well known to require a comprehensive explanation here. Readers are referred to Parker (10), Parker *et al.* (14), Reichenbaugh (16) and Stringfield (18) for such information. Suffice it to say that, in a coastal area of freely permeable materials, it will be 40 feet (12.2 m) down to the salt water contact for each foot (30.5 cm) that the water table averages above sea level. Thus, it will be about 80 feet (24.4 m) to salt water where the water level averages 2 feet (61 cm) above msl and 400 feet (122 m) where the water table stands 10 feet (3 m) above msl.

The natural equilibrium between the overlying lighter, fresh water and the denser, heavier underlying salt

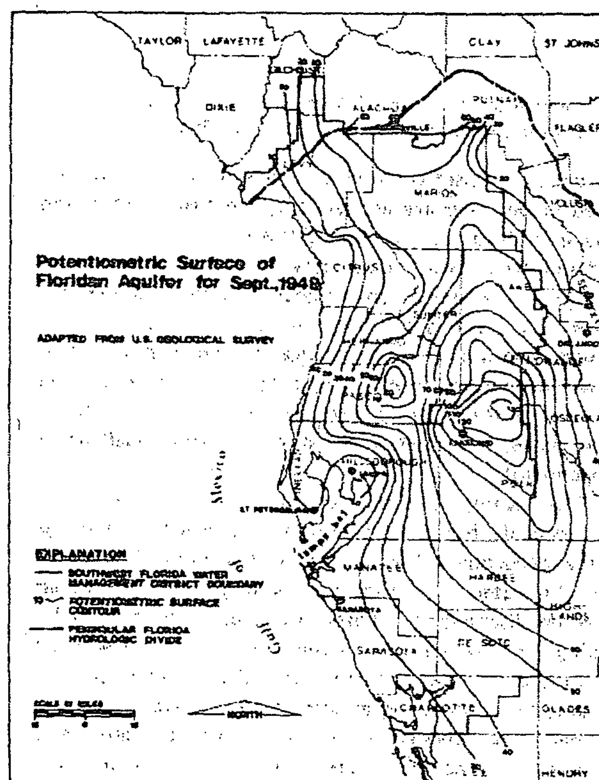



Fig. 5. Potentiometric map of Southwest Florida Water Management District and surrounding lands for Sept., 1949.

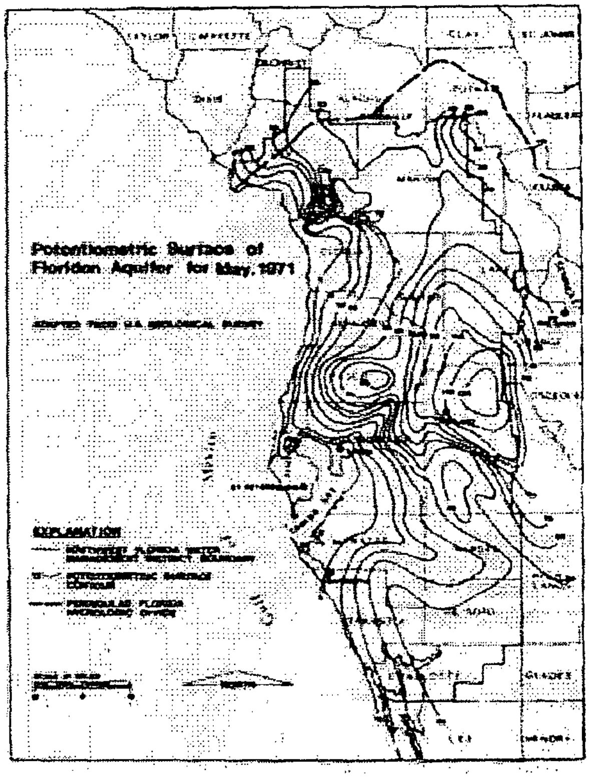



Fig. 8. Potentiometric map of Southwest Florida Water Management District and surrounding lands for May, 1971.

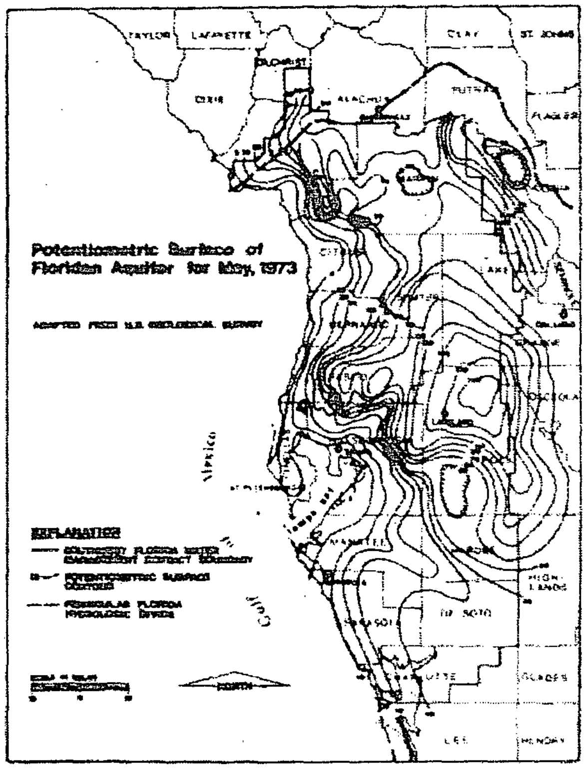



Fig. 9. Potentiometric map of Southwest Florida Water Management District and surrounding lands for May, 1973.

Three large and prominent highs dominate the potentiometric surface of the Floridan Aquifer in the Florida Peninsula: 1) the Green Swamp High, 2) the Pasco High and 3) the Putnam Hall High. Ground water continously flows centripetally outward in all directions from each of these elemental hydrologic features, indicating continuous recharge from rainfall that is required to sustain this continuous outflow.

Another important hydrologic feature is the Peninsular Florida Hydrologic Divide (12). No groundwater flow crosses this divide and no surface stream of any consequence crosses it except for the St. Johns in its tidal estuary near Palatka. Thus, water supplies in Peninsular Florida are totally dependent upon precipitation that falls on the land *south* of the Peninsular Florida Hydrologic Divide. No mysterious subterranean streams from the north flow under or over this divide. A glance at the Putnam Hall High shows the flow pattern with all flow arrows pointing away from the divide.

A comparison of potentiometric contours in Figs. 5 through 11 shows that little apparent change has taken place in the coastal zone of salt-water encroachment north of Pinellas County since 1949. The contours show only 2 km or so of eastward migration in the past 25 years. This small amount, however, involving a lowering of coastal water levels up to 5 feet (1.5 m) on the average, has been enough to cause the salt-water encroachment that brought about the loss of the St. Petersburg and Tampa well fields in the late 1920's and the gradual salinization of the New Port Richey Well Field beginning in the 1960's. Additionally, hundreds of private wells have turned salty in the urbanizing coastal strip from Pinellas County northward into Hernando County, especially since 1969 when building, dredging and filling on low lands west of US 19 began on a large scale, particularly in Pasco County.

The change of potentiometric contour conditions has been much more notable and hydrologically important in the area from Tampa southward. Perhaps the best way to see this change is to examine the change in location of particular contours, such as the 20-foot contour. The 1949 map (Fig. 5) shows it disappearing into the Gulf west of Bradenton. Presumably it turned southward and parallelled the shoreline at some distance seaward. Stringfield (18) found that water levels of artesian wells on the offshore islands of Sarasota County stood at 25 feet (7.6 m) or more in the early 1930's. Thus the 20-foot contour had to be somewhere seaward of these islands in those early days.

The 20-foot contour is noted to be gradually farther

The same conclusions may be reached regarding water-supply developments in the coastal area of salt-water encroachment and in those interior areas of over-draft, such as in the Central Florida Phosphate District. The maximum water supplies for municipalities, industry and agriculture can be developed without harm to the resource, the environment or prior users, with proper application of hydrogeologic principles.

*Nature gives the Florida Peninsula a larger supply of rain and natural recharge than she gives most places elsewhere on earth. All we need to enjoy these blessings is the intelligent management of water and related land resources.* Most of the "messes" we now suffer have developed without an understanding overview of the requirements of good water-and-land management. We have these understandings now and we need not repeat the errors of the past, given an intelligent use of the expertise and powers of the several regional Water Management Districts and the West Coast Regional Water Supply Authority and the assistance of competent consulting hydrologists to guide the development of the resources. We can, if we will, live within our individual and regional water crops and still have enough water to meet the needs of all. But, our most precious natural resource, our water supplies, can be needlessly ruined if we continue the careless and wasteful ways of the past.

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## QUESTIONS

*Q*: Considering the lakes you showed us and the shortage of water in them, is there some engineering principle which would prevent the drainage water in that area from being returned to the drainage field and the lakes instead of letting it run into Tampa Bay?

*Parker*: It's more political than anything else. The lakes are in Hillsborough County, but the water is being taken out by St. Petersburg. This conflict prevented anything from being done for a long time. However, drainage ditches were finally allowed under the road to

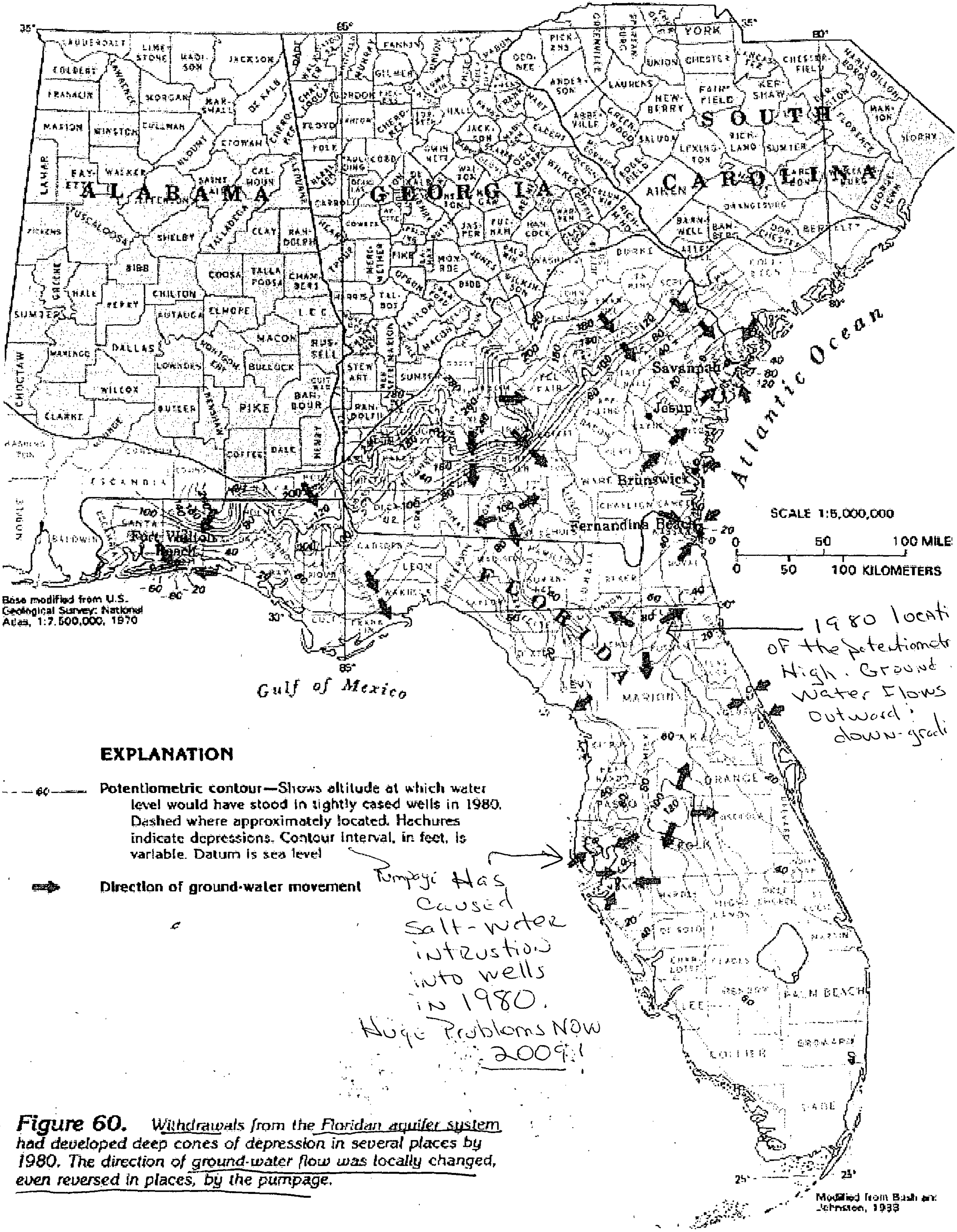
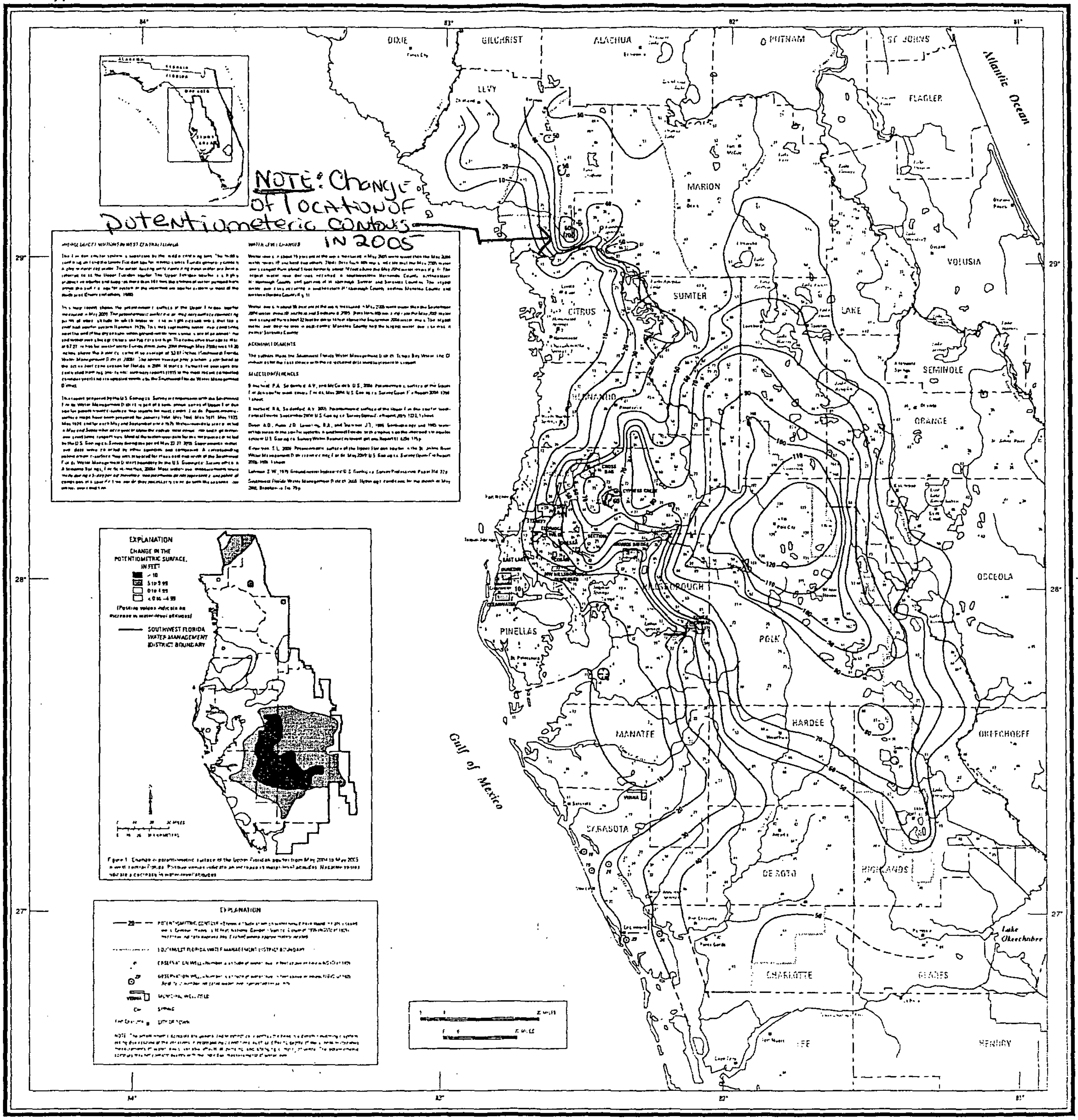


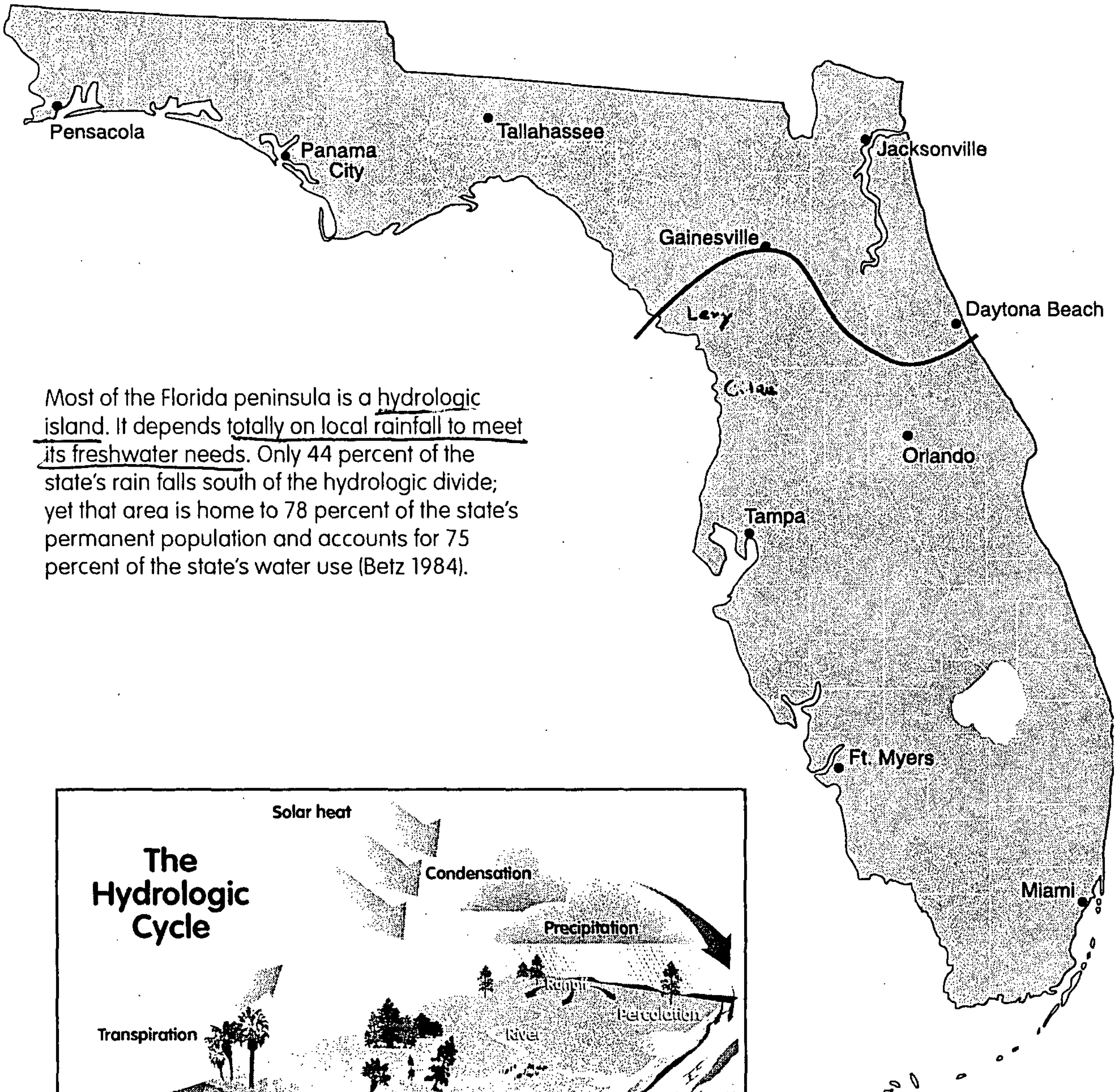

***Figure 60.*** *Withdrawals from the Floridan aquifer system had developed deep cones of depression in several places by 1980. The direction of ground-water flow was locally changed, even reversed in places, by the pumpage.*



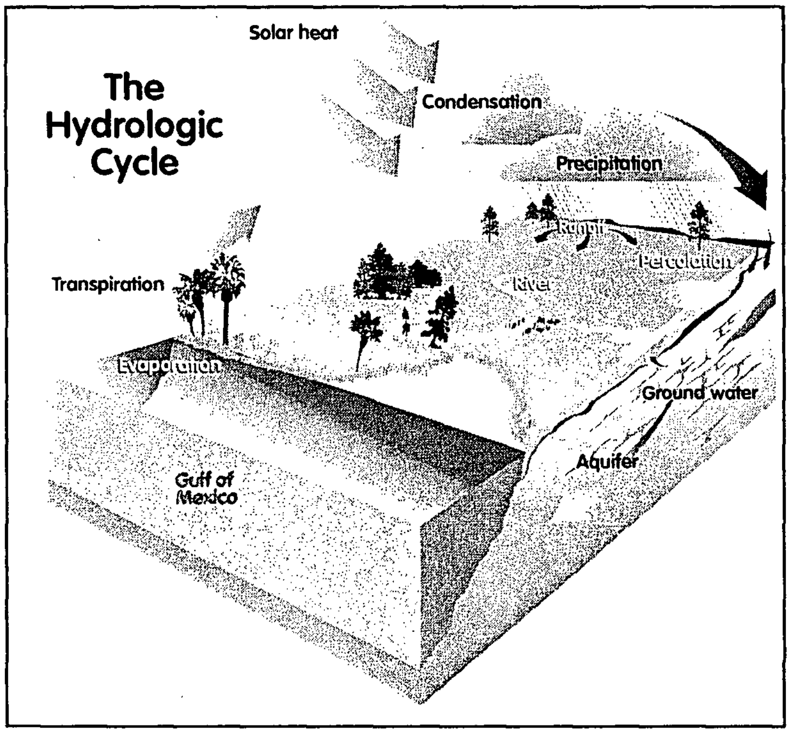

**POTENTIOMETRIC SURFACE OF THE UPPER FLORIDAN AQUIFER, WEST-CENTRAL FLORIDA, MAY 2005**

By
A.G. Ortiz and R.A. Blanchard

# Hydrologic Divide




Most of the Florida peninsula is a hydrologic island. It depends totally on local rainfall to meet its freshwater needs. Only 44 percent of the state's rain falls south of the hydrologic divide; yet that area is home to 78 percent of the state's permanent population and accounts for 75 percent of the state's water use (Betz 1984).



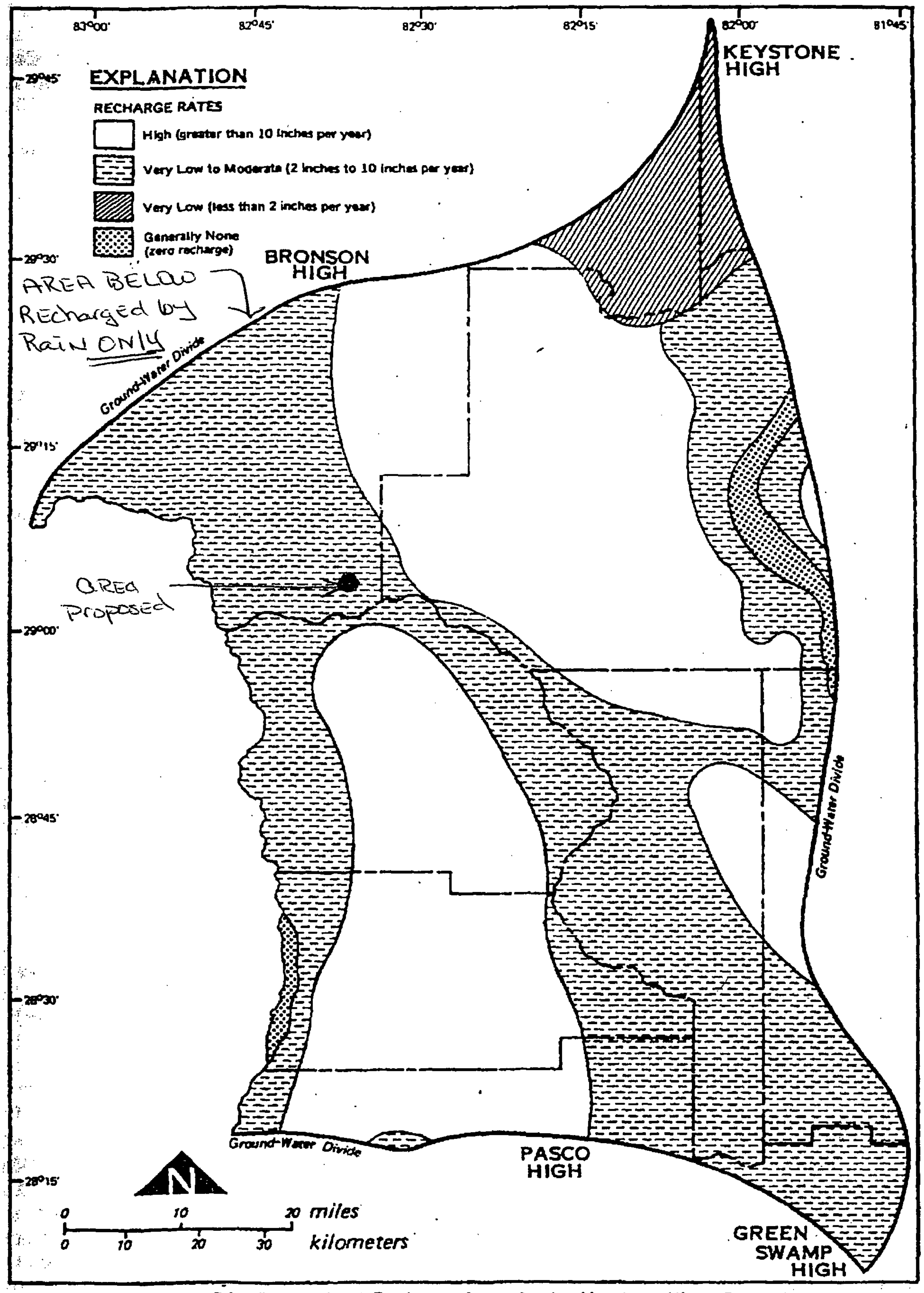



*Figure 21. Generalized Recharge Areas in the Northern West-Central Florida Ground-Water Basin (from Stewart, 1980).*

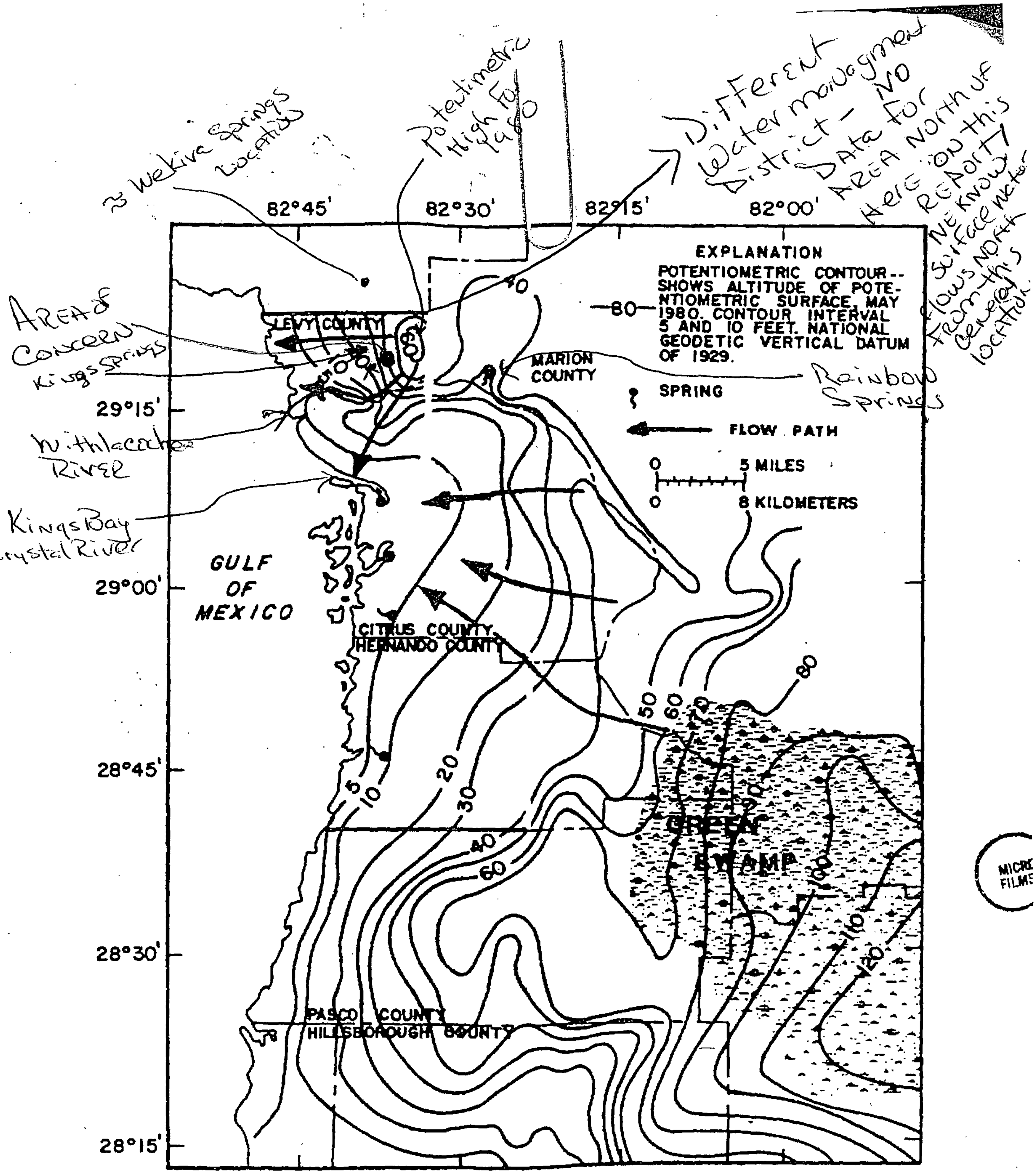



Figure 42. Potentiometric Surface of the Upper Floridan Aquifer Near Citrus County Showing Flow Paths, May 1980 (modified from Yobbi and others, 1980).

# ENVIRONMENTAL CONCERNS WITH SITING OF PROPOSED LEVY 1 & 2 NUCLEAR POWER PLANTS

## DOCKET #

Our economy is in crisis – Just not enough money for everyone to sustain their previous lifestyle and now several thing are occurring

1. Everyone is cutting back on their usage of money and making wise decisions on their purchases
2. Globally governments are bailing out financial institutions and big business who did not manage or use their money wisely in the past/
3. Everyone is learning that we can not continue with business as usually, all over the world people are having to make difficult choices about their finances that will effect the future of many generations to come
4. This country is in an important period where change needs to occur quickly and smartly, the world IS watching

Just like with the economy the world is beginning to realize that we are now experiencing the starting point of global water crises!!

1. People are slowly cutting back on unnecessary water usage and are starting to making wise choices on when and where to consume water
2. Globally people are suffering from the lack of clean, fresh water and there is no government that can bail us all out of this crisis
3. Everyone is learning that we can not continue with business as usually, all over the world people are having to make difficult choices concerning how much water they can obtain for food, cleanliness, health and industry uses, the choices made today will affect the future of not only many generations of humans to come but the health of all ecological systems on this planet!
4. This county is in an important period where change needs to occur quickly and smartly, the world IS watching

The above represents a quick snapshot of how the economy and water are expercing a similar crisis, the only way our environment is ever going to be able to recover from the water deficit is to allow the earths ecological banking system to work!!!

Where can this banking system be found and what types of resources are needed to make this accounting system function properly?? The recharge areas, which allow water from rainfall to percolate into the Floridan Aquifer quickly and the wetlands, which hold (save) water after the rainfall event, must be protected NOW!!

The location of the proposed Levy 1 and 2 nuclear power plants would be in a very unique area of Florida, known as the Transition Zone. It is both an important area for aquifer recharge and discharge for Levy County and thus for the Acacia Bay, the Big Bend Seagrass Beds, the Withlacoochee River and its associated watershed area, the Goethe State Forrest, the Gulf Hammock Wildlife Preserve, the Rainbow Springs Watershed area and all of the fishing and aquaculture farms in Cedar Key. The most important function for humans in the area is that fresh drinking water is provided to the inhabitants of most of the southern part of Levy and Marion Counties and to the northern part of Citrus County.

Progress Energy water use application states they could use up to 5,850,000 gpd for peak month quantity of water withdrawn from the Floridan Aquifer. They will be monitored for a short period of time (around 5 years) then monitoring could cease and PE will be left to do their own monitoring. I have included potentiometer maps that show how the water levels have changed over time.

1). Potentiometer Surface - 1975

Indicates the presences of two potential high recharge zones in this vicinity. it also indicates the presences of an Peninsular Hydrologic Divide occurring in north Levy County. This indicates within the area below the hydrologic divided the water to the aquifer is obtained by rainfall only.

2.) Effects of high water withdrawals in South Florida – 1988

Indicates that the flow of ground –water can be reversed due to high pumpage volume over time. When the flow of water changes direction salt-water intrusion into the fresh drinking waters occurs.

3.) Potentionmetric Surface Map – 2008

This map indicates that a change of the high recharge area has already occurred. What will happen when the flow of the aquifer is diverted when dewatering of the proposed site occurs?

FAVA STUDY

The next step is to study the Florida Aquifer Vulnerability Assessment Phase II/ Levy County, Floridan Aquifer System –

4.) Enclosed Packet – with colored copies.

The area surrounding the proposed plants is shown to be highly vulnerable to aquifer pollution due to the extremely karst topography. It is shown that many karst features are located within the site. With dewatering and dredging of this area the entire flow patterns of both the surface waters and the aquifer waters will be changed over time. This area is an important recharge and discharge area and when the patterns change the amount and quality of the waters flowing in all directions will change. Water is a vital compound, which life must have at all times, not just somethimes!

This small red zone shown on the Levy County, Floridan Aquifer Vulnerability Assessment map (ex.1) shows an area where our groundwater's quantity and quality are extremely vulnerable. It is a very karst area, meaning that the thin limestone covering of the Floridan Aquifer has lots of hole in it (sinkholes in fact) (ex 2), and water can and will flow in many different directions, it just depends on the amount of water in the system!

Surrounding the vulnerability recharge area (money spent quickly) is the most important assets Florida has, the wetlands (savings account). From Cedar Key through an area north of Bronson and over to Daytona Beach it is now known that the aquifer only receives water from rainfall. The monitoring well set up north of this area by USGS shows that the system is at a critical stage for water quantity a lot of the year. The less rainfall, the less water there is to go into the system. The less water in a system along with extremely high increases in consumption can and will be catastrophic to this area.

We tend to think of countries that have lots of oil under their feet as being rich. We should understand that an area with fresh, clean water has a treasure under their feet and it must not be wasted anymore. Placing the proposed plants in this area would contribute to the degradation of the ecological banking system that has worked for us in the past and will work better in the future if we can restore a lot of what has already been lost. Maybe we can use the wetlands and the trees that will grow there as part of the carbon sequestration banking system.

It has been estimated that to provide water needs for all uses through 2030, the world will need to invest as much as $1 trillion a year on technologies toward that end. By not placing even more demands on the Floridan Aquifer, but to restore habitat and allowing nature to work as it was intended to, there does exist a cost free system to provide the most precious commodity we all need; clean and fresh water.

**Tidewater Monitoring Well:**

Progress Energy's environmental report documents all wells in the area that have been used in the past for monitoring quantity and quality , except for ONE – *Tidewater*.

USGS website: wdr.water.usgs.gov
Tidewater #1 – Floridan Aquifer System

**The very one that is active, monitored and recording everyday**. It is north and a little east of the proposed plant location and thus gives a good picture of the water flowing within the Floridan Aquifer at any moment. This well for the past several years has been reading in the critical low water stages. This shows there is already stress on the system – what will **5 million gallons per day** or more, pumped out do to this system?? It is stated by PE that the water movement is west – southwest in the proposed area, which is just in line with the water supply for Inglis and Yankeetown.

From an important recharge zone in this area the water flows downward in all directions. Some available water flows toward the Rainbow Springs Watershed, some flows toward the Waccassassa River Basin and still some flows toward the Withlacoochee River Basin. It is hard to predict in the extremly karst area, just where the water will flow. It all depends on the amount of water in the system at any time. This area is just south of the hydrological divide, where the water that goes into the aquifer is only supplied by the amount of rainfall the area receives. The amount of rainfall in this area over time has declined thus leaving the springs in this area and their waters vulnerable to a decline in water quantity and thus water quality.

The UGSG groundwater station at Crackertown is at it a very critical stage. the importance of this is that it is located just a little north and east of the Yanketown water supply field. what is happening to their drinking water now?

The Tidewater and Crackertown graphs are included as exhibits - . At this time they both show a very stressed ecological system. What will happen when there is an increase in the amount of water withdrawn from the system and that systems flow rate and direction is changed? This important recharge and discharge area will not function properly for the generations to come. What a legacy to leave!!

Another method to turn turbines, which will move water, then generate heat and produce electrical energy, must be implemented NOW, not later and it will not waste water!!

GO SOLAR

Thank You,
Emily Casey
Southern Director
Environmental Alliance of North Florida
(EANoF)

The location of the proposed Levy 1 and 2 nuclear power plants would be in a very unique area of Florida, known as the Transition Zone. It is both an important area for aquifer recharge and discharge for Levy County and thus for the Waccassaa Bay, the Big Bend Seagrass Beds, the Withlacoochee River and its associated watershed area, the Goethe State Forrest, the Gulf Hammock Wildlife Preserve, the Rainbow Springs Watershed area and all of the fishing and aquaculture farms in Cedar Key. It is most importance for the area in that it provides fresh drinking water to the inhabitants of most of the southern part of Levy and Marion Counties and to the northern part of Citrus County

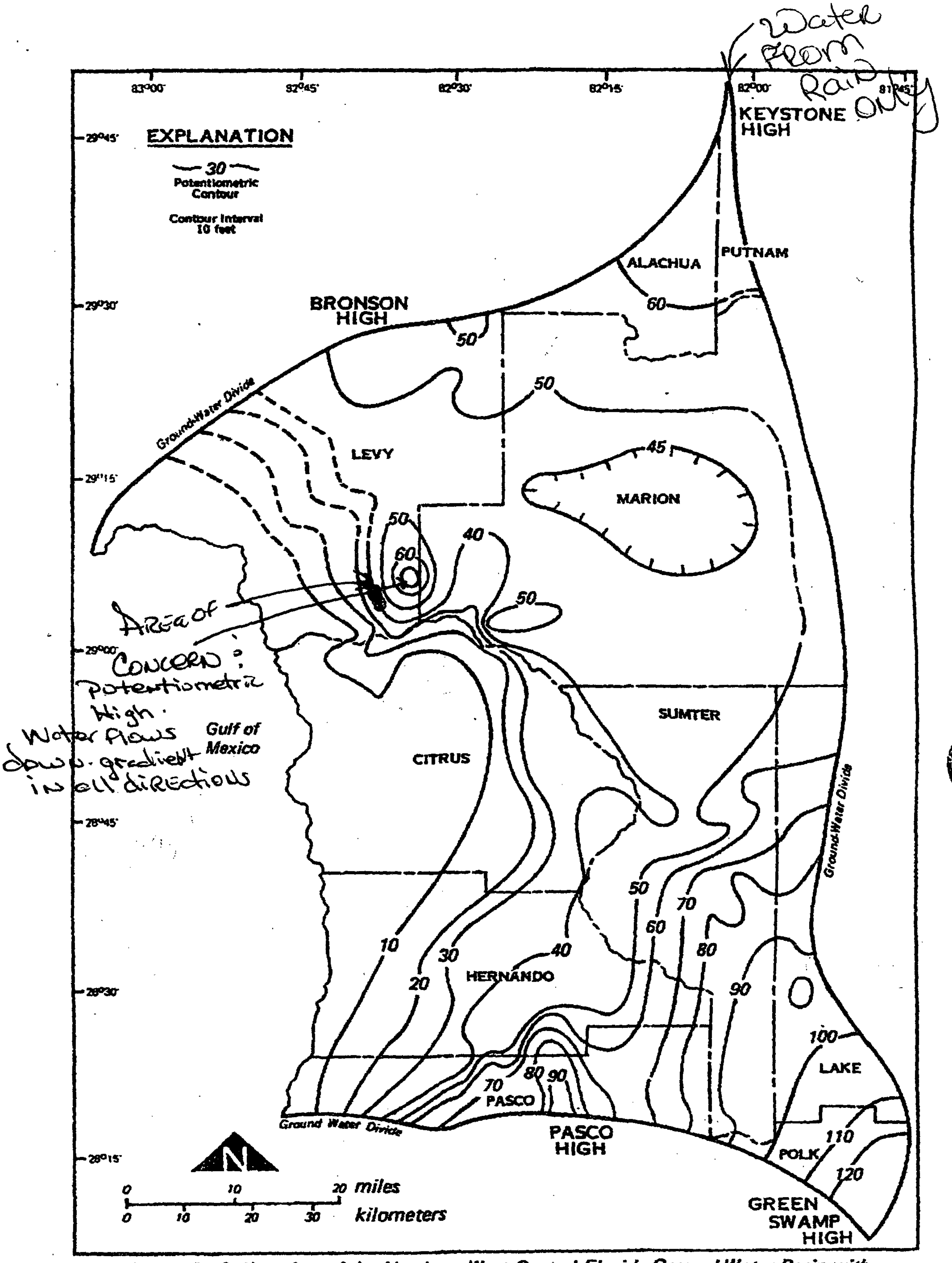



*Figure 2. Delineation of the Northern West-Central Florida Ground-Water Basin with the May 1986 Potentiometric Surface of the Floridan Aquifer. (Modified by Barr and Lewelling, 1986).*

The Basin is characterized by karst terrain, developed ... dissolution of the underlying limestone and dolomite resulting i numerous swamps, lakes, and shallow sinkholes. Surface drainage i absent or poorly developed in most of the Basin, but waters fro coastal springs, and the Withlacoochee and Little Withlacooche Rivers flow through well-defined stream channels.

The dominant river basin is the Withlacoochee flowing 120 miles fro the Green Swamp to the Gulf of Mexico at Yankeetown, Florida. Th extent of this basin is over 1980 square-miles and lies across th Tsala Apopka Plain and Webster Limestone Plain described by Brook (1981), (Figure 6). Located between the Brooksville and Centra Florida Ridges, the Withlacoochee River drains through the Dunnell gap in the Brooksville ridge (Figure 6). The sandy soils are thi to absent along the river and there are many areas of recharge int and discharge directly from the Floridan aquifer system's shall limestones. Three major wetland areas are the Green Swamp, Tsa Apopka Chain of Lakes, and Coastal Marsh. Recent studies indica that the Green Swamp is an area of low recharge (0-2 inches/yr), d to the aquifer system being nearly saturated, resulting in most rejected recharge (Grubb and Rutledge, 1979; Ryder, 1985; and Adam 1985). The coastal lowlands have essentially no recharge, and t Tsala Apopka area has a small net recharge. The wetlands are ve important biologically for water purification and, therefore need be considered as conservation areas.

There are 6 first magnitude springs and numerous second and th magnitude springs in the Basin. Many of the first magnitude spri are headwaters for coastal rivers. Virtually all springflow derived from the Floridan aquifer system.

The geology, topography, and drainage are all interdependent w water erosion shaping the limestone chemically and mechanica The karst nature of the limestone results in solution feat redirecting runoff underground. The sand and soft limes supporting the flat to hilly topography was first shaped by b erosion terracing the sand and stone. Afterwards, weak limes caverns collapsed and surface erosion reshaped the highland sa Nutrients and fresh water entering the Gulf also supports a l estuary system along the coast.



## CLIMATE

The climate of the NWCFGWB is characterized by long, warm, h summers and short, mild winters. Average monthly temperatures r from 60° F in January to 82° F in July and August (National Oc and Atmospheric Administration (NOAA), 1983). Average a temperature is 72° F.

Some rainfall normally occurs during each month, but a Basin rainfall season extends from June through September and a rainfall season extends from October through May. The w rainfall is relatively light because west-central Florida is of the normal southern limit of winter frontal systems. The av annual rainfall in the Basin is 55 inches per year. About percent of the annual rainfall occurs during the rainy season a derived principally from convectional storms. The Inverness W Bureau Station is centrally located in the NWCFGWB and Fi

Surface waters

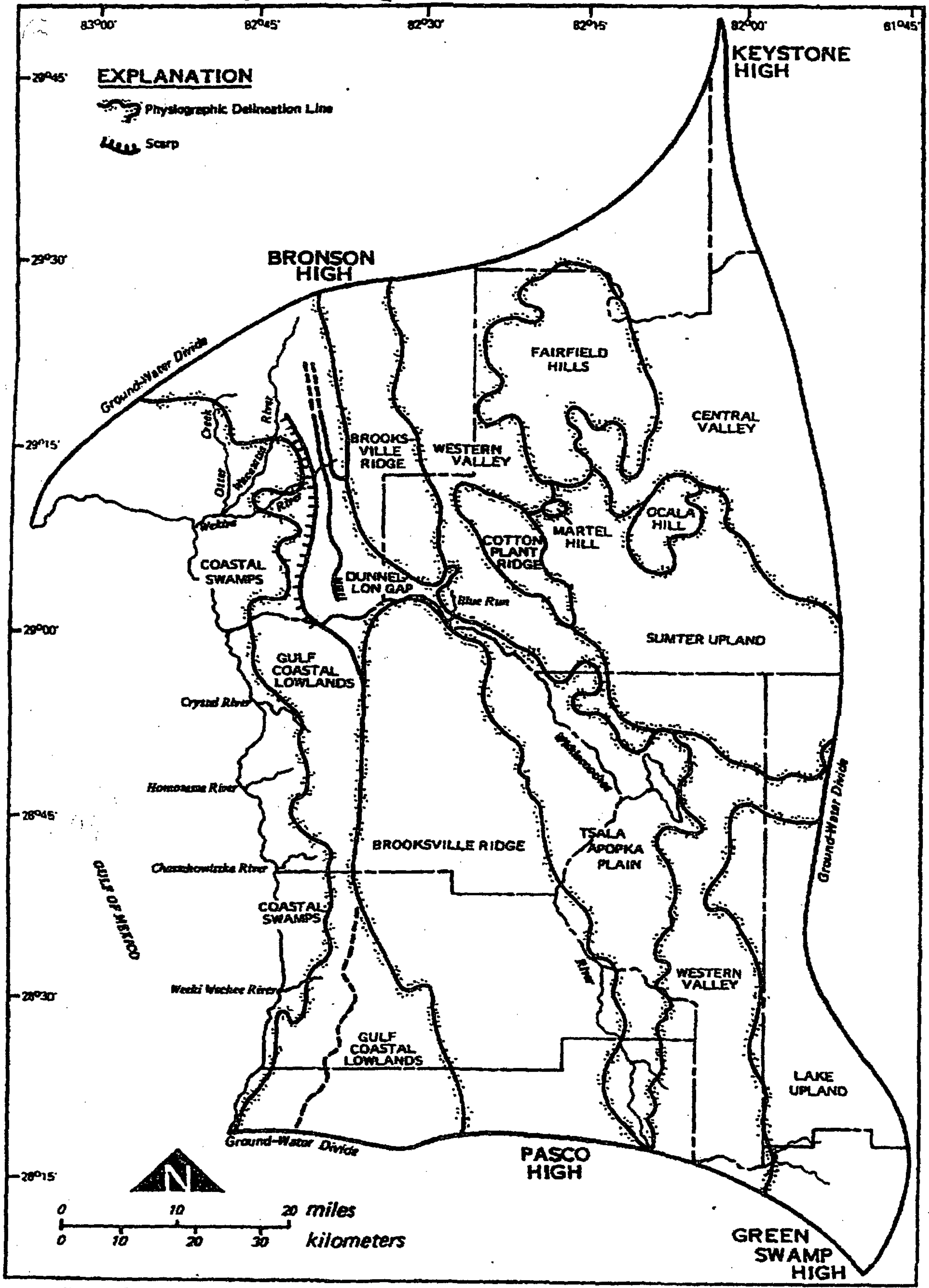
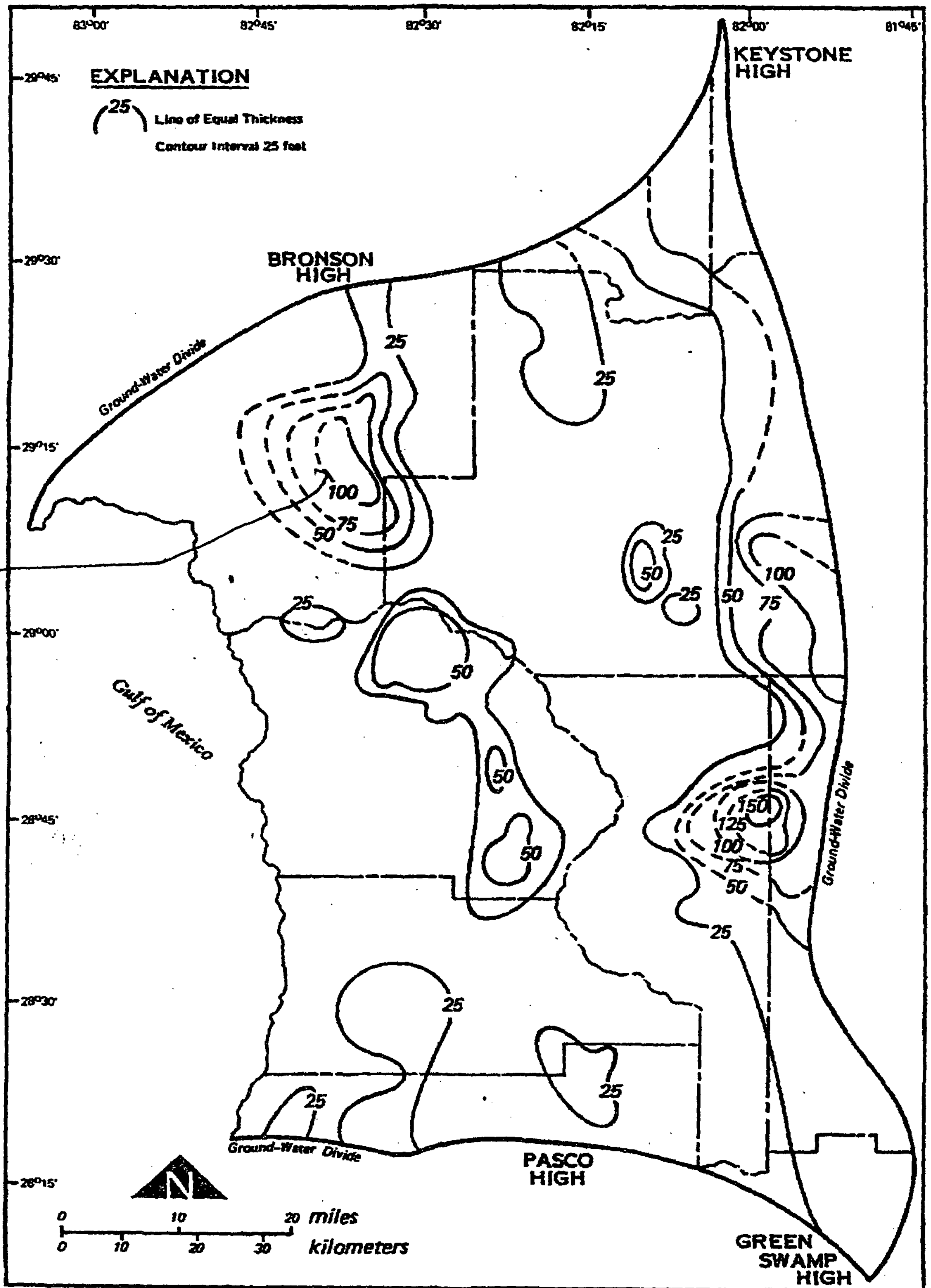



*Figure 6. Physiographic Map of the Northern West-Central Florida Ground-Water Basin (Modified from White, 1970).*




Surficial aquifer thickness high

*Figure 14. Thickness of the Surficial Deposits in the Northern West-Central Florida Ground-Water Basin (from Wolansky and Others, 1981; and Faulkner, 1970).*

## Confining Unit

The confining unit separating the surficial aquifer system from the Floridan aquifer system consist primarily of clays of the Alachua and Hawthorn Formations. The lithologies of these formations were previously described in the Stratigraphy section.

Where present, the confining unit ranges from less than 25 feet to greater than 50 feet (Figure 15), and restricts vertical ground-water flow between the aquifer systems. The rate and direction of vertical flow or leakage is dependent upon the vertical hydraulic conductivity, thickness of the confining unit and the head difference between the surficial and Floridan aquifer systems. Within the Basin, the confining unit is often breached by solution features, allowing ground-water recharge to directly enter the Floridan aquifer system.

## Floridan Aquifer System

The Floridan aquifer system, is the principal aquifer system and major source of water for consumptive use in the Basin. This aquifer system is generally comprised of limestone and dolomite. The thickness of the Upper Floridan in the Basin varies from less than 800 feet near Rainbow Springs to greater than 1,500 feet in the northeast section, to 600 feet near the Withlacoochee River and 800 feet in southern Hernando County (Figure 16). Throughout the area the Upper Floridan acts primarily as a semi-confined aquifer. Where the confining clay layer is absent the aquifer acts as unconfined. In general, this occurs westward of the coastal springs and is variable throughout the Basin area, especially to the north (Jones, 1985a). Limestone of the Upper Floridan aquifer is known to outcrop at different points throughout the Basin (Pride and others, 1966), as evidenced by the several springs that occur and Brook's surficial geology map.

Recharge to the Upper Floridan aquifer occurs directly via rainfall where the confining clays do not exist and sinkholes have a direct hydraulic connection, and also by downward leakage from the surficial aquifer system. Discharge from the Upper Floridan aquifer occurs through spring discharge, upward leakage to the water table when the potentiometric surface is higher than the water table, lateral outflow to the Gulf, and pumpage. Jones (1985a) noted that about ninety percent of the discharge in the portion of the Basin north of the Withlacoochee River occurs through Rainbow and Silver Springs.

The general direction of ground-water flow in the NWCFGWB is northwest from the Green Swamp and Pasco highs, and southwest from the Keystone and Bronson highs to the Gulf of Mexico (Figures 1 and 2). In the Green Swamp the potentiometric surface rises to 120 feet above NGVD. At the Keystone and Pasco highs the potentiometric surface is about 80 to 90 feet above NGVD. Troughs in the potentiometric surface can be seen near Rainbow and Silver Springs. Between Silver Springs and Rainbow Springs the potentiometric surface is relatively flat and constant. In areas where potentiometric contours are spaced far apart the gradient is small, indicating high transmissivity values.

addressed when the models are completed, however, areas suitable f development, based on existing information are discussed below.

General areas suitable for future water resource development withi the NWCFGWB, based on existing data are delineated in Figure 2 Areas suitable for future development have been delineated i Hernando, Marion, and Sumter counties by consultants completi Master Water Use Plans for the counties. Additionally, the Unite States Geological Survey (USGS) has delineated the location of th 250 mg/l chloride isochlor in the Upper Floridan aquifer whic greatly lessens the suitability for water resource developmen coastward of this isochlor. Areas of suitability in Citrus, Pasco Polk, Levy, and Lake counties have yet to be established. However as of January, 1987, Citrus County was nearing completion o delineating suitable areas.

Common to the areas found suitable for water resource development i Figure 23 is that these areas have sufficient water quality to mee public health standards (FAC, 17-22,) and sufficient quantity t minimize impacts to the environment and hydrology from withdrawal Russell and Axon, Inc. (1985) used a ranking system primarily base on DRASTIC maps to evaluate the existing water quality and quantity as well as the potential water quality and quantity in the area studied. As illustrated in this figure, ground-water quality, o the potential for ground-water contamination, may be the limitin factor for ground-water development, in the near-term, and not wate availability. Figure 23 is a compilation of existing data o suitability and will be updated at a later date to fill in those areas not delineated and adjust those areas that require refinement or reevaluation.

The SWFWMD is responsible for regulating the consumptive use of water and requires a consumptive use permit (CUP) for all ground-water withdrawals that exceed 100,000 gallons per day (gal/d) on an average-annual basis or have the potential of producing 1,000,000 gal/d, or are from wells with pipe casing diameters of 6 inches or greater. CUP applications must show reasonable and beneficial use of the water being withdrawn and that there is no interference with existing legal uses of water. The SWFWMD evaluates CUP applications based on similar criteria as listed above in an effort to balance the needs of water users with the needs of the environment.

Environmental and potential contamination concerns are presently being given more consideration for determining suitability of future development. In particular, proximity of heavily developed areas, industrial sites, mining sites, landfills, and surface-water bodies hydraulically connected to ground-water systems are factors which should affect site selection of future wellfields. Land use around wellfield areas must be evaluated carefully, since large ground-water withdrawals induce greater recharge rates, which in turn increases migration of contaminants through the ground-water system.

While the SWFWMD ultimately permits water resource development through its permitting process, proper planning of water resource development is achieved through a cooperative effort among SWFWMD, water supply authorities, and county governments. The large amount of information contained within SWFWMD's CUP files and Data Collection files, the completion of regional ground-water flow

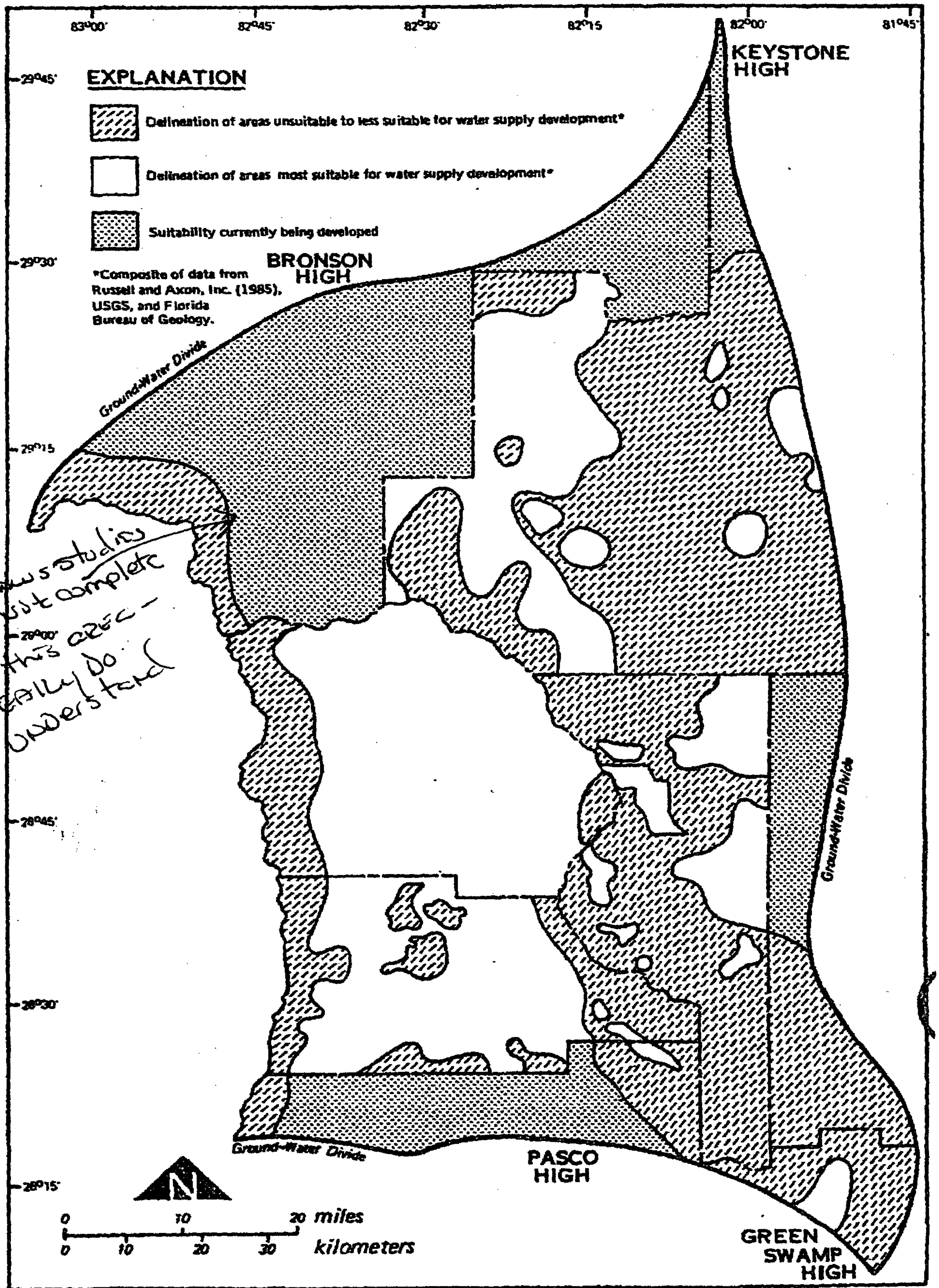



*Figure 23. Generalized Areas Most Suitable, and Less Suitable to Unsuitable for Ground-Water Supply in the Northern West-Central Florida Ground-Water Basin (modified from Russell and Axon, Inc., 1985).*

Shows studies are not complete for this area — We really do not understand

### Surficial Aquifer System

The surficial aquifer system consists of Miocene to Holocene aged clastic deposits that are contiguous with land surface. The clastics are usually sand, silty sand, and kaolinitic clay. The lower limit coincides with the top of laterally extensive and vertically persistent beds of much lower permeability (confining unit) (Southeastern Geological Society Ad Hock Committee on Florida Hydrostratigraphic Unit Definition, 1986). Since the majority of Citrus County has no extensive confining unit, most of the county does not have a surficial aquifer system. Figure 38 shows that only about 25% of the county is overlain by confining beds greater than 25 feet in thickness. Some areas are semiconfined, but most of the Floridan aquifer is unconfined in Citrus County.

### Floridan Aquifer System

In Citrus County, the freshwater-bearing part of the Floridan aquifer system is the Upper Floridan aquifer that is comprised of the Avon Park Formation, the Ocala Group and the Suwannee Limestone in ascending order. The top of the aquifer is usually defined as the uppermost vertically persistent permeable carbonate. The lower part of the Avon Park Formation contains evaporites consisting of gypsum and anhydrite that reduce permeability of the rock and are considered to be the base of the Upper Floridan aquifer. The lower part of the Avon Park Formation and rocks below it contain salty water; therefore, it is the lowermost unit studied. The Upper Floridan aquifer is generally unconfined in Citrus County, but it may be locally confined where it is overlain by thick clay beds.

The top of the Floridan aquifer is at land surface near the coast; it is more than 50 feet below land surface in the Brooksville Ridge area (Figure 39). Thickness of potable water in the Upper Floridan aquifer ranges from zero feet at the coast to about 1500 feet in the easternmost part of the county (Figure 40).

A highly developed secondary porosity system exists in the vicinity of Crystal River Springs and other large springs. In these areas, dissolution of limestone produced cavities and channels. Small passages in the limestone coalesced until water from many successively larger passages began moving through a single major channel toward a discharge point, or spring. A well in such a major channel will yield more water than a well developed in the immediately adjacent, less permeable part of the aquifer even though both may be constructed identically, be within a few tens of feet of each other, and be equipped with identical pumps (Fretwell, 1985).

## POTENTIOMETRIC SURFACE

The potentiometric surface of the Upper Floridan aquifer fluctuates in response to changes in the rates of recharge and the rates of discharge. Some factors in this process are rainfall, pumping, and, near the coast, tidal fluctuations. Figure 41 shows the potentiometric surfaces of the Upper Floridan aquifer for September 1985 and May 1986. September is normally the end of the wet season; May, the end of the dry season. Generally, more stress is placed on the aquifer in May because seasonal rains have not yet begun and crop irrigation is heaviest. Also, tourism is at its peak in late

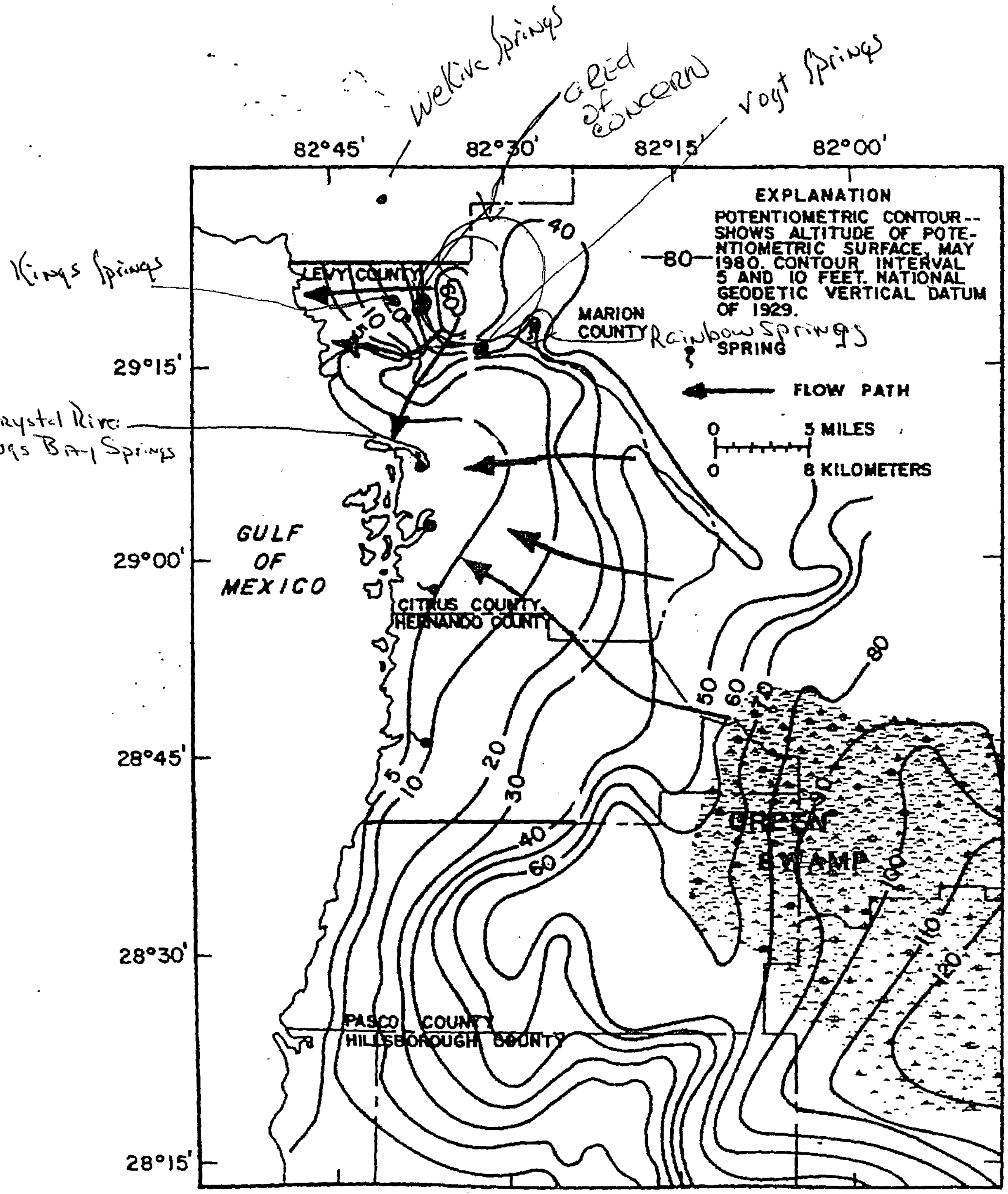



Figure 42. Potentiometric Surface of the Upper Floridan Aquifer Near Citrus County Showing Flow Paths, May 1980 (modified from Yobbi and others, 1980).

winter and early spring and places additional demands on the freshwater supply at a time when rainfall is least. However, the amount of rainfall is the most important factor in dictating the altitude of the potentiometric surface of the Upper Floridan aquifer.

In West-Central Florida, the potentiometric surface usually shifts slightly gulfward between May and September as the Floridan aquifer system is recharged by summer rains and pumping is minimal. This shift is generally very small in Citrus County and can actually be reversed in some areas due to a lack of rainfall or an excess of pumping (Figure 41).

Ground water flows downgradient and perpendicular to the potentiometric contours from high areas to low areas as shown by the arrows in Figure 42. Potentiometric highs occur in the Green Swamp and Pasco County to the south and in Levy County to the north. Reentrants of the contours indicate concentrated discharge. One reentrant occurs at the Withlacoochee River. The large reentrant of the 5 foot contour in the middle of the county is probably caused by discharge from Crystal River Springs and very flat topography.

Figure 43 shows water levels in Floridan aquifer Wells B, C, and D (located in Figure 30). The hydrographs exhibit normal seasonal trends with minimum water levels in the spring and maximum levels in the fall. Water levels fluctuated only about 4 feet over the 15-year period of record. Departures from the norm in Well B are illustrated by peaks in 1974 and 1978 and lows in 1968 and 1976.

Aquifer Characteristics

The quantity of water that an aquifer will yield to wells, depends upon the hydraulic characteristics of the aquifer. The principle hydraulic characteristics are: transmissivity, storativity, and leakance coefficient. The hydraulic properties vary from place to place because of heterogeneity of individual lithologic units. Site specific values for Upper Floridan aquifer transmissivities, storativity, and leakance coefficients were obtained from aquifer pumping tests and flow net analyses in the study area. Figure 44 shows where aquifer values have been determined for the Upper Floridan aquifer. Table 6 lists these aquifer values.

Table 6

| Site No. | Transmissivity ($ft^2$/day) | Storativity | Leakance ($ft^3/day/ft^3$) | Reference |
|---|---|---|---|---|
| T-1* | $2.0 \times 10^6$ | ---- | ---- | Cherry (1970) |
| T-2 | $3.8 \times 10^4$ | $8 \times 10^{-3}$ | 0.24 | Seaburn and Robertson (1980a) |
| T-3 | $1.2 \times 10^6$ | ---- | ---- | Parker (1980) |
| T-4 | $2.0 \times 10^5$ | ---- | 31 | Seaburn and Robertson (1980b) |
| T-5 | $2.2 \times 10^5$ | $5 \times 10^{-2}$ | ---- | Geraghty and Miller (1979) |
| T-6 | $2.7 \times 10^6$ | ---- | ---- | Leggette, Brashears and Graham (1985) |



* data from flow net analysis

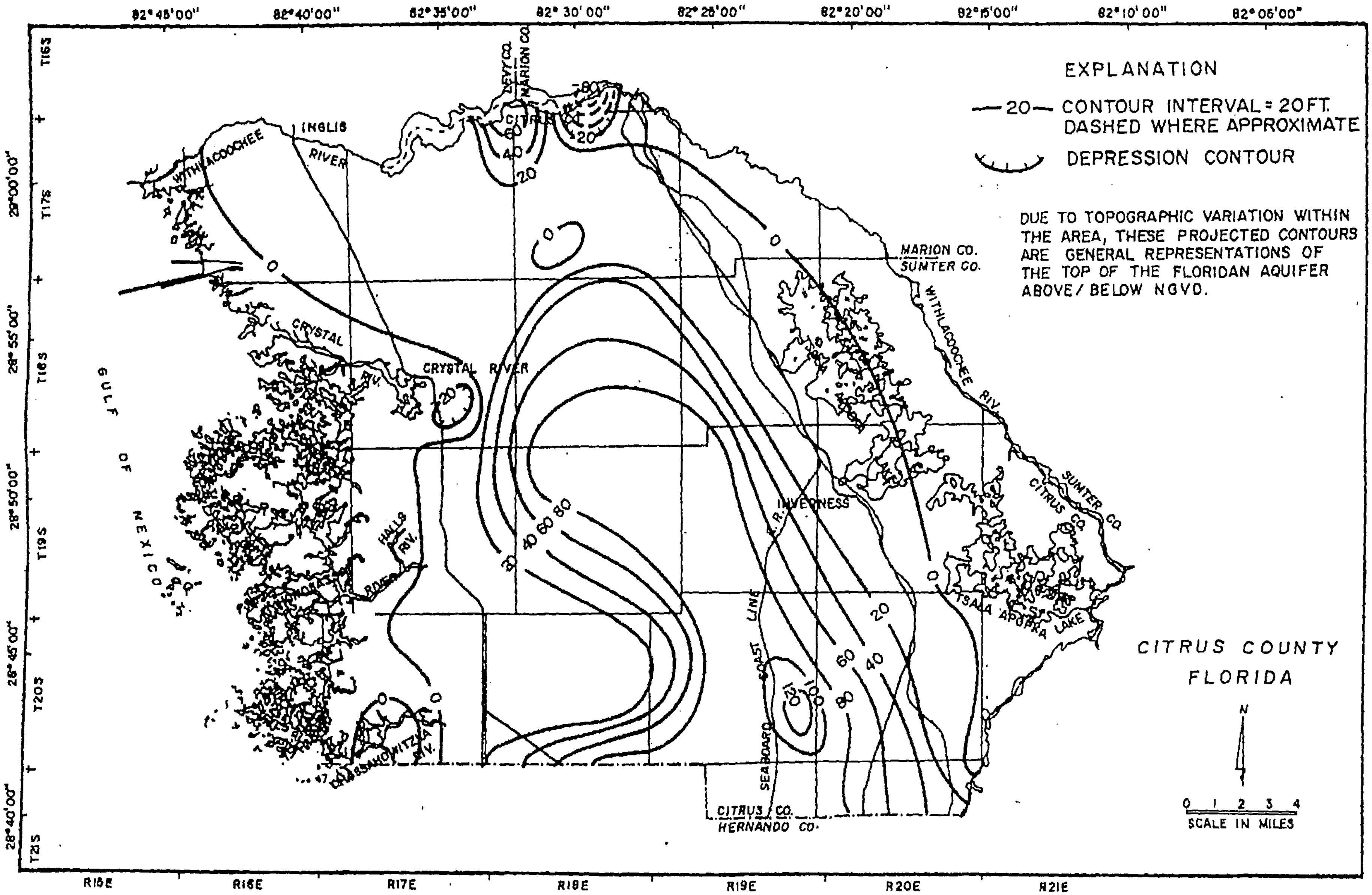



Figure 39. Structure Contour Map of the Top of the Floridan Aquifer Above/Below NGVD.

**USGS**
*science for a changing world*
**U.S. Geological Survey**

## Southwest Florida in 'Severe' Hydrologic Drought, While Panhandle Floods

**Released:** 4/7/2009 6:41:46 AM


| | |
|---|---|
| **Contact Information:** | Richard Kane |
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| Office of Communication | |
| 119 National Center | Richard Verdi |
| Reston, VA 20192 | Phone: 850-553-3676 |




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While the Florida panhandle is under flooding, water levels in the streams and wells of southwest Florida are approaching record low levels for this time of year, putting parts of the state at risk of extreme hydrologic drought in the next few months.

Conditions in the Tampa Bay region and central Florida are particularly dry for this time of year, and hydrologic conditions around the Florida peninsula generally remain parched. One gage on the Hillsborough River has already reached a new record low, and most of Tampa's index sites are well below normal.

"We're concerned about the areas in 'severe' drought, which are just one step away from the 'extreme' category" says US Geological Survey (USGS) Florida Integrated Science Center (FISC) hydrologist Richard Kane, pointing to a near real-time Droughtwatch map online, where southwest and central Florida are shaded in dark orange.

The Droughtwatch map compares the current level of water flowing in streams against an historic baseline of thirty or more years. The 'severe' category means that, in 30 or more years, less than 5 percent of all the readings in that gage's history has been lower. This puts surface-water levels well below normal conditions, which are defined as 25 to 75 percent range.

Hydrologic conditions are one factor used to measure drought, because they measure the amount of water on the landscape (surface water) and in the ground (groundwater). Together, surface and groundwater levels indicate the amount of water available for agriculture, public water supply, and other uses.

"The west coast of Florida didn't receive winter rains such as those in the panhandle, and it missed the rain from tropical storm Fay that helped to replenish groundwater in other parts of the state," said Leroy Pearman, Water Resources Data Chief for the USGS-FISC, "But all over Florida, groundwater has been depleted by an extended period of drought going back about 10 years, with only the 2003 to 2005 period approaching normal conditions."

In west-central Florida, lowered groundwater levels influence the amount of water available in streams due to their interconnection via wetlands. Wetlands collect rainfall and hold water in low-lying areas for long periods of time, releasing it slowly into surface streams and allowing it to seep down into aquifers.

"Floridians are used to thinking about droughts in terms of monthly or yearly rainfall," said Pearman. "So when they see rain, it may seem that a drought is over. But ground-water levels are important to the determination of how much of that rainwater is actually going to be available in the long run."

"When groundwater levels are low, rainfall doesn't accumulate in wetlands, instead it infiltrates through soil into the aquifer, essentially bypassing the wetlands. When we have less water in wetlands, there is less water flowing through surface-water features so we have less runoff and less streamflow", said Hydrologist Terrie Lee, lead author of a new USGS report that describes how wetlands function in the southwest Florida landscape.

Current hydrologic conditions around Florida can be viewed online, based on data collected by continuous streamflow gages that are satellite-linked and posted in near-real time.

In the Tampa Region, graphs are available comparing current groundwater levels with historical levels.

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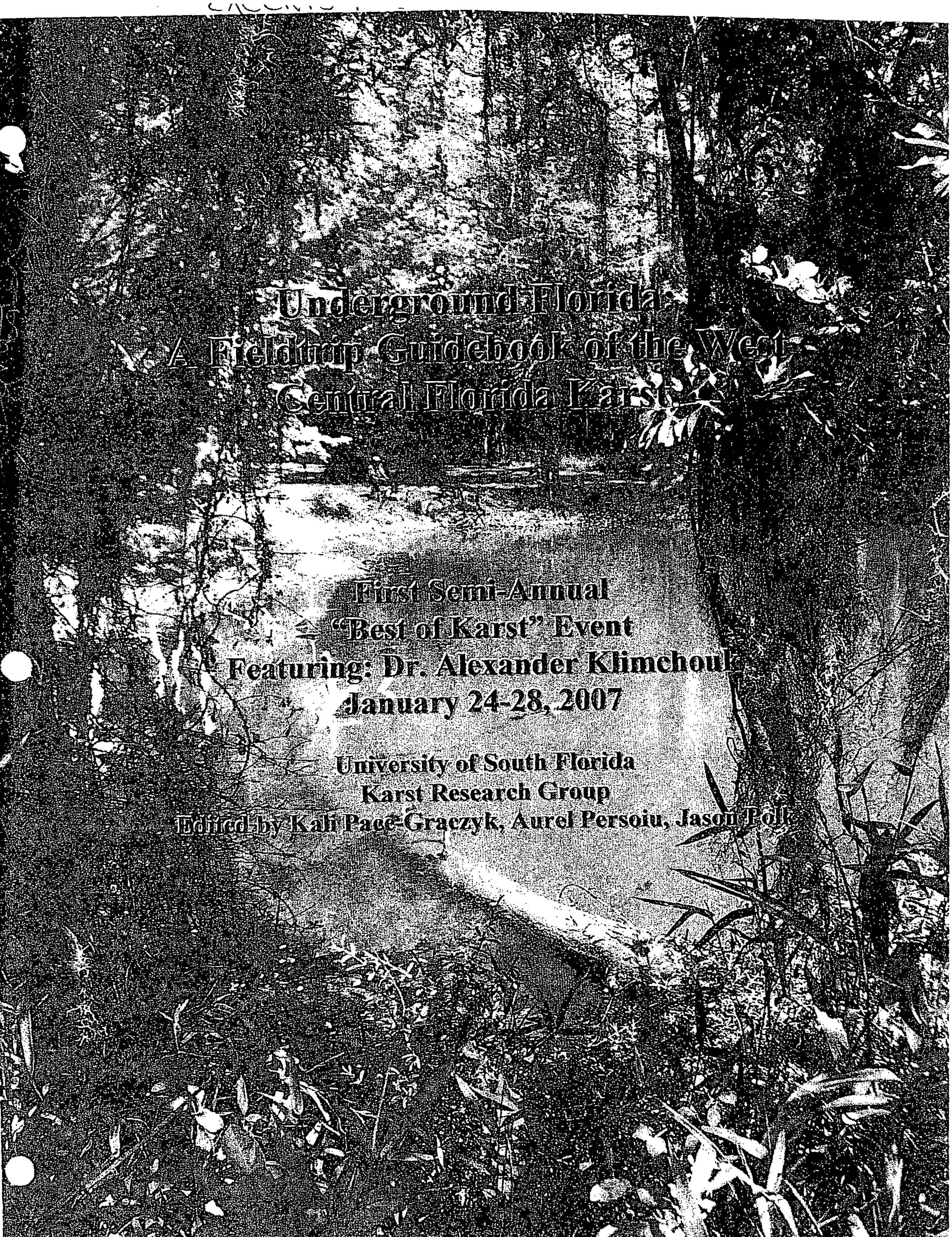


# Underground Florida: A Fieldtrip Guidebook of the West Central Florida Karst

## First Semi-Annual "Best of Karst" Event

**Featuring: Dr. Alexander Klimchouk**

**January 24-28, 2007**

**University of South Florida**
**Karst Research Group**
**Edited by Kali Pace-Graczyk, Aurel Persoiu, Jason Polk**

# I: Introduction to the karst issues in west central Florida

## By Robert Brinkmann, Sarah Koenig, Kali Pace-Graczyk

The Florida peninsula is known for its unique karst landscape (Lane, 1986). Karst, which forms as a result of the solution of soluble rocks, often is expressed by landforms particular to the karstic environment such as caverns, sinkholes, disappearing streams, lakes, and solution valleys (Kinglinger et al., 1999). All of these features are present in Florida (Randazzo, 1997).

Karst landscape covers approximately 20% of the world's land surface and significant areas of the United States (Fig. 1). The terrain is often considered marginal due to the droughty nature of the surface: most water quickly filters off of the surface into subsurface cavities. In addition, the soils are often quite poor. Unfortunately, there are currently tremendous development pressures in these areas due to expanding global populations. Thus, there are many areas in the Yucatan, Caribbean basin, China, the Philippines, and the United States that are undergoing significant environmental change. The karst landscape is especially vulnerable to this modification.

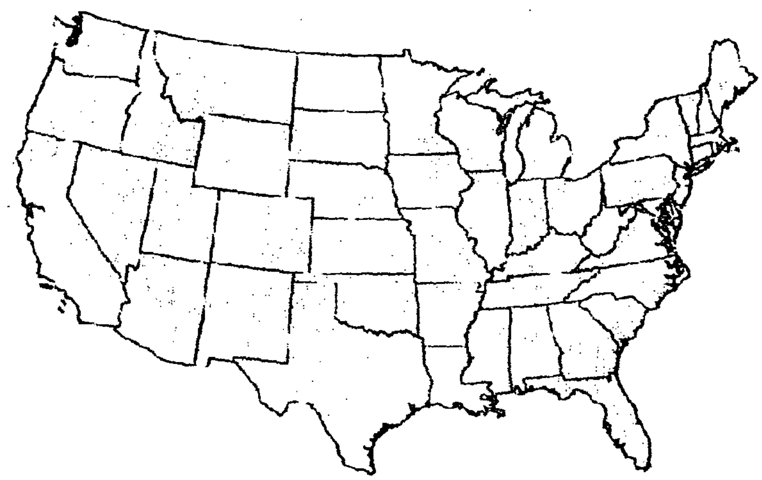


*Fig. 1. Distribution of karst in the lower 48 states of the United States (http://water.usgs.gov/ogw/karst/kig2002/jbe_map.html).*

It is important to recognize the influence karst has on hydrology in Florida for several reasons. Florida has an extremely high population density; as of 2003, an average of 315.2 people occupied each mile$^2$ (RAND, 2005). The principal geologic influence in Florida is karst related; 575 sinkholes have been recorded in Pinellas County (Seale, 2005). In Leon County, over 3,300 karst features have been identified including sinkholes, closed depressions, springs, large lake basins with known sinkholes, and open basins originating from solution processes (Benoit et al., 1992). Understanding karst hydrogeology in Florida will aid in environmentally responsible development.

The Floridan Aquifer extends through several southeastern U.S. states and is one of the most productive carbonate aquifers in the country. Limestones in the Upper Floridan Aquifer (UFA) are young (Eocene to Oligocene) and have retained much of their depositional porosity (White, 1988, Budd and Vacher, 2004). The majority of storage in the UFA occurs within the matrix which has a permeability between $10^{-11}$ $m^2$ to $10^{-13.8}$ $m^2$ (Worthington, 2000; Budd and Vacher, 2004; Florea and Vacher, in press). The UFA can be defined as having triple porosity flow. Groundwater flow occurs through primary pore spaces, secondary fractures as well as through karst conduits (Budd and Vacher, 2004; Screaton, 2004; Florea and Vacher, in press). Because the UFA exhibits porosities between 30-40% and extremely high hydraulic conductivities, matrix flow has the ability to compete with fracture flow significantly affect the isotope ratios found in drip waters of Florida caves (Florea and Vacher, in press). The UFA is in stark contrast to the Paleozoic and Mesozoic limestone aquifers located within the continent's interior. These limestones have undergone significant burial and diagenesis, and have matrix permeabilities on the order of $10^{-15}$ $m^2$ to $10^{-20}$ $m^2$ (Florea and Vacher, in press). Storage and flow in the matrix of the telogenetic karst is minimal as fractures and karst conduits offer the primary means of water transportation (Budd and Vacher, 2004).

In Florida, dominant features of the Floridan Aquifer are the springs emanating from the upper portions of the aquifer (Johnston and Bush, 1988). Twenty-seven first magnitude springs exist in the unconfined portions of the UFA (Spechler and Schiffer, 1995) five of which lie in the northern portion of the Southwest Florida Water Management District (SWFWMD). There are a number of environmental issues associated with the karst landscape (Sinclair and others, 1985). They involve water, environmental pollution, ground stability, and ecosystem management. The water issues include problems with water quantity and quality. The region receives most of its rainfall during the summer months from intense, convectional thunderstorms. Occasional hurricanes or tropical storms accentuate the rainfall totals in the summer and early fall and weak cold fronts bring moderate rainfall amounts in the winter (Fig. 2).

Even though the state has intense bursts of rainfall, there are few surface streams in the state to carry runoff. Instead, water filters through the ground to enter karst aquifers or it runs off through overland flow into lakes, ponds, or small rivers or creeks. Many communities rely on surface water of the low-flow streams, although groundwater is still the main source of drinking water in the state.

Evaluation of water quality trends for springs in the northern portion of the SWFWMD reveal increases in nitrate levels (Champion and Starks, 2001; Jones et al., 1997). Efforts to protect the quantity and quality of spring discharge have been implemented at the state-level. Various studies on the karst features in the UFA as well as on the stable isotopes and trace elements of water infiltrating the UFA are currently being conducted by students of the Karst Research Group at the University of South Florida to help link the poorly constrained mechanisms connecting hydrogeologic contamination issues and variations in climatic processes in Florida to other locations worldwide.

A cartoon cross-section of a typical Florida aquifer system is shown in Fig. 3. The state is known to have a type of karst landscape called a 'covered karst'. This means that the porous rocks are covered with some type of other material. In the upper Midwestern United States and in parts of Northern Europe, the rocks responsible for the development of a karst landscape are covered with glacial deposits. In contrast, the limestone rocks in Florida are covered with marine sands. There are a number of projects underway in the region to decrease the reliance on subsurface aquifers due to problems with regional decline in the aquifer system and associated land subsidence. For example, the nation's largest desalination plant is producing water in the region and a large 15 billion gallon, 1100 acre above ground reservoir is used to store excess water skimmed from rivers during the rainy season for delivery during dry months.

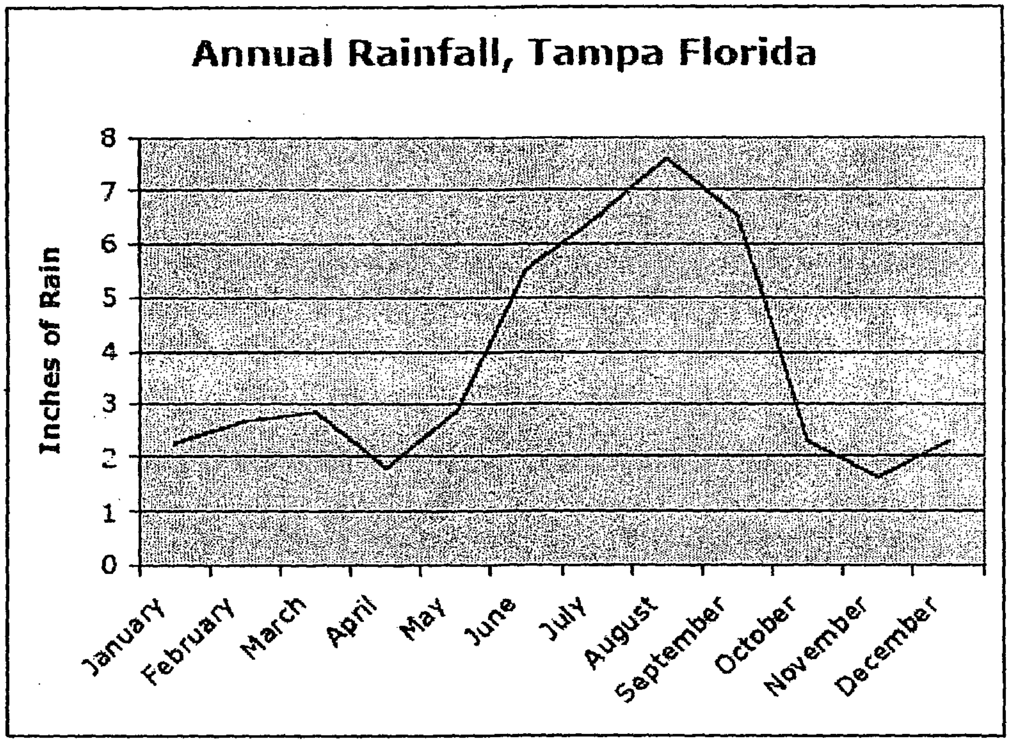



*Fig. 2. Average monthly rainfall in Tampa (National Weather Service).*

The karst aquifer systems have been badly damaged by over-pumping and associated saltwater intrusion and regional water table declines. In addition, the subsurface aquifer system is extremely porous. Some have compared the system to Swiss cheese with interconnected holes allowing pollutants to migrate very rapidly across the state. Some areas of the aquifer are known to have turbulent flow. One of the most permeable and productive units, the Ocala Limestone, is dominated by multiple 12-35 meter thick, shallowing upward depositional sequences (Randazzo, 1997; Copeland, 1991). The lower Ocala consists of grainstones to packstones and may show localized dolomitization; the upper unit shows increased mud content and is quite friable (Copeland, 1991). The Ocala Limestone is unconfined in central Florida, along the Ocala Uplift; the majority of caves in Florida are clustered here (Palmer, 2002). To the North, increased sediments derived from the Appalachians are present (Fig. 4). Where confined, the Ocala Limestone is overlain by the Hawthorn Group, a clay rich, partially laminated limestone to dolostone (Randazzo, 1997). The Hawthorn is often considered a confining unit for the UFA.

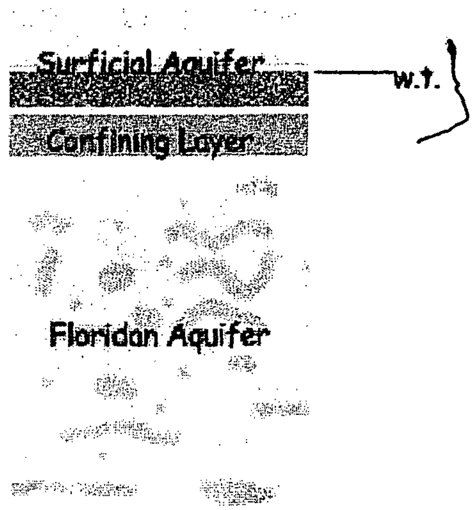



*Fig. 3. Approximate 20 m deep cross-section of the ground water hydrologic system in the Tampa area. The Surficial Aquifer is found within Quaternary marine sands. This system is highly variable and susceptible to pollution. The Surficial Aquifer is separated from the Floridan Aquifer by a confining layer of marine clay and residuum. The Floridan Aquifer is a highly productive aquifer that contains numerous subsurface voids. It is one of the main sources of drinking water in the state.*

Another challenge for Florida is sinkhole development (Beck, 1986). The state's karst landscape is perhaps best known for these features, largely as a result of the Winter Park sinkhole that is featured in introductory physical geography texts around the world. The formation of sinkholes occurs largely as a result of slow raveling of the sediments in the surface aquifer into voids in the Floridan Aquifer. Thus, most sinkholes form very slowly in a fashion similar to the movement of sand within an hourglass. Because of this, the dramatic sinkholes like the Winter Park sinkhole event are rare. Instead, most sinkhole damage is in the form of cracked foundations and walls, broken windows, or broken pipes. Unfortunately, these seemingly small problems can cause a home to become condemned.

Florida is unique in the United States in that it requires all property owners in the state to be insured for sinkhole damage to property. This is a controversial issue because sinkholes are not distributed evenly throughout the state. Indeed, even in one of the most sinkhole-prone regions, Tampa Bay, the distribution of sinkholes is distinctly regional (Fig. 5). There are very few sinkholes that cause property damage from Lake Okeechobee south. However, all of the residents in the communities in these areas, including major metropolitan areas like Miami, Fort Myers, and Fort Lauderdale pay for sinkhole insurance.

| | | PANHANDLE FLORIDA | | NORTH FLORIDA | | SOUTH FLORIDA | |
|---|---|---|---|---|---|---|---|
| SYSTEM | SERIES | LITHOSTRATIGRAPHIC UNIT | HYDROSTRATI-GRAPHIC UNIT | LITHOSTRATIGRAPHIC UNIT | HYDROSTRATI-GRAPHIC UNIT | LITHOSTRATIGRAPHIC UNIT | HYDROSTRATI-GRAPHIC UNIT |
| QUARTERNARY | HOLOCENE<br>PLEISTOCENE | UNDIFFERENTIATED PLEISTOCENE-HOLOCENE SEDIMENTS | SURFICIAL AQUIFER SYSTEM | UNDIFFERENTIATED PLEISTOCENE-HOLOCENE SEDIMENTS | SURFICIAL AQUIFER SYSTEM | UNDIFFERENTIATED PLEISTOCENE-HOLOCENE SEDIMENTS<br>MIAMI LIMESTONE<br>KEY LARGO LIMESTONE<br>ANASTASIA FORMATION<br>FORT THOMPSON FORMATION<br>CALOOSAHATCHEE FORMATION | SURFICIAL AQUIFER SYSTEM |
| TERTIARY | PLIOCENE | CITRONELLE FORMATION<br>MICCOSUKEE FORMATION<br>COARSE CLASTICS | | MICCOSUKEE FORMATION<br>CYPRESSHEAD FORMATION<br>NASHUA FORMATION | | TAMIAMI FORMATION | |
| | MIOCENE | ALUM BLUFF GROUP<br>PENSACOLA CLAY<br>INTRACOASTAL FORMATION<br>HAWTHORN GROUP<br>BRUCE CREEK LIMESTONE<br>ST. MARKS FORMATION<br>CHATTAHOOCHEE FORMATION | INTERMEDIATE CONFINING UNIT | HAWTHORN GROUP<br>STATENVILLE FORMATION<br>COOSAWHATCHEE FM.<br>MARKSHEAD FORMATION<br>PENNY FARMS FORMATION<br>ST MARKS FORMATION | INTERMEDIATE AQUIFER SYSTEM OR CONFINING UNIT | HAWTHORN GROUP<br>PEACE RIVER FORMATION<br>BONE VALLEY MEMBER<br>ARCADIA FORMATION<br>TAMPA - NOCATEE MEMBERS | INTERMEDIATE AQUIFER SYSTEM OR CONFINING UNIT |
| | OLIGOCENE | CHICKASAWHAY LIMESTONE<br>SUWANNEE LIMESTONE<br>MARIANNA LIMESTONE<br>BUCATUNNA CLAY | FLORIDAN AQUIFER SYSTEM | SUWANNEE LIMESTONE | FLORIDAN AQUIFER SYSTEM | SUWANNEE LIMESTONE | FLORIDAN AQUIFER SYSTEM |
| | EOCENE | OCALA LIMESTONE<br>CLAIBORNE GROUP<br>UNDIFFERENTIATED SEDIMENTS | SUB-FLORIDAN CONFINING UNIT | OCALA LIMESTONE<br>AVON PARK FORMATION<br>OLDSMAR FORMATION | | OCALA LIMESTONE<br>AVON PARK FORMATION<br>OLDSMAR FORMATION | |
| | PALEOCENE | UNDIFFERENTIATED PALEOCENE ROCKS | | CEDAR KEYS FORMATION | SUB-FLORIDAN CONFINING UNIT | CEDAR KEYS FORMATION | SUB-FLORIDAN CONFINING UNIT |
| CRETACEOUS AND OLDER | | UNDIFFERENTIATED | | UNDIFFERENTIATED | | UNDIFFERENTIATED | |

*Fig. 4. Stratigraphic sections of southern, northern and panhandle Florida. Many formations present in the panhandle are absent in northern and southern Florida. (Copeland, 1991).*

Another problem associated with sinkholes insurance is how the state defines the term 'sinkhole'. By state insurance law, sinkholes are defined as having topographic or *subsurface* characteristics. This means that property damage may be covered if a property owner can prove that there is some sort of void under the property and that there is a raveling zone where sand is filtering into the void. This is difficult to prove and many geologic consulting firms work with insurance companies and property owners in insurance evaluations. Also, there are other subsurface anomalies that can cause structural damage that are not covered by insurance. These anomalies include peat, buried trees, and the presence of shrink-swell clays. Many law firms in the state focus on helping homeowners or insurance companies evaluate claims.

Another issue in the region is ecosystem management of karst lands. Many of the lakes, wetlands, and ponds that occur in the region are small sinkholes. Unfortunately, these small features are very susceptible to destruction in Florida's hyper real estate market. While there are rules that require wetland mitigation and preservation, the unfortunate outcome is that the rules are not

# III: Springs of Florida

## Reprinted from USGS Fact Sheet FS-151-95, Rick Spechler, Donna Schiffer

Florida's springs are among the State's most valued natural and scenic resources. Springs are an important part of Florida's history, dating back to the days of early Spanish explorers including Ponce de León, who came in 1513 seeking "the Fountain of Youth." Archeological evidence indicates that Indian villages were located near springs; native Floridians used the springs for their water supply and fished in the streams formed by the springs. Many of Florida's springs are tourist attractions; the best known is Silver Springs which has been a location for movie and television productions. Most of Florida's springs are located in the northern half of the State (Fig. 12). Springs are the surface evidence of a vast underground water resource, the Floridan aquifer system, which supplies most of the State's drinking water. The large quantities of water discharged from Florida springs indicate the large capacity of the underground aquifer system to store and transmit water.

Wekiva Springs magnitude 2 North of area

Kings Springs just West of 19 ; proposed Level 1:2 magnitude 3 (see enclosed packet)

Crystal River (Kings Bay Springs) ; origin of nutrients to Groundwater Discharging from the Kings Bay Study ; also see Ground Water Resource Availability

Rainbow Springs magnitude 1 just East of proposed Level 1:2

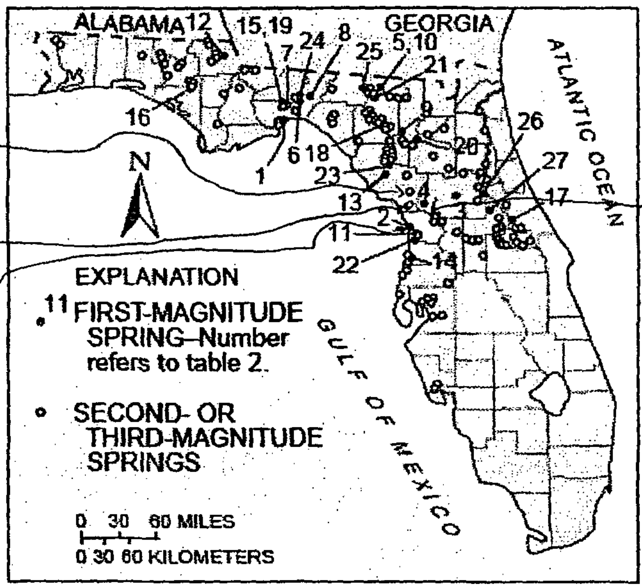



*Fig. 12. Location of selected springs in Florida.*

Springs provide base flow for many of the streams and rivers that are used for boating, fishing, swimming, scuba diving, and snorkeling. The nearly constant temperature of spring water creates an ideal habitat for many plants and animals; one example is the manatee, which seeks out the warmer waters of spring "runs" during cooler winter months. The 320 known springs in the State discharge about 12,300 cubic feet per second (ft3/s) or nearly 8 billion gallons per day. This exceeds the 7.5 billion gallons per day of freshwater used in the State (from ground-water and surface-water sources) for public supply, agricultural, industrial, domestic, and thermoelectric power purposes in 1990.

## How Springs are Formed

Florida has an abundance of springs because the State is underlain by a thick sequence of limestone and dolomite—rocks that are easily dissolved by the rainwater that seeps into the ground. Carbon dioxide carried by the recharging rainwater forms carbonic acid, a weak acid that dissolves the rocks, thus creating cavities and caverns. The result is a landform called karst, which is characterized by the presence of springs and sinkholes and the absence of a well developed surface-drainage system. Instead, most of the surface drainage enters the rocks of the Floridan aquifer system (Fig. 13). A spring is formed when the ground water, which is under pressure, flows out through a natural opening in the ground.

## Source of Spring Water

The source of Florida's spring water is rain that falls on land surrounding the spring. Contrary to popular belief, underground rivers do not bring water into Florida from other states. Instead, rainwater replenishes the aquifers which in turn supply the springs with water. Water in the aquifer flows through the permeable rocks and the various-sized openings in the rocks. Although many caverns in the aquifer can be quite large and interconnected, there are no underground rivers as such.

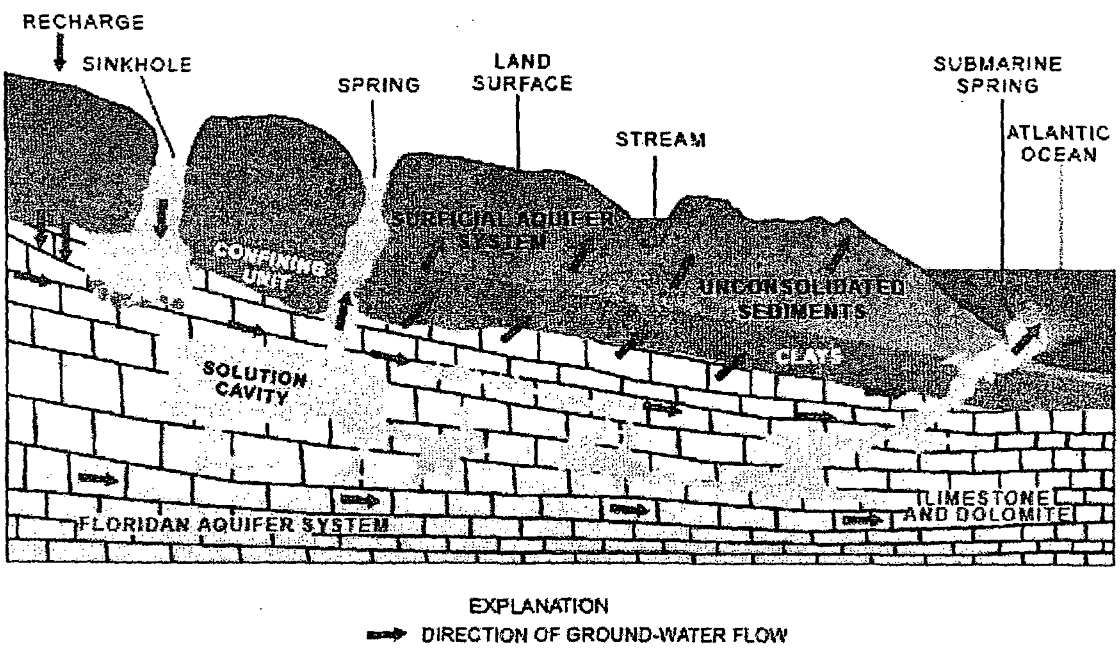



*Fig. 13. Generalized cross section showing the geohydrology and springs of Florida.*

## Characteristics of Springs

Springs can be classified on the basis of several characteristics including the following: the discharge of the spring; the aquifer supplying the spring; or the water temperature of the spring. The most common classification of Florida's springs is by discharge. O.E. Meinzer, a pioneer ground-water scientist of the U.S. Geological Survey, devised a classification system in 1927 based on discharge; the system relates magnitudes to ranges of discharge (Table 1). Discharge from Florida's springs can range from less than 1 pint per minute to more than 1 billion gallons per day. The amount of water that flows from springs depends on many factors, including the size of the caverns within the rocks, the water pressure in the aquifer, the size of the spring basin, and the amount of rainfall. Human activities also can influence the volume of water that discharges from a spring—ground-water withdrawals in an area can reduce the pressure in an aquifer, causing water levels in the aquifer system to drop and ultimately decreasing the flow from the spring.

From the potentiometric high in southeastern Levy Co the water travels in all directions Thus enabling all springs in All directions to be influenced by such Large, continual amount of water withdrawn

| Magnitude | Average Flow |
|---|---|
| 1 | 100 $ft^3/s$ or more (65 Mgal/d) |
| 2 | 10-100 $ft^3/s$ (6.5-65 Mgal/d) |
| 3 | 1-10 $ft^3/s$ (0.65-6.5 Mgal/d) |
| 4-8 | Less than 1 $ft^3/s$ (0.65 Mgal/d) |

*Table 1. Classification system for springs according to average discharge ($ft^3/s$, cubic feet per second; Mgal/d, million gallons per day).*

Also will affect people wells! hence drinking water.

Florida has more first-magnitude springs than any other state in the Nation. The sum of the average flow from Florida's 27 first-magnitude springs (Table 2, Fig. 12) is estimated to be 9,400 ft3/s (6,075 Mgal/d), or about 76 percent of the average flow of all the known springs in Florida. Several first-magnitude springs are nationally or even internationally known, such as Silver Springs, Rainbow Springs, Wakulla Springs, and Weeki Wachee Springs. About 70 springs are second-magnitude springs; these collectively discharge about 2,600 ft3/s (1,680 Mgal/d) or about 21 percent of the total discharge from all known Florida springs. More than 190 springs are third-magnitude or less; these collectively discharge more than 300 ft3/s (194 Mgal/d), or about 3 percent of total discharge from all Florida springs.

Spring Creek Springs and Crystal River Springs are the two largest springs in Florida. Discharge measured from Spring Creek Springs (a group of eight known spring vents) in 1974 was about 2,000 ft3/s (1,293 Mgal/d). The average discharge from Crystal River Springs is 878 ft3/s (567 Mgal/d) from 30 individual spring vents. Both of these springs are located near the coast. The discharge of springs near the coast commonly is affected by tides.

Silver Springs in Marion County is the largest inland spring in the State (based on average discharge). Measured discharge from this spring ranges from 517 to 1,290 ft3/s (334 to 834 Mgal/d), and the average discharge is 799 ft3/s (516 Mgal/d) based on records from 1933 to 1993. The highest recorded discharge from any inland Florida spring is 1,910 ft3/s (1,234 Mgal/d), measured at are geologically recent or are forming today. This paper presents a case study of the morphology of caves within the coastal karst aquifers of west-central Florida.

## GEOLOGIC FRAMEWORK OF THE BROOKSVILLE RIDGE AND THE UPPER FLORIDAN AQUIFER

The Tertiary limestones that compose the highly productive Upper Floridan Aquifer are intensely karstified in regions that experience active groundwater circulation (*e.g.*, Lane, 1986; Stringfield and LeGrand, 1966), particularly in the portion of west-central Florida where the Upper Floridan Aquifer is semiconfined to unconfined. This region, characterized by 33 springs with average discharge greater than 2.8 m3 s–1 (*e.g.*, Scott *et al.*, 2004; Roseneau *et al.*, 1977; Meinzer, 1927), stretches from the panhandle near Tallahassee in the north to Tampa in peninsular Florida (Fig. 1A) and encompasses several physiographic provinces including the Brooksville Ridge (White, 1970). The Brooksville Ridge, a linear, positive-relief topographic feature extending from northern Citrus County, through Hernando County, and into southern Pasco County (White, 1970), is bounded by coastal lowlands to the west and south and wetlands of the Withlacoochee River to the east and north. The ridge system is a consequence of a localized geologic high termed the Ocala Platform by Scott (1988), who attributed this topographic feature to a westward tilt of thickened Eocene strata. Elevations in the Brooksville Ridge range from five to more than 75 m above sea level (Fig. 1B). The topography is rolling with internal drainage (Fig. 2). Upland mesic-hardwood hammocks separate sinkhole lowlands that are mostly occupied by wetlands or lakes. The Withlacoochee State Forest manages more than 525 km2 (157,000 acres) in the region, including the 100-km2 (30,000 acre) Citrus Tract that includes much of the study area. Pasture land and lime-rock quarries compose the remaining land uses. The city of Brooksville lies in the heart of the Brooksville Ridge (Fig. 1A). Upper-Eocene and Oligocene carbonates (42–33 Mya) compose the Upper Floridan Aquifer, which is semi-confined to unconfined in the Brooksville Ridge. The strata of the Upper Floridan Aquifer thicken to the south along a regional dip that averages less than half of one degree (Scott *et al.*, 2001; Miller *et al.*, 1986). Miocene-age sands and clays of the Hawthorn Group thicken to more than 150 m in northern and southern Florida where the Upper Floridan Aquifer is confined (Scott, 1988). The Hawthorn Group is thin to missing in the center of the Brooksville Ridge in northern Hernando and southern Citrus Counties (Fig. 3). The Suwannee Limestone, a pale-orange, partially recrystallized limestone that is extensively quarried in northern Hernando County, is more than 30 m thick to the south. In the up-dip sections of the northern Brooksville Ridge of Citrus County, the Suwannee Limestone is thin to nonexistent as a result of post-Oligocene exposure and erosion (Yon and Hendry, 1972). As a result, the Suwannee Limestone is thickest beneath the topographic highs and missing in many topographic lows (Yon *et al.*, 1989). Paleokarst filled with Miocene-age siliciclastics pierces the Suwannee Limestone throughout the Brooksville Ridge (Yon and Hendry, 1972). These paleokarst sinkholes indicate a period of intense karstification during the end-Oligocene exposure.

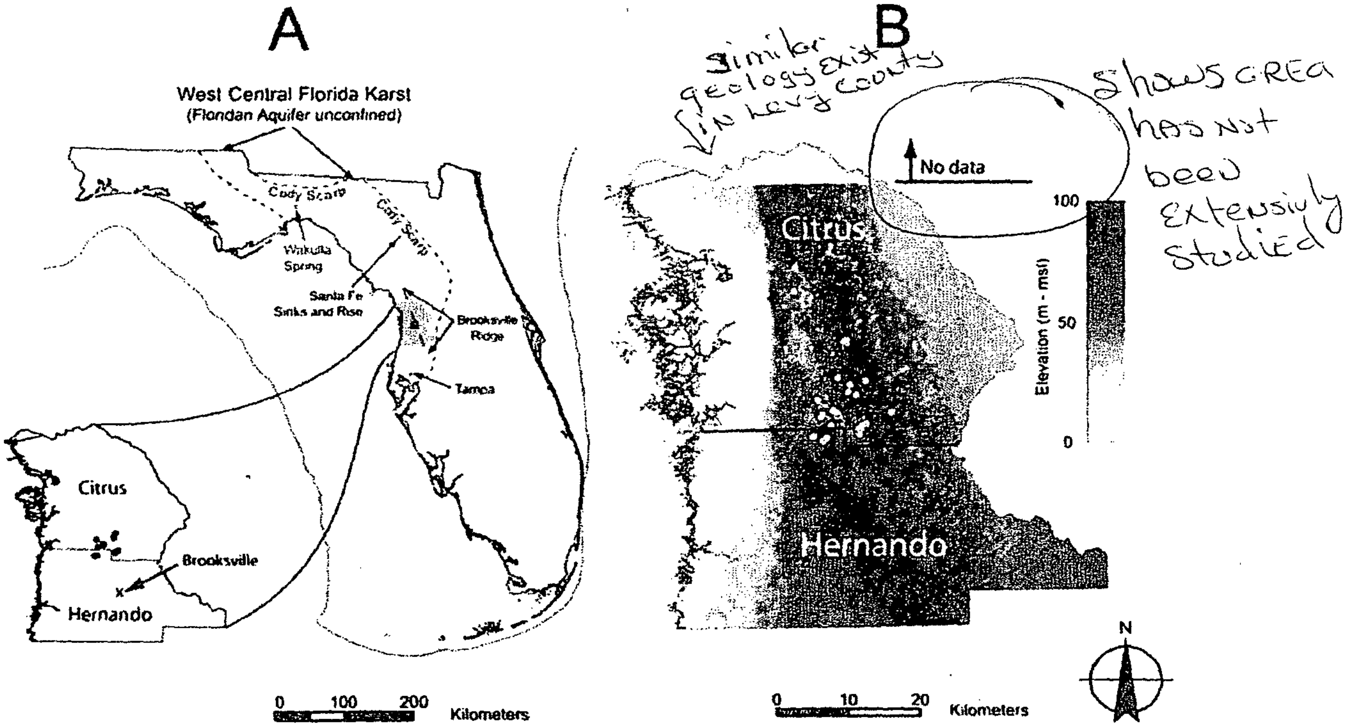



*Fig. 1. Data locations and topographic elevations. A) The grey line surrounding Florida is the –120 m bathymetric contour on the continental shelf. Inset is included for Citrus and Hernando Counties. Air-filled caves surveyed in this study are indicated by black dots. An "x" indicates the location of the city of Brooksville. B) Elevations for the Brooksville Ridge in Citrus and Hernando Counties are generated using GIS topographic data. Known air filled caves in the Brooksville Ridge are indicated by white circles.*

An irregular exposure surface with chert lenses, clay-rich marls, and a transition to non-recrystallized limestone marks the boundary between the Oligocene carbonates and the Ocala Limestone of late Eocene age. The Ocala Limestone is cream to white, soft, friable, and very porous in the Brooksville Ridge. It ranges in thickness from 30 m north of the study area to more than 120 m south of the Brooksville Ridge (Miller, 1986). Petrographic investigations of the Ocala Limestone by Loizeaux (1995) demonstrate three 3rd-order cycles of deposition. Shallow-water, high-energy facies, such as cross-bedded, low-mud grainstones and mixed-skeletal packstones, dominate all three cycles of the Ocala Limestone in the Brooksville Ridge.

The geologically young carbonates of the Upper Floridan Aquifer retain much of their original porosity and permeability, which is highly heterogeneous and facies-dependent (Budd and Vacher, 2004). Measurements during this study from cave and core samples from the Brooksville Ridge indicate that the matrix permeability of the Ocala Limestone averages 10–12.7m2, which compares to an estimated value of 10–17.7 m2 for the much older Paleozoic limestones of the Mammoth Cave region of Kentucky (Worthington *et al.*, 2000).

## PASSAGE DIRECTIONALITY

Caves in west-central Florida, regardless of cross-section, exhibit a preferred orientation of passages along fractures in the aquifer (Figs. 4 and 7). The datasets from the Brooksville Ridge and from Marion County are similar; both generally reveal a regional NW-SE and NE-SW pattern of passages.

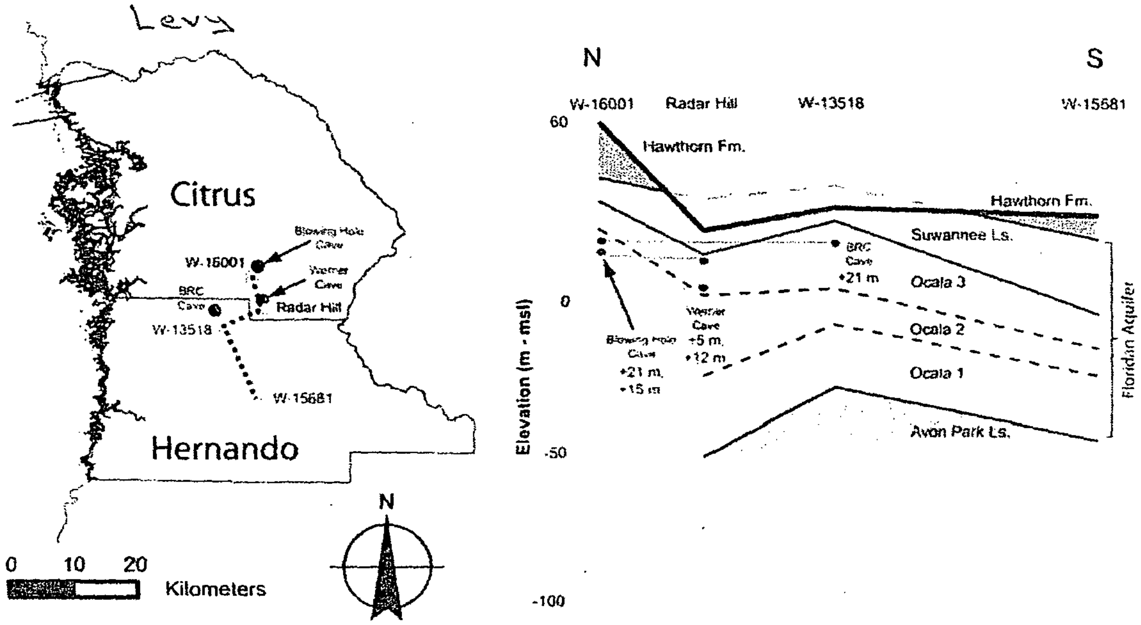



*Fig. 12. North-south cross-section through the study area in the Brooksville Ridge. Dashed line on the map at left indicates the location of the cross-section. White squares are the wells used for lithologic identification. Black dots are the caves from this study near the line of cross-section. Note that the levels within these caves do not occur in the same geologic units throughout the study area.*

Vernon (1951), who looked at topographic and physiographic features (such as linear segments of the Withlacoochee River), and Littlefield *et al.* (1984), in a detailed study of sinkhole alignments in west-central Florida, identified a large number of photo-linear features attributed to fractures that follow this NW-SE and NE-SW pattern. The widespread nature of this pattern is a manifestation of a pervasive cause of the fractures that is not yet identified.

Individually, the rose diagrams of passage orientations vary amongst the caves in the study area and in the caves in Marion County (Fig. 7). However, these data do not provide credible evidence that explains the reason for the variation. For instance, it is unclear whether the passages surveyed in a particular cave are a representative subset of all passages in the vicinity of that cave. What is clear is that the passages are some measure of the anisotropy of the aquifer at the time the cave formed.

## PASSAGE HORIZONTALITY

Cave passages in west-central Florida are not only laterally expansive, they occur at particular elevations much like the levels of cave passages within ancient limestones, such as at Mammoth Cave (Palmer, 1987). At Mammoth

Cave, cave levels formed near the water table as the elevation of the Green River experienced staged base-level lowering during glacial-interglacial cycles (Granger *et al.*, 2001). In Florida, the origin of cave levels may also result from changing positions of the water table, but one must also consider the role of lithology and, more specifically, variations in matrix permeability.

This second option, variations in matrix permeability, is often ignored in the study of caves in ancient limestones. However, the matrix permeability of the young carbonates that comprise the Upper Floridan Aquifer may be more than 105 times more permeable than the ancient limestones of the midcontinent. Additionally, matrix permeability in the Upper Floridan Aquifer is facies-dependent and spans three orders of magnitude (Budd and Vacher, 2004). Such variations would provide preferred horizons of ground-water flow (Vacher *et al.*, 2006).

If the cave levels in Florida are related to lithologic units with high matrix permeability, the elevations of these cave levels would change in accordance with the geologic structure. However, the widespread levels of cavities do not follow the geologic structure; the cave levels are at the same elevation even though the lithologic units dip to the south (Fig. 12). Therefore, lithologic variability does not exert the first-order. Influence on the locus of cave development.

There is, however, some correspondence between the cave levels in the study area and modes in the histogram of topographic data for Citrus and Hernando Counties (Fig. 5). The modes in the topographic data manifest the classic marine terraces identified in Florida by Cooke (1945) and later Healy (1975) including the Silver Bluff (+2.4 m), Talbot (+12.8 m), Penholoway (+21.3 m), and Wicomico (+30.5 m) terraces. These marine terraces are directly related to previous elevations of sea level.

In this near-coastal setting, the position of sea level has a direct influence on the position of the water table. Since the elevations of cave levels in the survey data generally correspond to the elevation of marine terraces, it appears that the development of air-filled caves in west-central Florida may be related to positions of the water table, and thus sea level, when they were higher than present.

## PASSAGE CONNECTIVITY

Of the seven caves in the Brooksville Ridge surveyed during this study, none contain continuous conduits that connect sites of recharge to points of discharge within the Upper Floridan Aquifer. Neither do passages in the surveyed caves comprise a dendritic network of conduits with tributary passages.

Only one cave, BRC Cave, receives occasional water from a sinking stream and contains natural indicators of localized directional flow such as sediment ripples and pebble imbrication. Three other caves, Big Mouth, Morris, and Werner, receive recharge from artificial sinking streams created during quarry reclamation. Discharge for the water that enters all seven caves rises some 15–20 km to the west at the large springs along the coast.

Connections between the caves and the surface are limited in the karst of west-central Florida. Many caves in the Brooksville Ridge, including four of the caves in this study (BRC, Big Mouth, Morris, and Werner), had no known human scale entrance prior to lime-rock mining. In fact, most air-filled caves that are known in the karst of west-central Florida were discovered by human alteration of the land, in particular limerock quarries that excavate to the level of the cave passages. The subdued topography of Florida contributes to the lack of entrances by restricting the natural intersection of the land surface with the horizontal cave passages. The implication is that there are many more caves in west-central Florida than are currently known. The burgeoning sinkhole insurance industry in Florida is a manifestation of this fact.

Surveyed passages within the air-filled caves of west-central Florida do not extend long distances. Tabular passages pinch into low cavities. Fissure-type passages thin into increasingly-narrowing fractures. Quaternary-age siliciclastic sediments and structural collapse features are pervasive, and further segment the caves. The connections between human scale passages at the same level, therefore, are small, and additional exploration requires excavation by dedicated cavers (Turner, 2003). Vertical exploration in the caves is achieved where structural collapse features or solution-enlarged fractures connect multiple levels (Fig. 4).

## POSSIBLE HYDROLOGIC IMPLICATIONS

Data from the air-filled caves in the Brooksville Ridge of west-central Florida contradict the notion of an integrated network of conduits above the modern water table. If the observations from this study are representative of conditions below the present water table, then connectivity between input and output points within the Upper Floridan Aquifer may be limited.

It also appears that caves in west-central Florida do not follow the sinking stream-spring model so widely accepted by karst scientists who study the ancient limestones of the midcontinent. Rather, water in the karst aquifers of west-central Florida may travel through a maze of passages, fractures, sediment fills, and rock matrix at several horizons.

Available data support this conjecture of multi-level discontinuous mazes. For instance, maps of underwater caves reveal passages throughout west-central Florida that occur at specific depths up to 120 m below the water table (Florea and Vacher, in review). Furthermore, Quaternary-age siliciclastic sediments infiltrate these underwater caves, and these sediments are commonly recovered from cavities encountered during well construction (*e.g.*, Hill and DeWitt, 2004).

Disjunct or occluded underwater passages in the Upper Floridan Aquifer would impede ground-water flow, resulting in higher elevations of the water table and steep hydrologic gradients. These are both observed within the karst of west-central Florida. As one example, a regional, finite-difference ground-water model that includes the northern portions of the Brooksville Ridge, developed for the Southwest Florida Water Management District by GeoTrans (1988), concluded that model calibration to known elevations of the water table is possible only if fractures or solution features are not regionally extensive or hydraulically connected. If the opposite case were true (*i.e.*, if solution features were regionally extensive or hydraulically connected), the gradient of the water table would reduce to near-zero and the elevation of the water table would equilibrate near sea level. The coastal, carbonate aquifers in the Yucatań Riviera of Mexico, with more than 400 km of mapped underwater cave and water-table gradients of less than 0.00001 (Worthington *et al.*, 2000), illustrates this possibility. This hydrogeologic contrast between the great peninsulas of Florida and Yucatań, and its relation in part to the presence of infiltrating clastics in the case of Florida, was pointed out more than 30 years ago by Back and Hanshaw (1970).

## CONCLUDING REMARKS

This study of air-filled caves in the Brooksville Ridge of west-central Florida offers an improved understanding of cave-scale porosity in the Upper Floridan Aquifer. How does the architecture of these caves compare with that of other cave systems? It is instructive to review summaries from two contrasting geologic settings, the caves of ancient low-permeability limestones of the mid-continent (Palmer, 2003) and the caves of small islands composed of Pleistocene limestone (Mylroie *et al.*, 1995).

The first example, the caves of the mid-continent, is important because it is the paradigm view of near-surface caves. Palmer (2003, p. 2) uses the following description for such caves:

Most accessible caves are surrounded by rock in which the vast majority of openings have hardly enlarged at all. The conduits are not surrounded by porous zones, with walls like a sponge, where progressively smaller openings extend indefinitely into the cave wall. The conduits are quite discrete.

Cave passages in the young carbonates of west-central Florida do not fit this description. Tabular passages are laterally extensive, and fissure-type passages thin into increasingly narrowing fractures; both extend beyond the limits of human exploration. The walls of the passages are porous and complex, with small-scale solution features such as pockets and tafoni structures extending into the host bedrock, which itself has high permeability. Cave passages in the Brooksville Ridge are not discrete conduits, and they do not connect together into a dendritic-style drainage system as described by Palmer (1991). Ground water in the Upper Floridan Aquifer may readily exchange between the cave and the rock matrix (Martin and Dean, 2001).

The second example, from the young carbonate islands, is important because it is the paradigm for caves in young limestone. These flank margin caves, which form by mixing at the water table and at the freshwater-saltwater interface, are summarized as follows by Mylroie and Carew (1995, p. 252-253):

Typically these caves are dominated by large globular chambers that are broad in the horizontal plane but vertically restricted...At the rear of the chamber there is usually a series of smaller chambers that change into tubular passages...Commonly there are many cross-connections between adjacent chambers and passages that give the caves a maze-like character. The passages...end abruptly. The chamber and passage walls are often etched into a variety of dissolution pockets and tubes...Flow markings, such as ablation scallops, are absent.

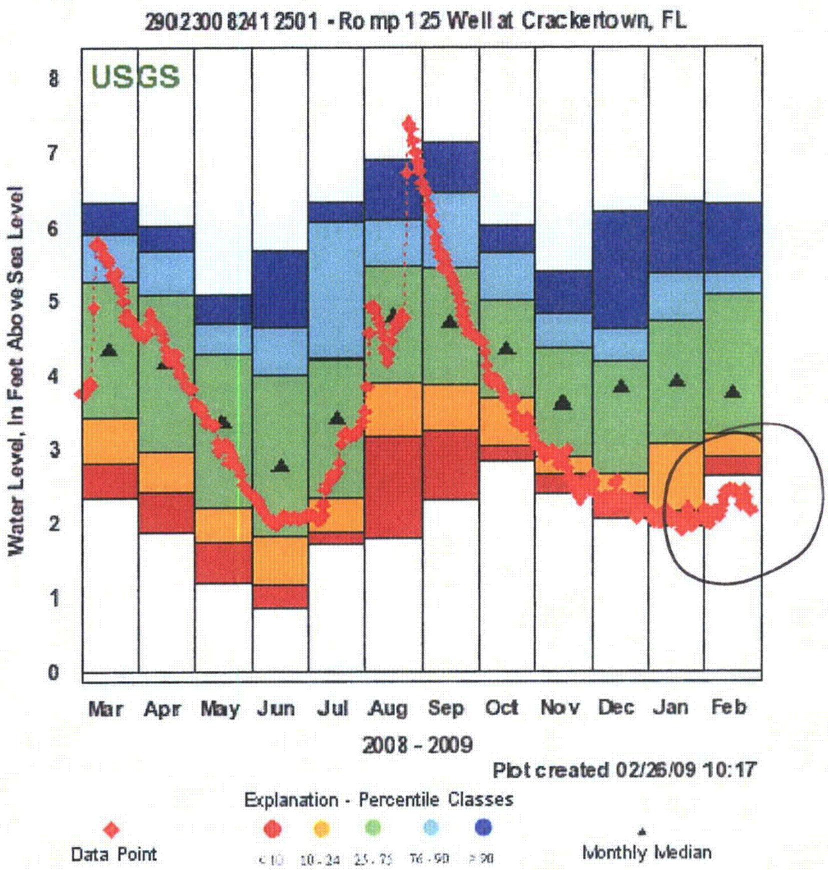
Many of the features found in the caves of the Brooksville Ridge are remarkably similar to this description. Laterally extensive cavities contain bedrock pillars and cuspate dissolution features, and the passages often terminate in blind pockets. Flow indicators are generally not present. However, there are distinct differences between caves of west-central Florida and caves on young, carbonate islands. Whereas flank margin caves, for example, are composed of amorphous voids and rudimentary, sponge work mazes (Palmer, 1991), the caves in west-central Florida contain passages with a sense of directionality imposed by fractures in the rock matrix. The result is maps that resemble network maze caves in plan view, such as those in the Black Hills of South Dakota (Palmer, 1991).

In conclusion, caves in west-central Florida do not fit existing models of cave architecture. They represent a style of cavern development important within coastal karst aquifers composed of young carbonates.

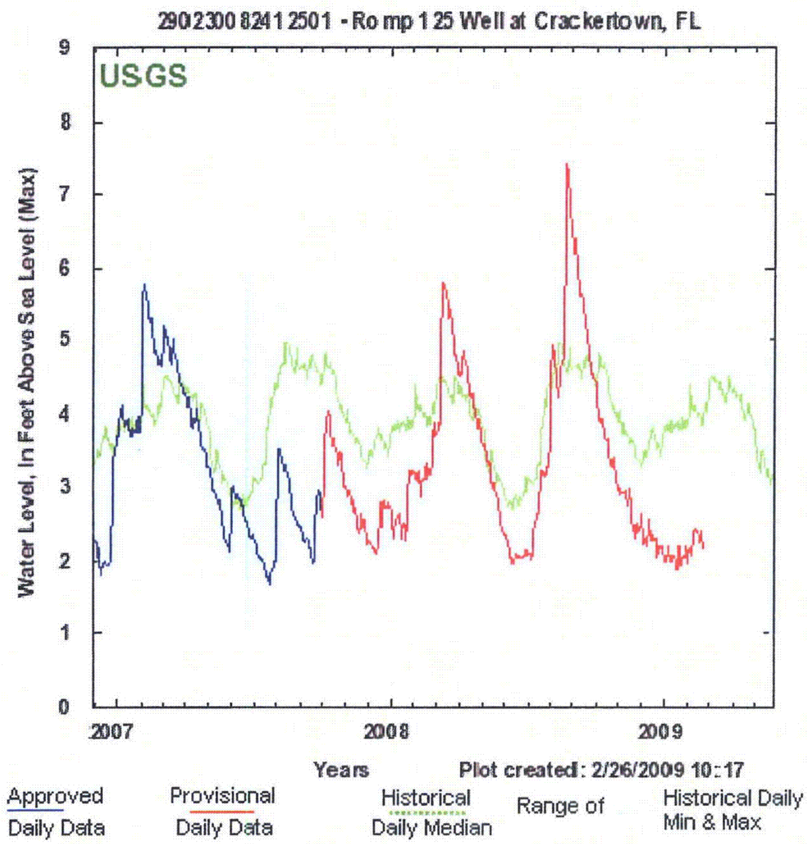
These west-central-Florida caves that lie above the water table demonstrate the extreme heterogeneity of permeability within the unconfined Upper Floridan Aquifer that lies below. This study offers the following insights to the architecture of cave-scale porosity in this critical-use aquifer: 1) cave-scale porosity is widespread but often composed of isolated or partially connected passages; 2) cave passages are generally restricted to specific elevations within the aquifer framework, and 3) the direction of cave passages in these levels occurs along a NE-SW and NW-SE system of fractures.

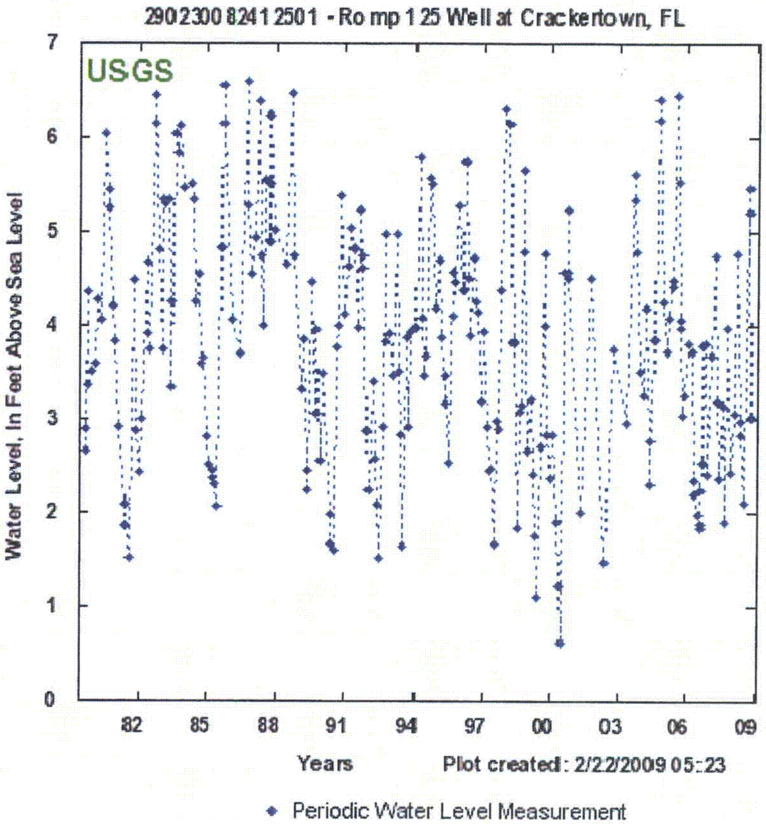
## ACKNOWLEDGMENTS

This project is indebted to the hard work of cavers and cave surveyors in Florida. I extend personal gratitude to members of the Florida Cave Survey, the Florida Speleological Society, the Tampa Bay Area Grotto, and the Withlacoochee State Forest – in particular Robert Brooks, Sean Roberts, Dan



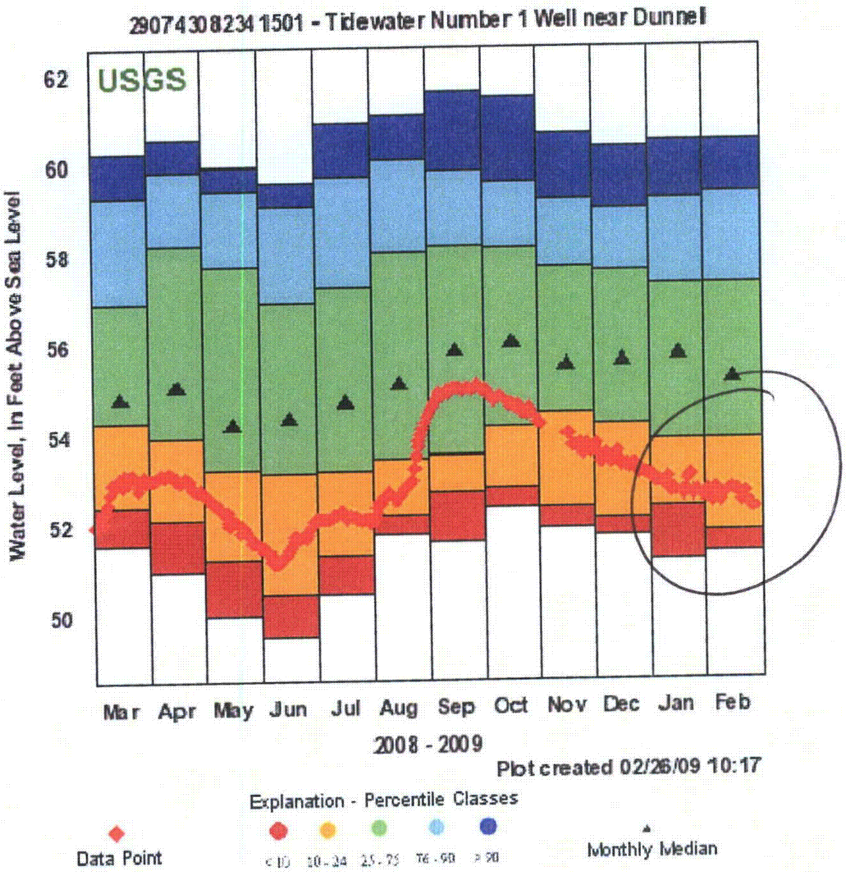

South West of Concerned Area - Very close to Yankeetown Water Supply Field

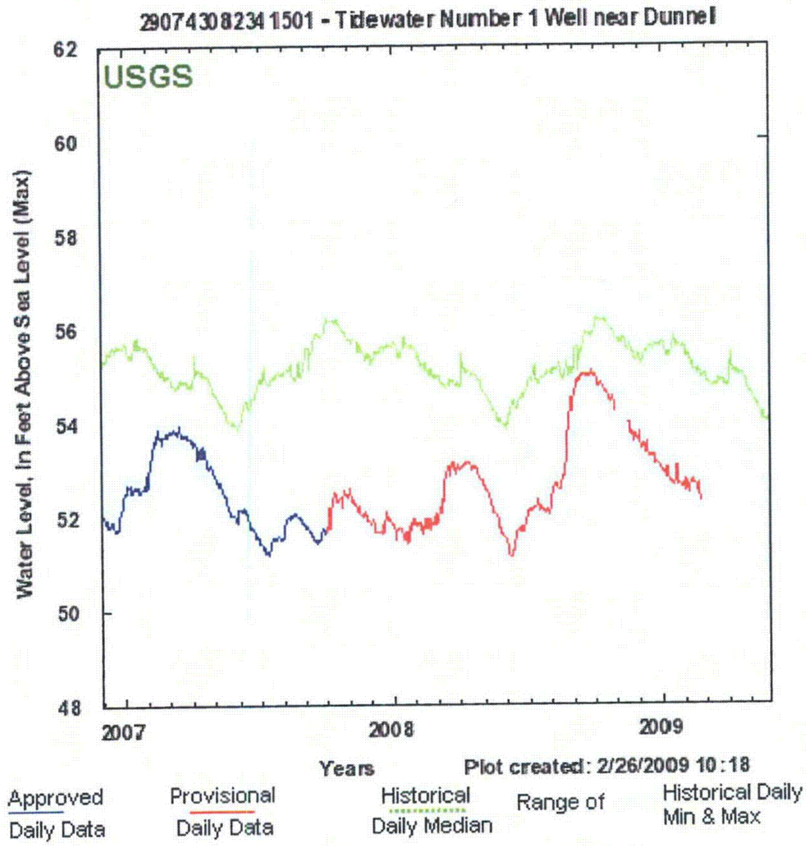

290230082412501 - Romp 125 Well at Crackertown, FL
USGS
Water Level, In Feet Above Sea Level (Max)
0
1
2
3
4
5
6
7
8
9
2007
2008
2009
Years
Plot created: 2/26/2009 10:17
Approved Daily Data
Provisional Daily Data
Historical Daily Median
Range of
Historical Daily Min & Max

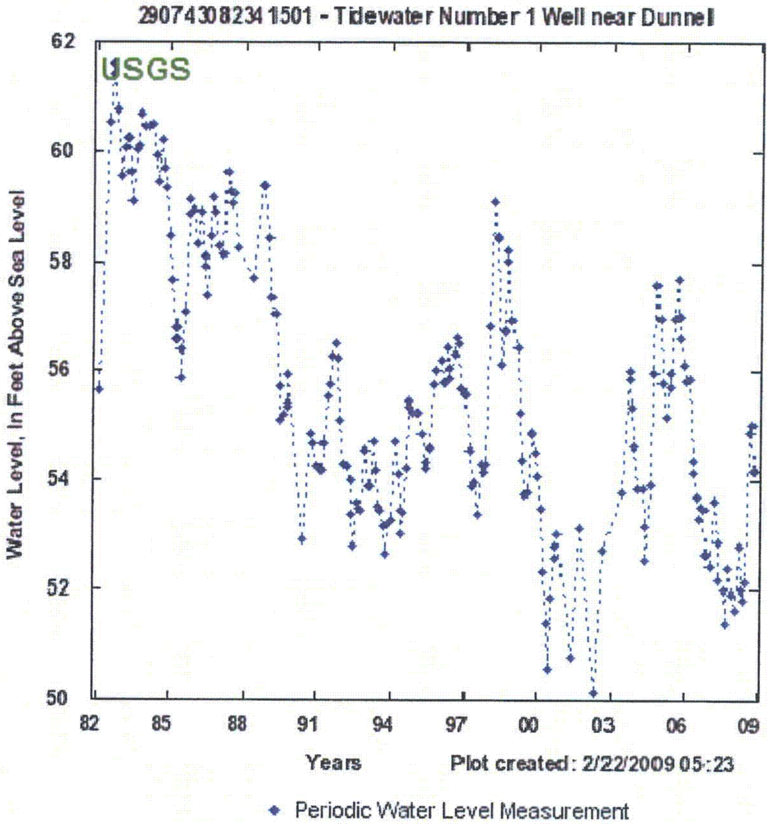


290230082412501 - Romp 125 Well at Crackertown, FL
USGS
Water Level, In Feet Above Sea Level
0
1
2
3
4
5
6
7
82
85
88
91
94
97
00
03
06
09
Years
Plot created: 2/22/2009 05:23
Periodic Water Level Measurement

North East
Of Concerned
Area.




290743082341501 - Tidewater Number 1 Well near Dunnel
USGS
Water Level, In Feet Above Sea Level (Max)
62
60
58
56
54
52
50
48
2007
2008
2009
Years
Plot created: 2/26/2009 10:18
Approved Daily Data
Provisional Daily Data
Historical Daily Median
Range of Historical Daily Min & Max


290743082341501 - Tidewater Number 1 Well near Dunnell
USGS
Water Level, In Feet Above Sea Level
62
60
58
56
54
52
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Years
Plot created: 2/22/2009 05:23
Periodic Water Level Measurement

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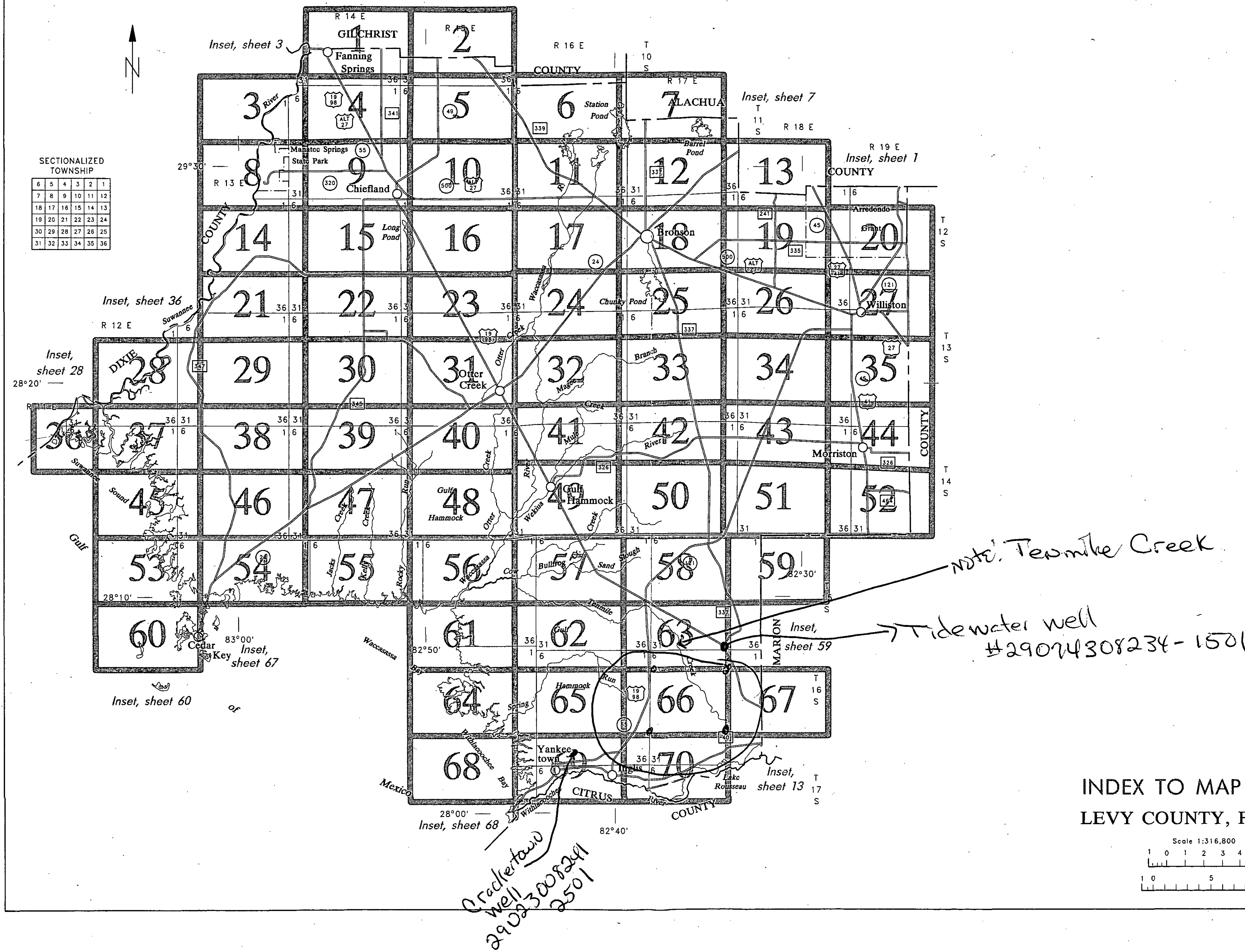



# INDEX TO MAP SHEETS
## LEVY COUNTY, FLORIDA

Scale 1:316,800

1 0 1 2 3 4 5 Miles

1 0 5 10 Km

# SOIL LEGEND

The publication symbols are numerical. An alphabetical legend will also be shown on the legend page preceding the map sheets. Soil map unit names without a slope phase are either nearly level, or they are miscellaneous areas.

| SYMBOL | NAME |
|---|---|
| 2 | Tavares fine sand, 1 to 5 percent slopes |
| 3 | Orsino fine sand, 0 to 8 percent slopes |
| 4 | Millhopper fine sand, 1 to 5 percent slopes |
| 5 | Immokalee fine sand |
| 6 | Candler fine sand, 1 to 5 percent slopes |
| 7 | Candler-Apopka complex, 1 to 5 percent slopes |
| 8 | Smyrna fine sand |
| 9 | Pomona fine sand |
| 10 | Placid fine sand |
| 11 | Placid and Samsula soils, depressional |
| 12 | Otela-Candler complex, 1 to 5 percent slopes |
| 13 | Wekiva fine sand |
| 14 | Shadeville-Otela complex, 1 to 5 percent slopes |
| 15 | Holopaw-Pineda complex, frequently flooded |
| 16 | Chobee-Gator complex, frequently flooded |
| 17 | Adamsville fine sand, 0 to 5 percent slopes |
| 18 | Wauchula fine sand |
| 19 | Sparr fine sand |
| 21 | Pompano fine sand |
| 22 | Holopaw fine sand |
| 23 | Zolfo sand |
| 24 | Terra Ceia muck, depressional |
| 25 | Pits and Dumps |
| 26 | Gator and Terra Ceia soils, frequently flooded |
| 27 | Placid and Popash soils, depressional |
| 29 | Chobee-Bradenton complex, frequently flooded |
| 31 | Jonesville-Otela-Seaboard complex, 1 to 5 percent slopes |
| 32 | Otela-Tavares complex, 1 to 5 percent slopes |
| 33 | Wulfert muck, frequently flooded |
| 34 | Cassia-Pomello complex |
| 35 | Pineda fine sand, limestone substratum |
| 37 | Myakka mucky sand, occasionally flooded |
| 38 | Myakka sand |
| 39 | Waccasassa-Demory complex, flooded |
| 40 | Pineda fine sand |
| 41 | Demory sandy clay loam, occasionally flooded |
| 42 | Ousley-Albany complex, occasionally flooded |
| 43 | Tidewater mucky clay, frequently flooded |
| 45 | Cracker mucky clay, frequently flooded |
| 46 | Chobee fine sandy loam, limestone substratum, frequently flooded |
| 48 | Lutterloh-Moriah complex, 0 to 5 percent slopes |
| 49 | Hicoria fine sand |
| 50 | Hicoria loamy fine sand, depressional |
| 51 | Ft. Green-Bivans complex, 2 to 5 percent slopes |
| 55 | Pedro-Jonesville-Shadeville complex, 0 to 5 percent slopes |
| 56 | Moriah-Bushnell-Mabel, limestone substratum, complex, 0 to 5 percent slopes |
| 57 | Paola fine sand, gently rolling |
| 58 | Boca-Holopaw, limestone substratum, complex |
| 59 | Aripeka-Matmon complex |
| 60 | EauGallie-Holopaw complex, limestone substratum |
| 62 | Millhopper-Bonneau complex, 1 to 5 percent slopes |
| 65 | Sparr-Lochloosa complex, 1 to 5 percent slopes |
| 66 | Levyville-Shadeville complex, 2 to 5 percent slopes |
| 67 | Immokalee, limestone substratum-Janney complex |
| 68 | Myakka, limestone substratum-Immokalee complex |
| 69 | Broward-Lutterloh, limestone substratum, complex |
| 70 | Hallandale-Boca-Holopaw complex |
| 71 | Pender loamy fine sand |
| 72 | Levyville-Hague complex |
| 73 | Orlando fine sand, 1 to 5 percent slopes |
| 74 | Arents, 0 to 5 percent slopes |
| 75 | Orlando fine sand, 5 to 8 percent slopes |
| 76 | Astatula fine sand, 1 to 8 percent slopes |
| 77 | Candler fine sand, 5 to 8 percent slopes |
| 78 | Micanopy loamy fine sand, 1 to 5 percent slopes |

| SYMBOL | NAME |
|---|---|
| 17 | Adamsville fine sand, 0 to 5 percent slopes |
| 74 | Arents, 0 to 5 percent slopes |
| 59 | Aripeka-Matmon complex |
| 76 | Astatula fine sand, 1 to 8 percent slopes |
| 58 | Boca-Holopaw, limestone substratum, complex |
| 69 | Broward-Letterloh, limestone substratum, complex |
| 7 | Candler-Apopka complex, 1 to 5 percent slopes |
| 6 | Candler fine sand, 1 to 5 percent slopes |
| 77 | Candler fine sand, 5 to 8 percent slopes |
| 34 | Cassia-Pomello complex |
| 46 | Chobee fine sandy loam, limestone substratum, frequently flooded |
| 29 | Chobee-Bradenton complex, frequently flooded |
| 16 | Chobee-Gator complex, frequently flooded |
| 45 | Cracker mucky clay, frequently flooded |
| 41 | Demory sandy clay loam, occasionally flooded |
| 60 | EauGallie-Holopaw complex, limestone substratum |
| 51 | Ft. Green-Bivans complex, 2 to 5 percent slopes |
| 26 | Gator and Terra Ceia soils, frequently flooded |
| 70 | Hallandale-Boca-Holopaw complex |
| 49 | Hicoria fine sand |
| 50 | Hicoria loamy fine sand, depressional |
| 22 | Holopaw fine sand |
| 15 | Holopaw-Pineda complex, frequently flooded |
| 5 | Immokalee fine sand |
| 67 | Immokalee, limestone substratum-Janney complex |
| 31 | Jonesville-Otela-Seaboard complex, 1 to 5 percent slopes |
| 72 | Levyville-Hague complex |
| 66 | Levyville-Shadeville complex, 2 to 5 percent slopes |
| 48 | Lutterloh-Moriah complex, 0 to 5 percent slopes |
| 78 | Micanopy loamy fine sand, 1 to 5 percent slopes |
| 4 | Millhopper fine sand, 1 to 5 percent slopes |
| 62 | Millhopper-Bonneau complex, 1 to 5 percent slopes |
| 56 | Moriah-Bushnell-Mabel, limestone substratum, complex, 0 to 5 percent slopes |
| 38 | Myakka sand |
| 37 | Myakka mucky sand, occasionally flooded |
| 68 | Myakka, limestone substratum-Immokalee complex |
| 73 | Orlando fine sand, 1 to 5 percent slopes |
| 75 | Orlando fine sand, 5 to 8 percent slopes |
| 3 | Orsino fine sand, 0 to 8 percent slopes |
| 12 | Otela-Candler complex, 1 to 5 percent slopes |
| 32 | Otela-Tavares complex, 1 to 5 percent slopes |
| 42 | Ousley-Albany complex, occasionally flooded |
| 57 | Paola fine sand, gently rolling |
| 55 | Pedro-Jonesville -Shadeville complex, 0 to 5 percent slopes |
| 71 | Pender loamy fine sand |
| 40 | Pineda fine sand |
| 35 | Pineda fine sand, limestone substratum |
| 25 | Pits and Dumps |
| 10 | Placid fine sand |
| 27 | Placid and Popash soils, depressional |
| 11 | Placid and Samsula soils, depressional |
| 9 | Pomona fine sand |
| 21 | Pompano fine sand |
| 14 | Shadeville-Otela complex, 1 to 5 percent slopes |
| 8 | Smyrna fine sand |
| 19 | Sparr fine sand |
| 65 | Sparr-Lochloosa complex, 1 to 5 percent slopes |
| 2 | Tavares fine sand, 1 to 5 percent slopes |
| 24 | Terra Ceia muck, depressional |
| 43 | Tidewater mucky clay, frequently flooded |
| 39 | Waccasassa-Demory complex, flooded |
| 18 | Wauchula fine sand |
| 13 | Wekiva fine sand |
| 33 | Wulfert muck, frequently flooded |
| 23 | Zolfo sand |

# CONVENTIONAL AND SPECIAL SYMBOLS LEGEND

## CULTURAL FEATURES

BOUNDARIES
- National, state, or province
- County or parish
- Minor civil division
- Reservation (national forest or park, state forest or park, and large airport)
- Land grant
- Limit of soil survey (label)
- Field sheet matchline and neatline

AD HOC BOUNDARY (label) — Davis Airstrip
- Small airport, airfield, park, oilfield, cemetery, or flood pool — FLOOD POOL LINE

STATE COORDINATE TICK
1 890 000 FEET

LAND DIVISION CORNER (sections and land grants)

ROADS
- Divided (median shown if scale permits)
- Other roads
- Trail

ROAD EMBLEM & DESIGNATIONS
- Interstate — 173
- Federal — 287
- State — 52
- County, farm or ranch — 1283

RAILROAD

POWER TRANSMISSION LINE (normally not shown)

PIPE LINE (normally not shown)

FENCE (normally not shown)

LEVEES
- Without road
- With road
- With railroad

DAMS
- Large (to scale)
- Medium or Small (Named where applicable) — water

PITS
- Gravel pit
- Mine or quarry

MISCELLANEOUS CULTURAL FEATURES
- Farmstead, house (omit in urban area) (occupied)
- Church
- School
- Indian mound (label) — Indian Mound
- Located object (label) — Tower
- Tank (label) — Gas
- Wells, oil or gas
- Windmill
- Kitchen midden

## WATER FEATURES

DRAINAGE
- Perennial, double line
- Perennial, single line
- Intermittent
- Drainage end
- Canals or ditches
  - Double-line (label) — CANAL
  - Drainage and/or irrigation

LAKES, PONDS AND RESERVOIRS
- Perennial — water
- Intermittent — int

MISCELLANEOUS WATER FEATURES
- Marsh or swamp
- Spring
- Well, artesian
- Well, irrigation
- Wet spot

## SPECIAL SYMBOLS FOR SOIL SURVEY

SOIL DELINEATIONS AND SYMBOLS — 2 65

ESCARPMENTS
- Bedrock (points down slope)
- Other than bedrock (points down slope)

SHORT STEEP SLOPE

GULLY

DEPRESSION OR SINK

SOIL SAMPLE (normally not shown)

MISCELLANEOUS
- Blowout
- Clay spot
- Gravelly spot
- Gumbo, slick or scabby spot (sodic)
- Dumps and other similar non soil areas
- Prominent hill or peak
- Rock outcrop (includes sandstone and shale)
- Saline spot
- Sandy spot
- Severely eroded spot
- Slide or slip (tips point upslope)
- Stony spot, very stony spot

2

N

10 000 Feet

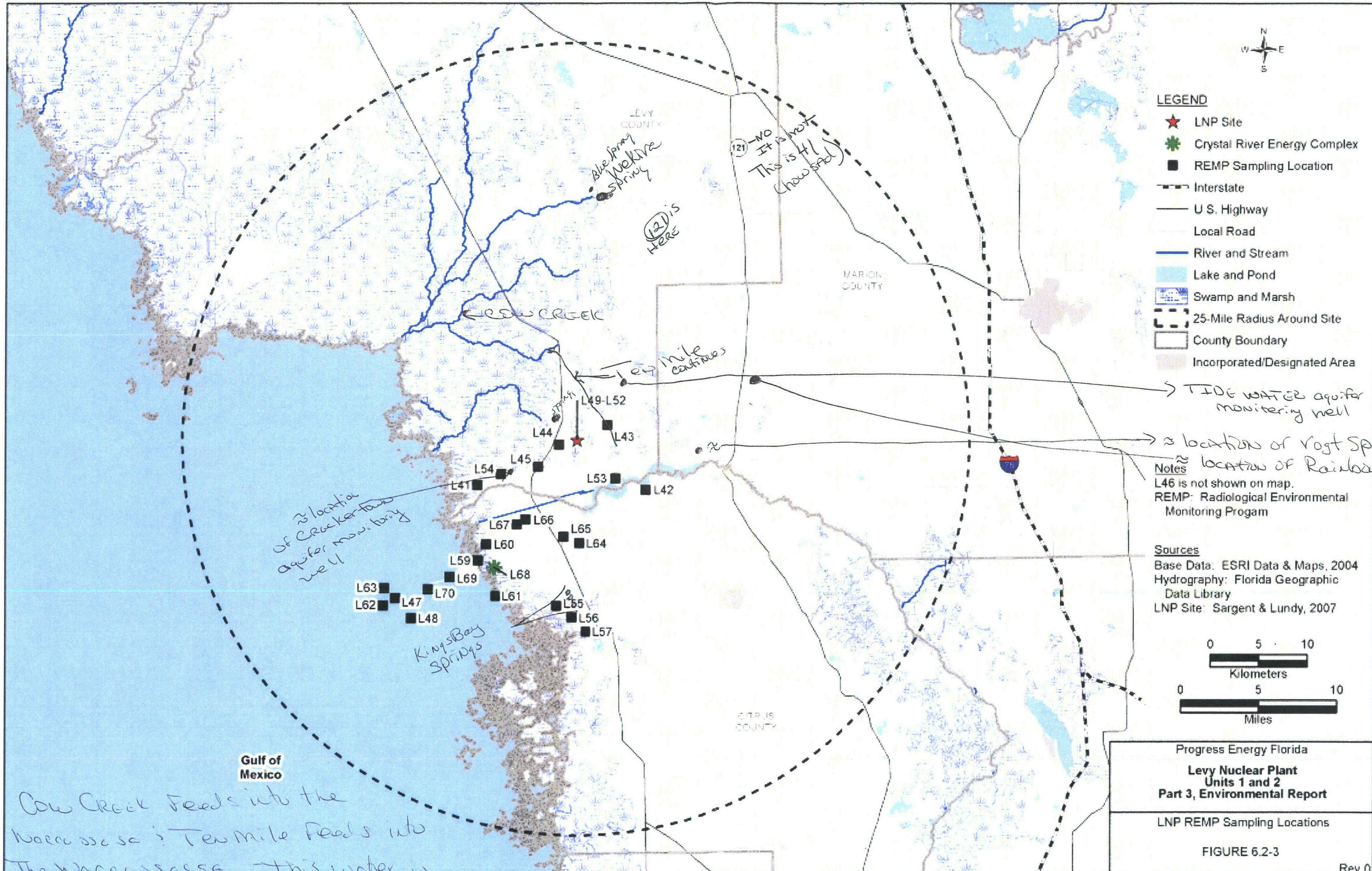
5000

note: All wetlands - Now it is not the same because of poor forestry practices: But it can be Restored


LEVY COUNTY, FLORIDA NO. 66

This soil survey map was compiled by the U.S. Department of Agriculture, Soil Conservation Service, and cooperating agencies.
Base maps are from 1979–1980 aerial photography. Coordinate grid ticks and land division corners, if shown, are approximately positioned.

This soil survey map was compiled by the U.S. Department of Agriculture, Soil Conservation Service, and cooperating agencies.
Base maps are from 1979–1980 aerial photography. Coordinate grid ticks and land division corners, if shown, are approximately positioned.




Progress Energy Florida
**Levy Nuclear Plant Units 1 and 2 Part 3, Environmental Report**
LNP REMP Sampling Locations
FIGURE 6.2-3
Rev 0

necessary to maintain the flow/level & to keep

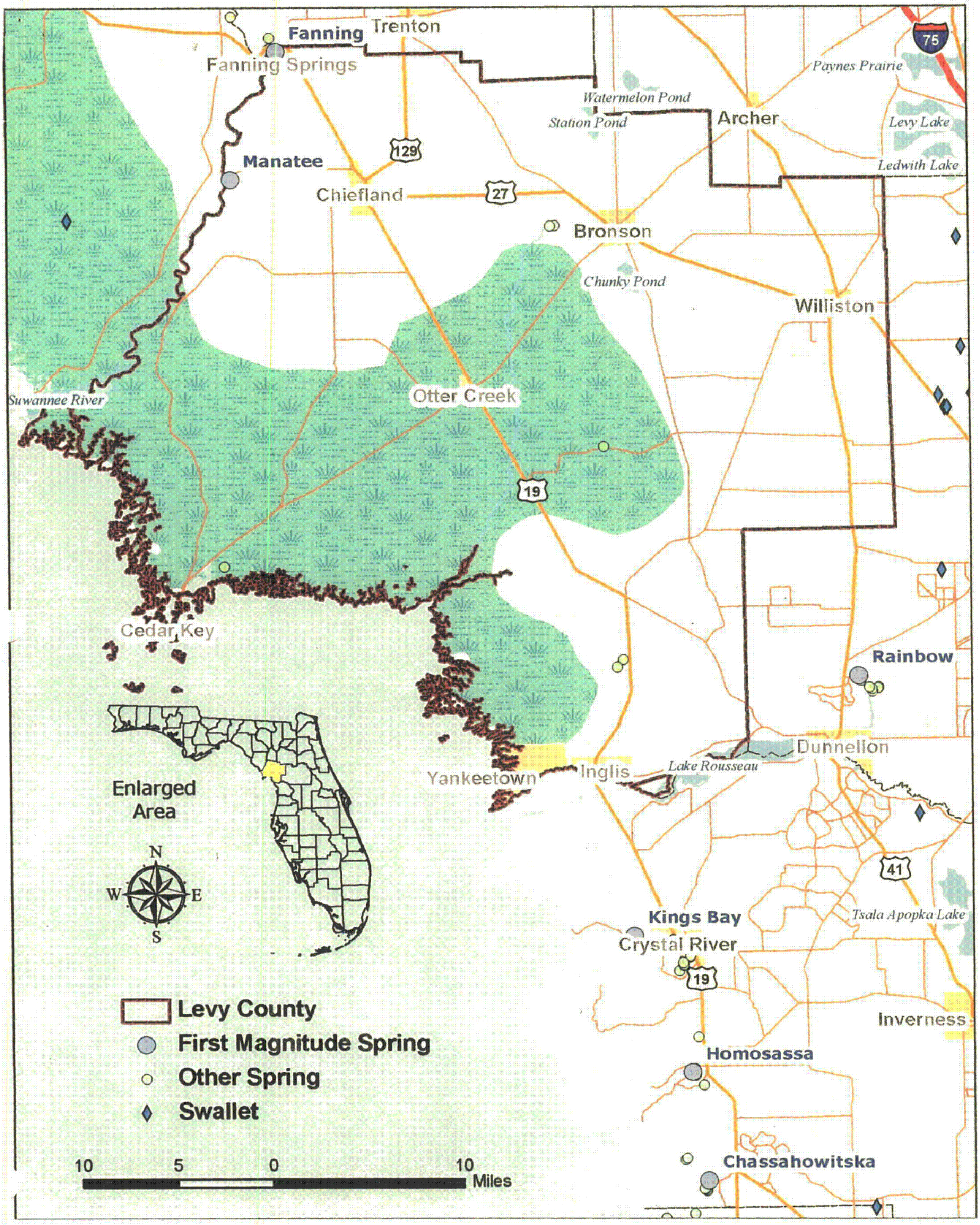



**Figure 1. Levy County Aquifer Vulnerability Assessment project study area corresponds to the County's political boundary.**

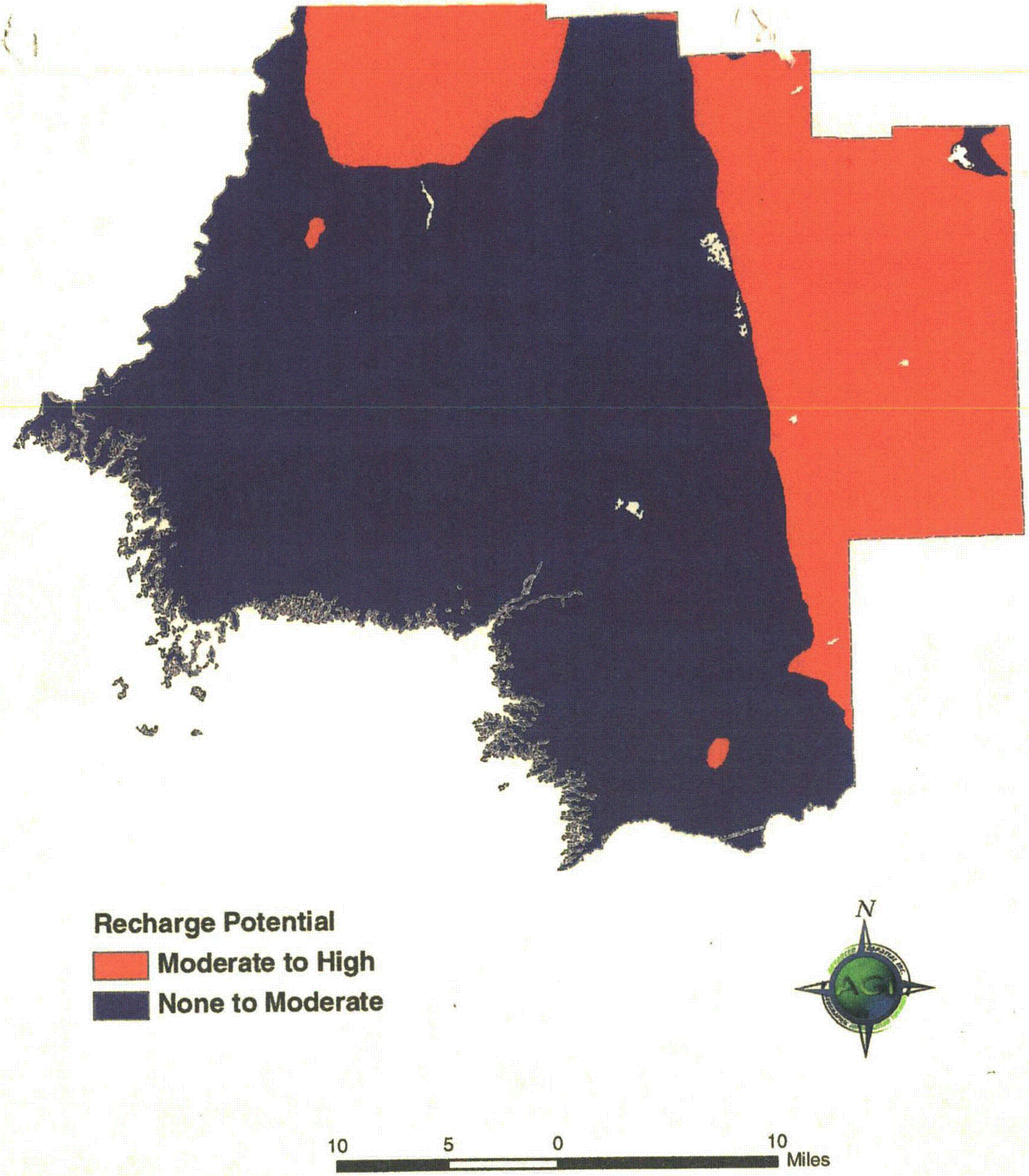



**Figure 11. Generalized recharge potential evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby aquifer vulnerability, whereas red areas share a stronger association with training points.**

Exhibit 1

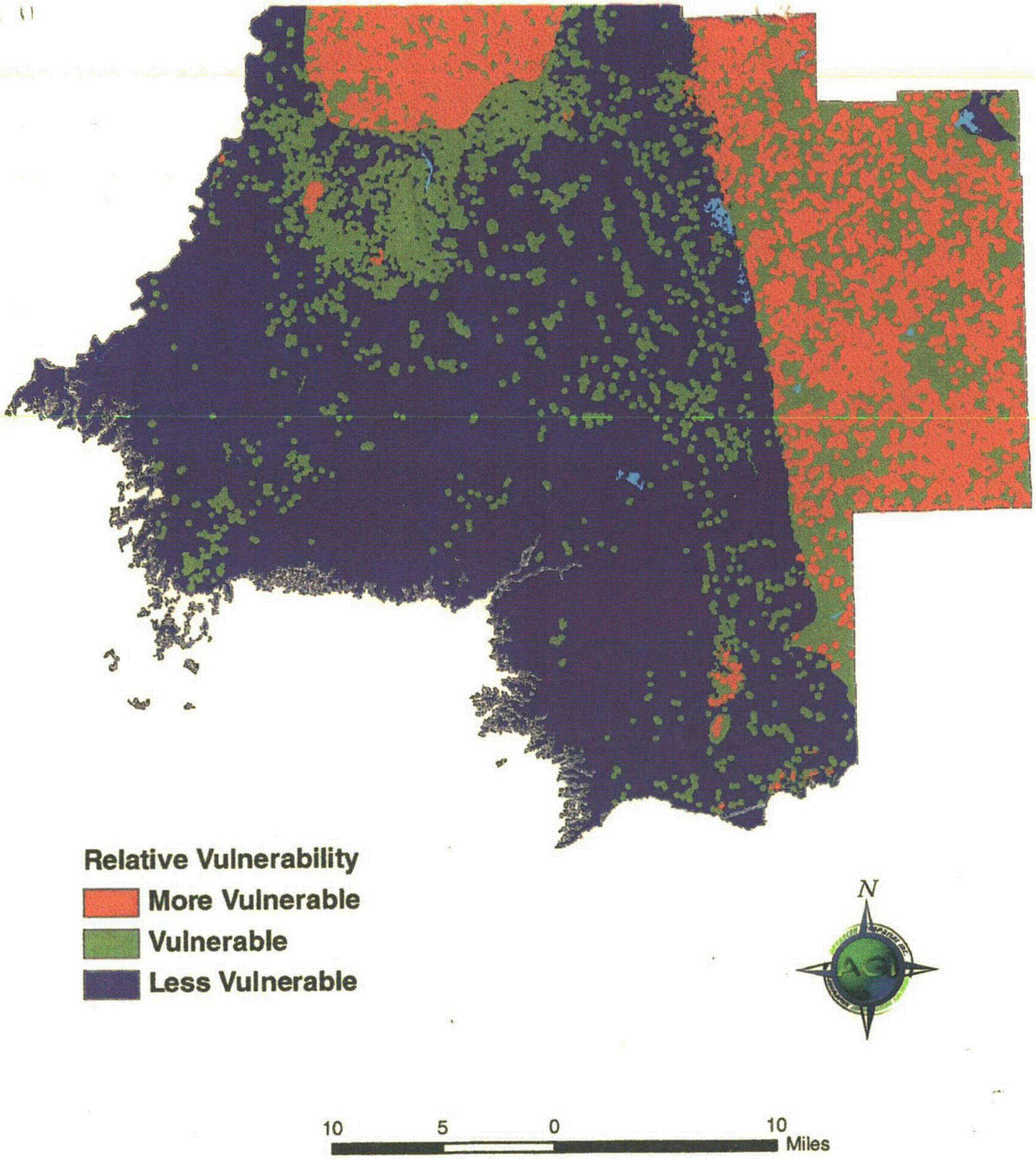



**Figure 14. Relative vulnerability map for the Levy County Aquifer Vulnerability Assessment project. Classes of vulnerability are based on calculated favorability of a unit area containing a training point, or a monitor well with water quality sample results indicative of vulnerability.**

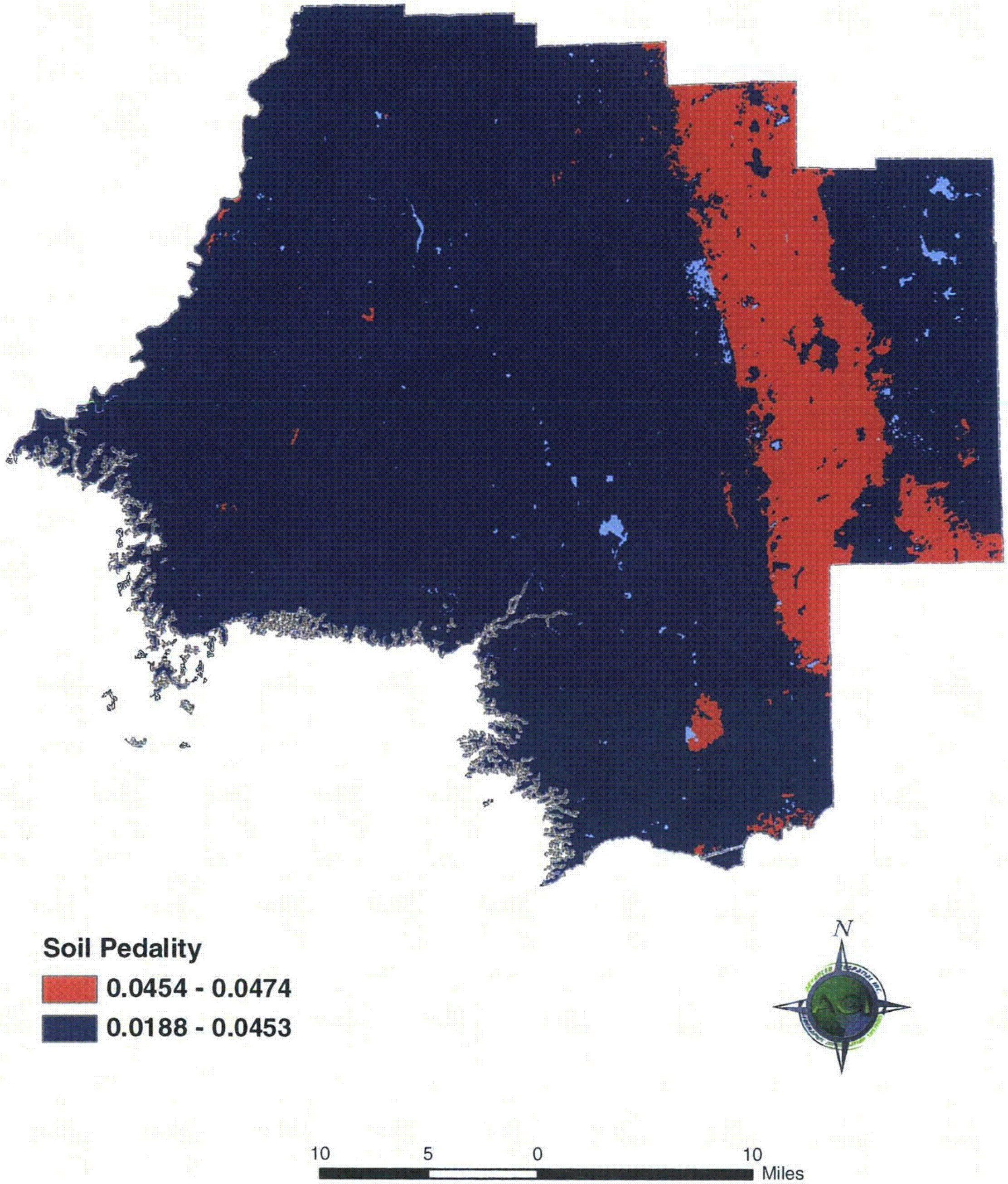



**Figure 10. Generalized soil pedality evidential theme; based on calculated weights analysis blue areas share a weaker association wi[illegible] training points and thereby aquifer vulnerability, whereas red areas share a stronger association with training points.**

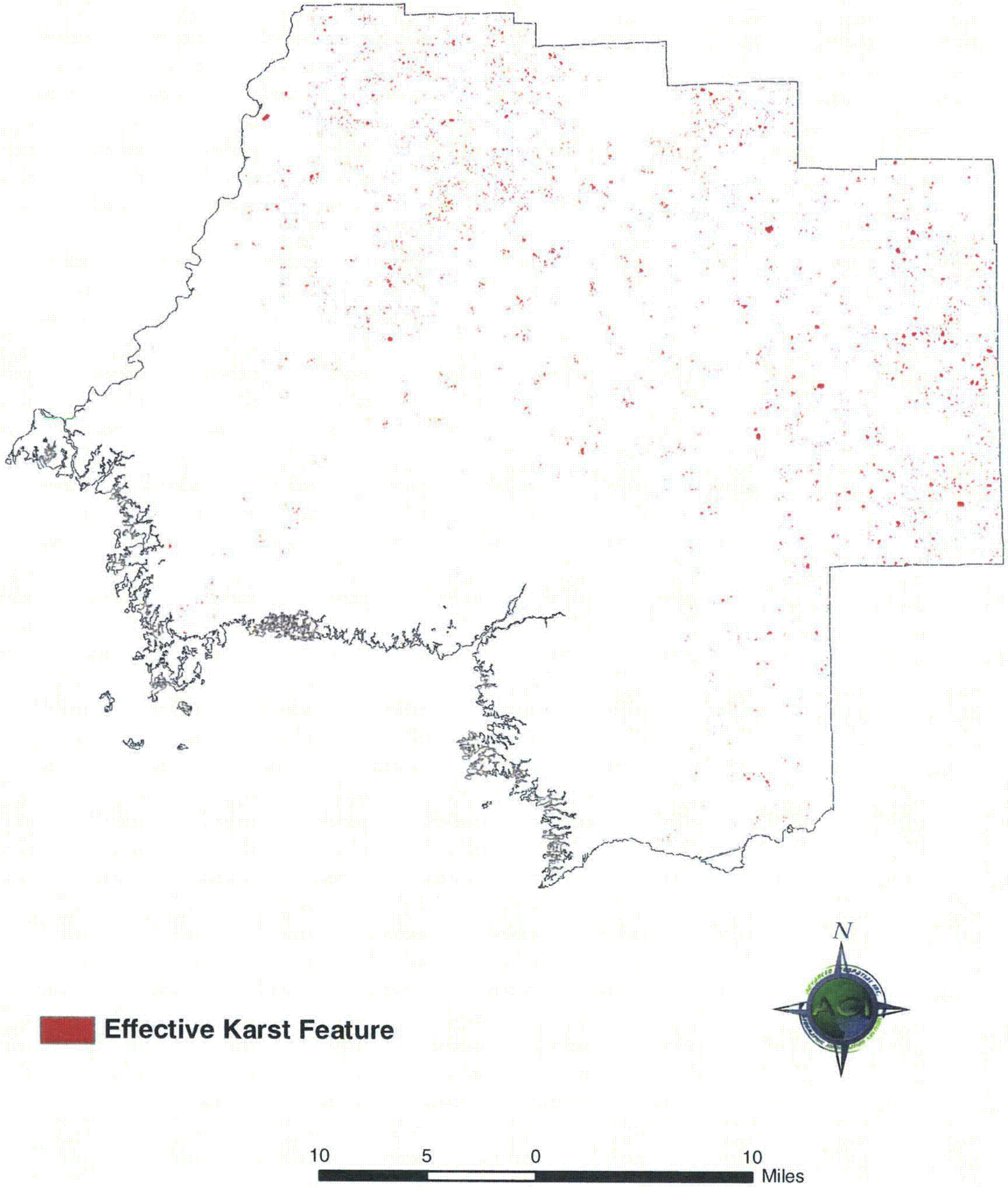



**Figure 9. Effective karst features resulting from circular index method applied to U.S. Geological Survey 7.5-minute topographical contour lines combined with sinkholes from the Florida Geological Survey sinkhole database.**

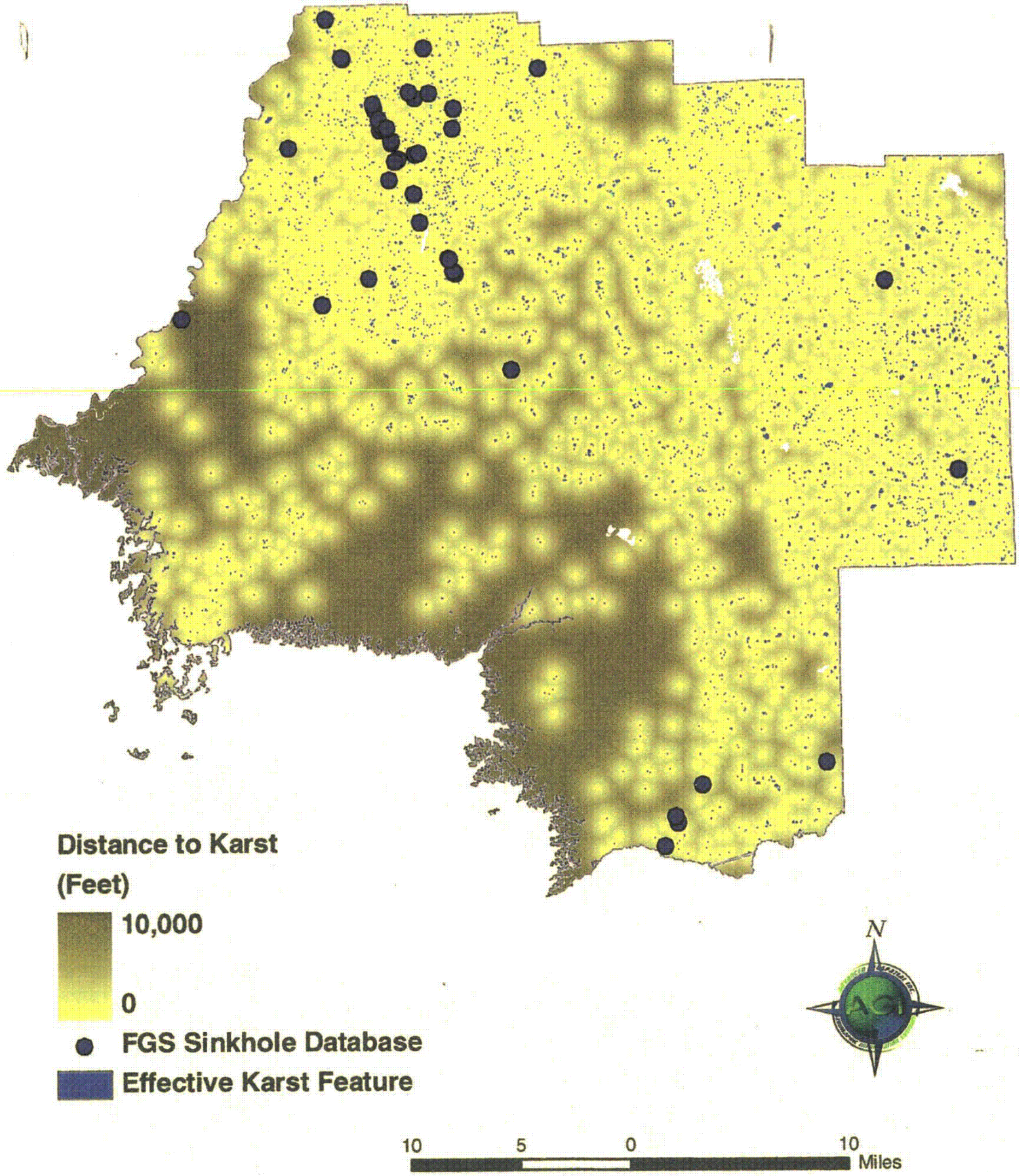



**Figure 12. Effective karst features evidential theme buffered into 100-ft zones for proximity analysis in the weights of evidence analysis.**

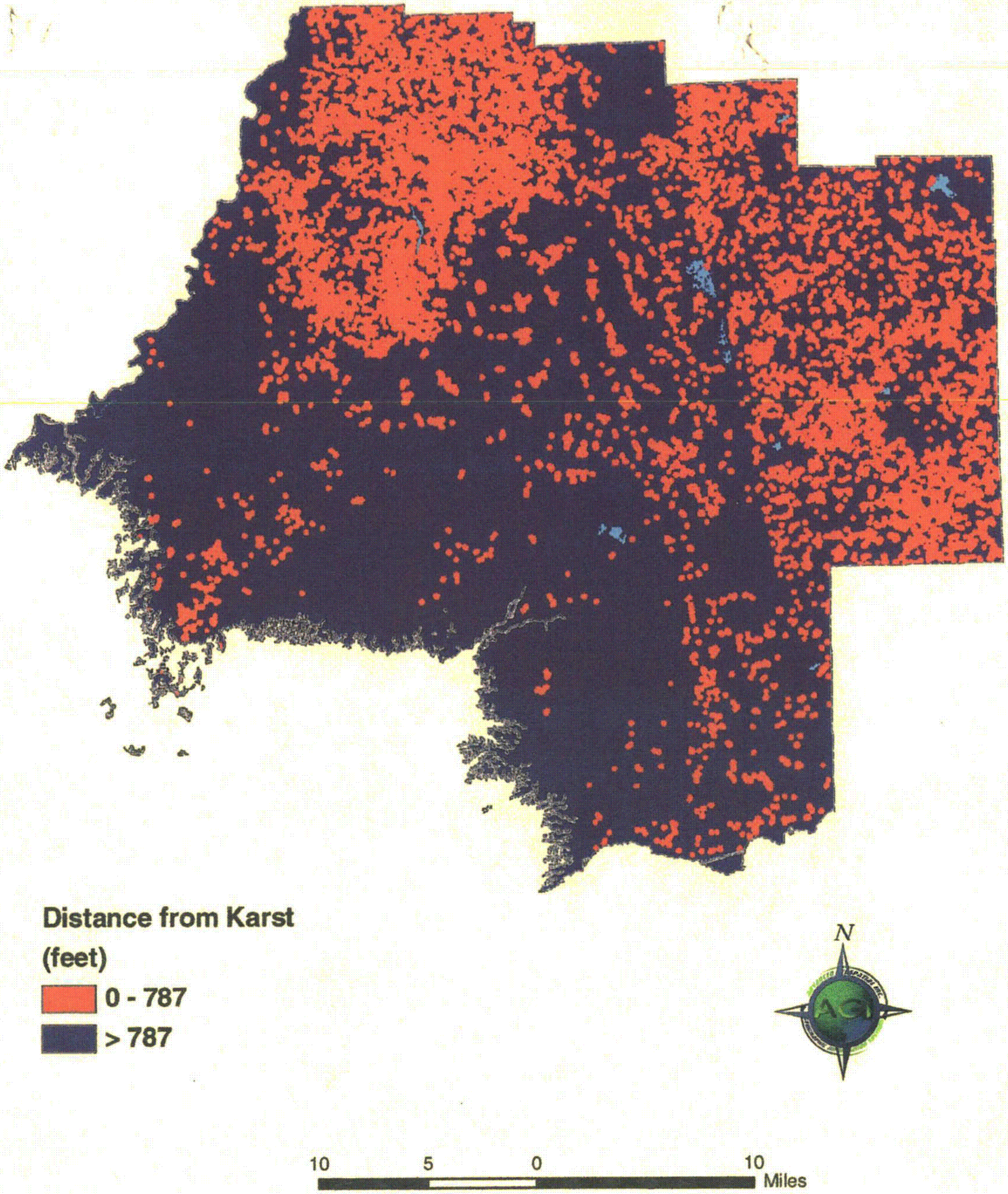



Exhibit 2

Figure 13. Generalized effective karst feature evidential theme; based on calculated weights analysis blue areas share a weaker associatio

# Florida Aquifer Vulnerability Assessment Phase II
# Levy County, Floridan Aquifer System

## INTRODUCTION

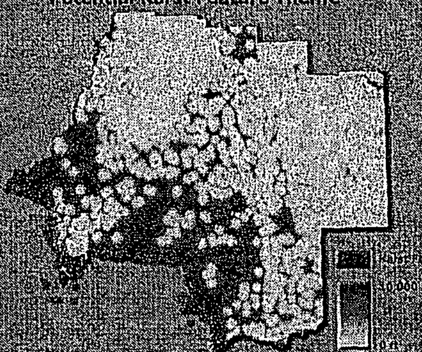
The Floridan aquifer system is the most important and prolific source of fresh water in Levy County. Groundwater use from the Floridan aquifer system in Levy County is an estimated 57 million gallons of water per day for public supply, agricultural and other uses. In addition to this amount, there are over [illegible] self-supply wells in the county tapping the Floridan aquifer system providing fresh water to homeowners [illegible] Levy County's 34,450 residents (U.S. Census Bureau, 2000) rely almost exclusively on the Floridan aquifer system for their fresh water needs.

[illegible] Maps of three types of data were used to determine aquifer vulnerability in Levy County: soil pedality, karst features and recharge potential. Maps explaining these data are displayed below.

## Soil Pedality Theme

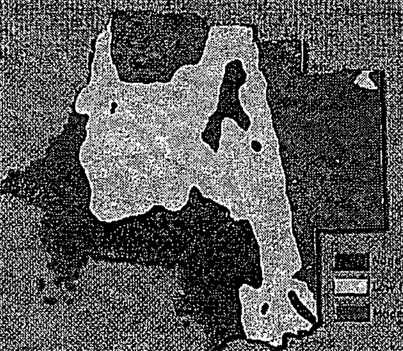
[illegible]

## Potential Karst Feature Theme



[illegible]

## Recharge Potential Theme



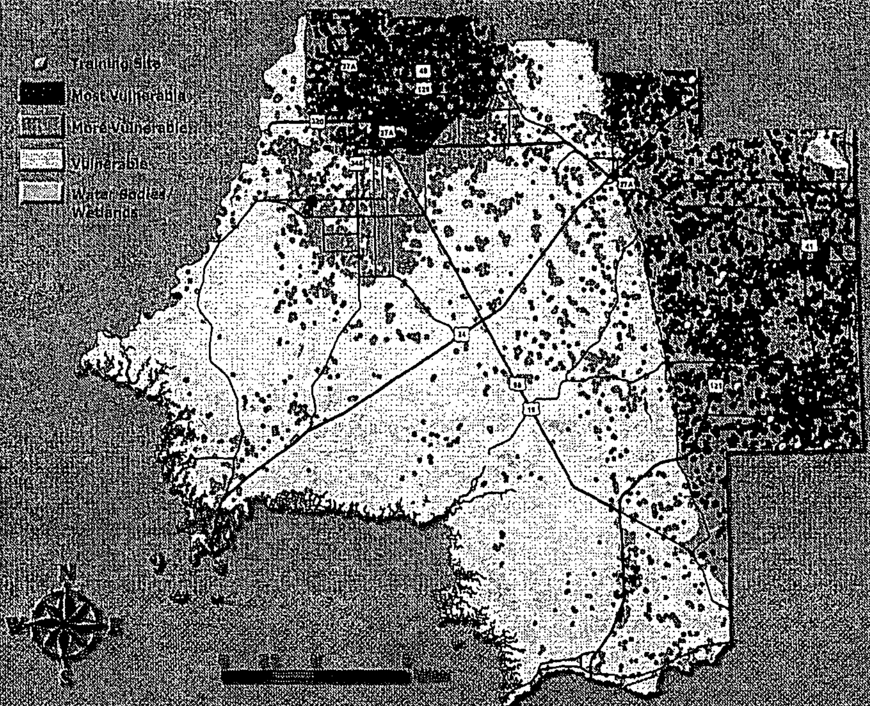
[illegible]

## APPROACH TO MODEL DEVELOPMENT

The primary purpose of the Levy County Aquifer Vulnerability Assessment, or LCAVA, is to provide a science-based water-resource management tool that can be used to help minimize adverse impacts on ground-water quality, including focused protection of sensitive areas such as springsheds and groundwater recharge areas. The modeling process used for the LCAVA project is Weights of Evidence, and is based in a geographic information system (GIS). The approach used in the project is a modification of the technique used in Phase I of the Florida Aquifer Vulnerability Assessment project (Arthur et al., 2007). One of the main benefits of applying this technique to the LCAVA project is that it is data-driven rather than expert-driven, and model output is dependent upon a training site dataset, which produces a self-validated model output. For LCAVA, training sites are groundwater wells with water quality indicative of a good connection between the aquifer and land surface, or simply, aquifer vulnerability.

[illegible]

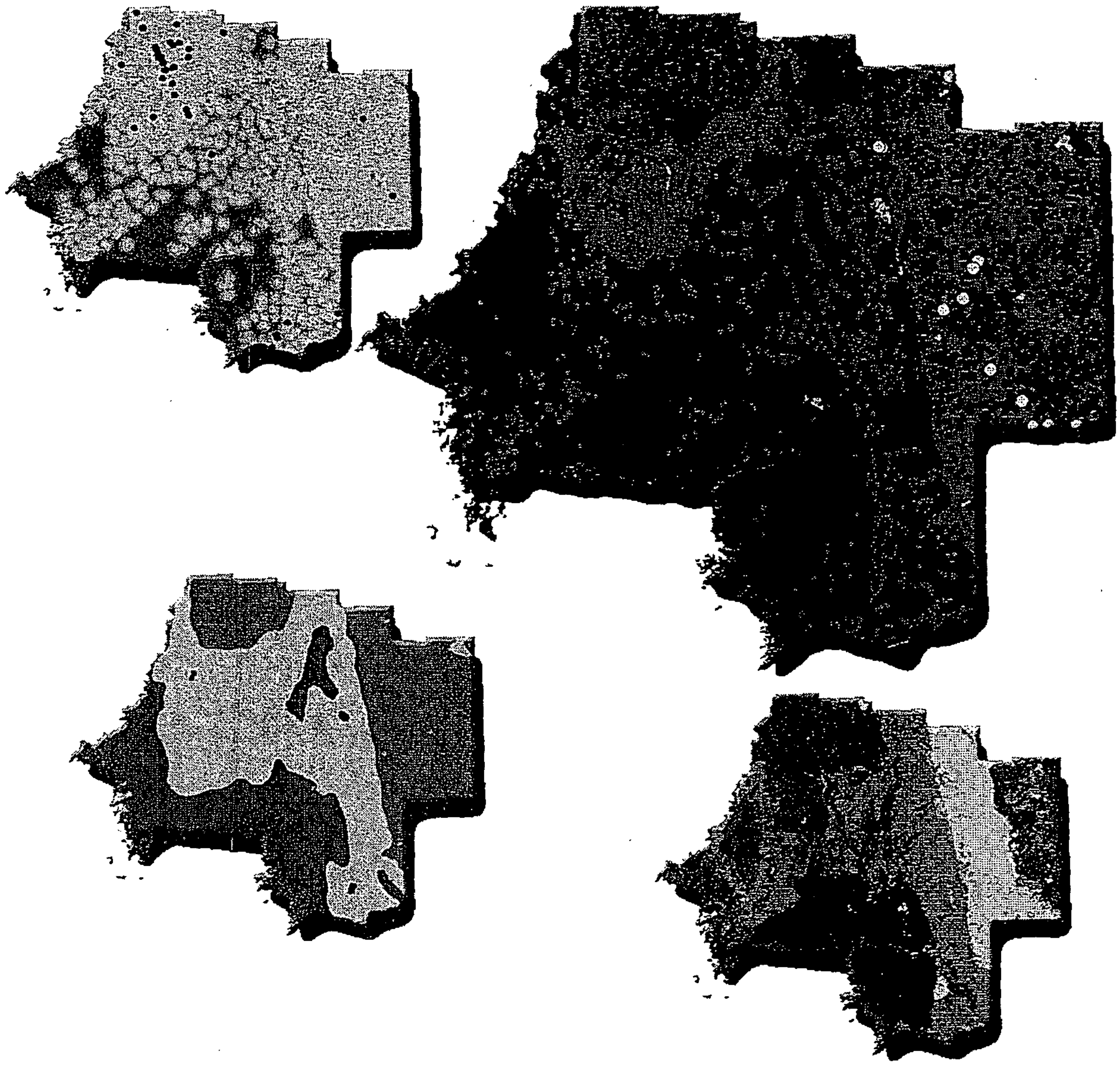
## VULNERABILITY OF THE FLORIDAN AQUIFER SYSTEM, LEVY COUNTY




[illegible]

# THE LEVY COUNTY AQUIFER VULNERABILITY ASSESSMENT

**Part of the Florida Department of Environmental Protection Florida Aquifer Vulnerability Assessment Phase II Project, RM059**



Prepared for the Florida Department of Environmental Protection by Advanced GeoSpatial Inc.

Version 1.1: August 13, 2007

# THE LEVY COUNTY AQUIFER VULNERABILITY ASSESSMENT

**Prepared For:**
**The Florida Department of Environmental Protection as part of the Florida Aquifer Vulnerability Assessment (FAVA) Phase II Project, Contract No. RM059**

**Prepared by**


**Alan E. Baker, P.G. 2324, Alex R. Wood, and James R. Cichon of Advanced GeoSpatial Inc., 2441 Monticello Drive, Tallahassee, FL 32303**


**August 2007**

## PROFESSIONAL GEOLOGIST CERTIFICATION

I, Alan E. Baker, P.G., no. 2324, have read and agree with the findings in this report titled THE LEVY COUNTY AQUIFER VULNERABILITY ASSESSMENT and do hereby certify that I currently hold an active professional geology license in the state of Florida. The model and report were prepared by Advanced GeoSpatial Inc., a State of Florida Licensed Geology Business (GB491), and have been reviewed by me and found to be in conformance with currently accepted geologic practices, pursuant to Chapter 492 of the Florida Statutes.

Alan E. Baker, P.G.
Florida License No. 2324

Date

## LIST OF FIGURES



## LIST OF TABLES



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For additional information regarding this project, please refer to the associated 24" x 36" interpretive poster of the same title as this report, and/or the GIS project data and associated metadata. At the time of this report, these GIS files may be accessed using ArcMap™, version 9.x.

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# THE LEVY COUNTY AQUIFER VULNERABILITY ASSESSMENT

**Alan E. Baker, P.G. 2324, Alex R. Wood, and James R. Cichon**
**Advanced GeoSpatial Inc., 2441 Monticello Drive, Tallahassee, FL 32303**

## INTRODUCTION

The Floridan Aquifer System is the most important and prolific source of fresh water in Levy County. According to Southwest Florida and Suwannee River water management districts, permitted ground-water use from the Floridan Aquifer System in Levy County is approximately 57 million gallons of water per day for public supply, agriculture, and other uses. In addition to this amount, there are over 6,257 self-supply wells in the county tapping the Floridan Aquifer System providing fresh water to homeowners (SRWMD Water Use Specialist, 2007; SWFWMD, 2006). Levy County's nearly 34,450 residents (U.S. Census Bureau, 2000) rely almost exclusively on the Floridan Aquifer System for their fresh water needs.

Levy County is underlain by thick and highly permeable carbonate rocks which comprise the Floridan Aquifer System. Clastic sediments overlying this aquifer system are chiefly composed of permeable silica sands with lower permeability clayey sand and silty clays present on the Brooksville Ridge and Wacassassa Flats. Most of the aquifer system is unconfined except where the lower permeability sediments provide limited aquifer confinement. Karst features are very prominent throughout the area and include sinkholes, swallets, and springs such as Manatee and Fanning Springs, both first magnitude springs. (Scott et al., 2004).

Identifying areas of Levy County where the Floridan Aquifer System is more vulnerable to contamination from activities at land surface is a critical component of a comprehensive ground-water management program. Protection of the Floridan Aquifer System is an important measure to take in helping ensure viable, fresh water is available from the Floridan Aquifer System for continued future use in Levy County. Aquifer vulnerability modeling allows for a pro-active approach to protection of aquifer systems, which can save significant time and increase the value of protection efforts. Successful implementation of an aquifer vulnerability assessment benefits:

- Environmental protection
- Wellhead protection
- Development of wastewater guidelines
- Source-water protection
- Land-use planning
- Sensitive land acquisition

### *Project Objective*

The Florida Department of Environmental Protection (FDEP) through the Florida Geological Survey (FGS) contracted with Advanced GeoSpatial Inc. (AGI) in November of 2006 to develop Phase II of the Florida Aquifer Vulnerability Assessment (FAVA) project. As part of this project, AGI developed the Levy County Aquifer Vulnerability Assessment (LCAVA) model characterizing the natural (or intrinsic) vulnerability of the Floridan Aquifer System (FAS) in Levy County. The primary purpose of this project is to provide the FDEP and Levy County with a scientifically-defensible, water-resource management tool that can be used to help minimize adverse impacts on ground-water quality. The project intent is to allow end users of the model to make improved decisions about aquifer vulnerability with regard to model input selected, including focused protection of sensitive areas such as springsheds and ground-water recharge areas.

### *Derivative Products: Protection Zones*

Relative vulnerability zones defined in this project may be applied to develop derivative maps, such as a protection-zone map. Ideally, data layers not included as input in the aquifer vulnerability model would be considered to help in defining such protection zones and may include ground-water flow modeling, stream-sink features, induced drawdown areas from large well fields, and distribution of drainage wells. These layers, while important to aquifer vulnerability, do not form usable input into this aquifer vulnerability assessment project.

### *Aquifer Vulnerability*

All ground water and therefore all aquifer systems are vulnerable to contamination to some degree (National Research Council, 1993) and, as a result, different areas overlying an aquifer system require different levels of protection. An aquifer vulnerability assessment provides for the identification of areas which, based on predictive spatial analysis, are more vulnerable to contamination from land surface. AGI uses a definition of aquifer vulnerability similar to that of the FDEP in the FAVA Phase I report: the tendency or likelihood for a contaminant to reach the top of a specified aquifer system after introduction at land surface based on best available data coverages representing the natural hydrogeologic system (Arthur et al., 2005).

## APPROACH

AGI is currently the single source provider of aquifer vulnerability assessment analysis using weights of evidence as defined by FDEP. The weights of evidence methodology, and the weighted logistic regression methodology, were employed in FDEP's FAVA project (for detailed information please refer to Arthur et al., 2005). Use of these methods involves combination of diverse spatial data which are used to describe and analyze interactions and generate predictive models (Raines et al., 2000). The following sections provide a brief overview of the methodologies; project-specific and more detailed information is presented in *Project Results*.

### *Weights of Evidence/Weighted Logistic Regression*

Weights of evidence and weighted logistic regression were used in the LCAVA project to develop an aquifer vulnerability assessment model of the FAS. The data-driven weights of evidence method was used to measure the spatial association between training points and evidential themes. Resulting from conditional independence issues, weighted logistic regression was then used to combine the binary layers to predict the distribution of the training points and generate final model output (see *Discussion* for more information.

These modeling techniques are based in a geographic information system (GIS) and executed using Arc Spatial Data Modeler (Arc-SDM), an extension to ESRI's ArcGIS software package. For more information on these methods please refer to Arthur et al. (2005), Kemp et al. (2001), Raines et al. (2000), and Bonham-Carter (1994). Primary benefits of applying these techniques to the LCAVA project are that they are data-driven methods, rather than expert-driven, and model generation is dependent upon a training dataset resulting in a self-validated model output.

### *Data Acquisition and Development*

The initial phase of an aquifer vulnerability assessment project comprises acquisition, development and attribution of various GIS data coverages representing natural hydrogeologic conditions for use as input into the model. The input data chosen during this phase determines the level of detail, accuracy, and confidence of final model output, i.e., vulnerability maps. Examples of data typically used in an aquifer vulnerability assessment include:

- Digital Elevation Data
- Aquifer Recharge
- Confinement or Overburden Thickness
- Karst Features/Topographic Depressions
- Water-Quality Data
- Soil Hydraulic Conductivity and Soil Pedality
- Recharge Potential

### *Vulnerability Modeling*

Upon completion of the development and adaptation of necessary data coverages for the vulnerability assessment, the modeling phase using weighted logistic regression is initiated to generate aquifer vulnerability response themes, which, for the LCAVA project, are expressed as favorability maps.

#### *Study Area and Training Points*

The initial step in implementing the vulnerability modeling phase is the identification and delineation of a study area extent. Levy County political boundary served as the model study area for this project. Training points are locations of known occurrences. In an aquifer vulnerability assessment, ground-water wells with water quality indicative of high recharge are selected as known occurrences. Dissolved oxygen or dissolved nitrogen analytical concentrations were used to develop training point datasets. The occurrence of a training point does not directly correspond to a site of aquifer system contamination, but is indicative of aquifer vulnerability.

#### *Evidential Themes (Model Input)*

An evidential theme is defined as a set of continuous spatial data that is associated with the location of the training points and is analogous to the data layers listed and described above, such as soil hydraulic conductivity or thickness of confinement. Weights are calculated for each evidential theme based on the presence or absence of training points with respect to the study area and spatial associations between training points and evidential themes are established. Themes are then generalized to determine the threshold or thresholds that maximize the spatial association between the evidential theme and the training points (Bonham-Carter, 1994).

#### *Response Theme (Vulnerability Maps)*

Following generalization of evidential themes, output results (response themes) are generated and display the probability that a unit area contains a training point based on the evidential themes provided. The response theme generated in this project is a probability map displayed in classes of relative vulnerability for the FAS in Levy County.

#### *Sensitivity Analysis and Validation of Model Results*

Sensitivity analysis and validation are a significant component of any modeling project as they allow evaluation of the accuracy of results. Sensitivity analysis is applied during development of each evidential theme and validation exercises are applied to assess model strength and confidence.

### *LCAVA Technical Advisory Committee*

An advisory committee was formed to provide technical review and support during the development of the FAVA Phase II project. From within this committee, specific members were assigned to the LCAVA project and consisted of professionals in the water resource, planning, engineering, hydrogeology and other environmental fields. Members, listed below, participated in workshop meetings, provided technical review of model progress and final results and report.

**Table 1. LCAVA Technical Advisory Committee members.**

| Name | Organization |
|---|---|
| Allan Stodghill, P.G. | Florida Department of Environmental Protection |
| David Dewitt, P.G. | Southwest Florida Water Management District |
| Larry Gordon, P.G. | Florida Department of Health |
| Richard Deadman | Florida Department of Community Affairs |
| Carlos Herd, P.G. | Suwannee River Water Management District |
| Gail Mowry, P.E. | Marion County Clean Water Program |
| William Wise, Ph.D., P.E. | University of Florida |
| Gary Maidhof | Citrus County |
| Tom Greenhalgh, P.G. | Florida Geological Survey/FDEP |

## PROJECT RESULTS

### *Study Area*

The political boundary of Levy County was used as the LCAVA model study area extent (Figure 1). Because of the sizes of some polygons representing soil data, a grid cell size of approximately 10,000 square feet ($ft^2$) was selected for evidential theme development. This grid cell size, while necessary to capture resolution available in some input data layers, does not reflect appropriate resolution of final model output. Appropriate scale of use of model results is discussed in *Model Implementation and Limitations.*

Water bodies were omitted from the model extent for two main reasons: first, the main goal of this project is to estimate vulnerability of the FAS and not vulnerability of surface water features, and second, data for water bodies is typically not available – i.e., wells are not drilled in water bodies, nor do soil surveys normally contain information regarding lake and stream bottoms.

### *Training Point Theme*

In the LCAVA model, training points are ground-water wells tapping the FAS with water quality data indicative of high recharge. Dissolved oxygen analytical values served as training point data for the LCAVA model, and dissolved nitrogen concentrations were used for validation of model output. Naturally occurring oxygen and nitrogen are generally considered ubiquitous at land surface as primary components of the atmosphere; moreover, relatively low concentrations of these analytes occur in well protected – or less vulnerable – aquifer systems. Accordingly, where these analytes occur in elevated concentrations in ground-water, they are good indicators of aquifer vulnerability (Arthur et al., 2007).

Water quality data sources explored include the FDEP background water quality network, FDEP STATUS network, Florida Department of Health, and Southwest Florida Water Management District (SWFWMD). From these data sources, 51 wells measured for dissolved oxygen were identified as being potential candidates for training points. Statistical analyses revealed that there were no wells considered statistical outliers. The upper 25$^{th}$ percentile of this set – or all wells with median dissolved oxygen values greater than 4.45 milligrams per liter (mg/L) – served as the training point theme and consists of eleven wells. Figure 2 displays the distribution of water wells used to derive training points and the resulting training point theme across the study area.

Training points are used to calculate prior probability, weights for each evidential theme, and posterior probability of the response theme (see *Glossary*). Prior probability (training point unit area divided by total study area) is the probability that a training point will occupy a defined unit area within the study area, independent of evidential theme data. The prior probability value, a unitless parameter, is 0.0038

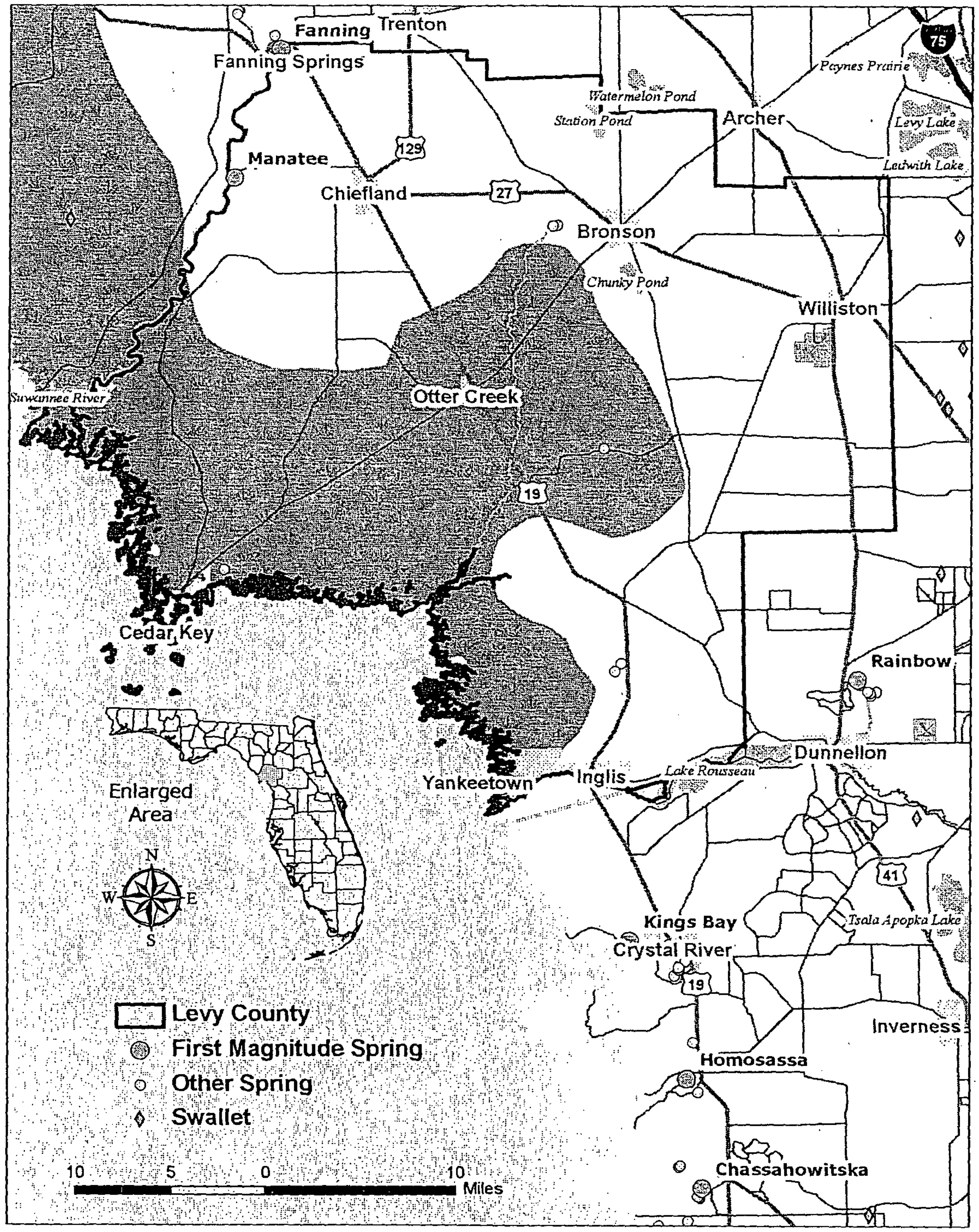


**Figure 1. Levy County Aquifer Vulnerability Assessment project study area corresponds to the County's political boundary.**

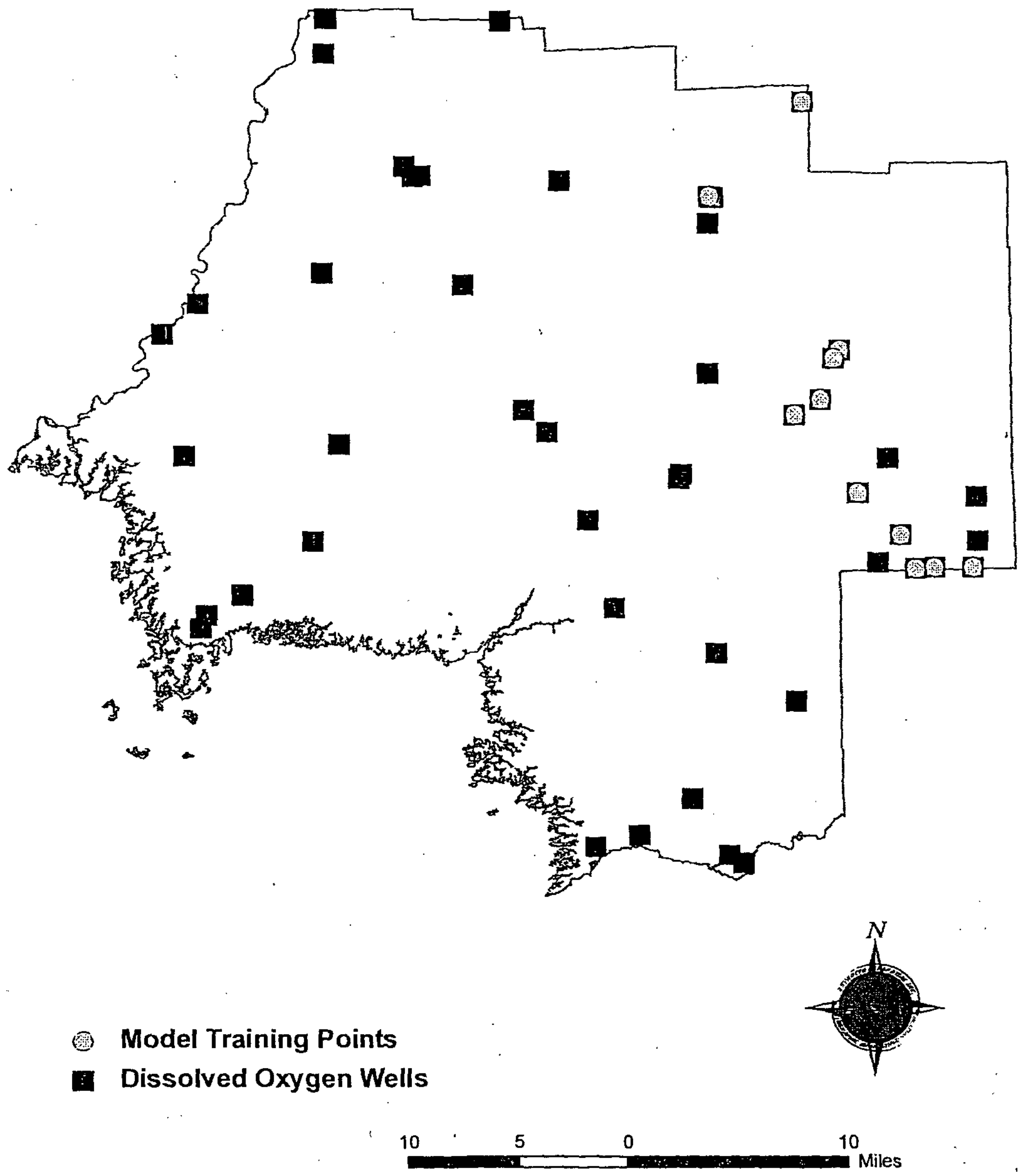


**Figure 2. Location of all wells measured for dissolved oxygen, and locations of training point wells with median dissolved oxygen values higher than 4.45 mg/L.**

for LCAVA. Posterior probability values generated during response theme development are interpreted relative to the value of prior probability with higher values generally indicating higher probability of containing a training point.

### Evidential Themes – Model Input Layers

Input data layers, or evidential themes, representing hydrogeologic factors controlling the location of training points, and thereby vulnerability, were developed for model input. Because of the local scale nature of the LCAVA project, availability of new data, and implementation of new methodologies for estimating karst, all model inputs represent previously unavailable county-specific datasets. The factors considered for the LCAVA project include karst features, recharge potential, thickness of aquifer confinement, soil pedality, and soil hydraulic conductivity. In support of this project, FGS developed data surfaces representing the tops of the FAS and the Intermediate Confining Unit (ICU).

#### Soil Hydraulic Conductivity and Soil Pedality Themes

The rate that water moves through soil is a critical component of any aquifer vulnerability analysis, as soil is literally an aquifer system's first line of defense against potential contamination (Arthur et al., 2005). Two parameters of soils were evaluated for input into the LCAVA model: *soil hydraulic conductivity*, which is the "amount of water that would move vertically through a unit area of saturated soil in unit time under unit hydraulic gradient" (U.S. Department of Agriculture, 2005); and *soil pedality*, which is calculated based on soil type, soil grade, and soil pedon size, and is a unitless parameter. Soil pedality is a relatively new concept used to estimate the hydrologic parameter of soil and is generated for LCAVA using the pedality point method developed by Lin et al. (1999).

In 2006, Levy County soils data were redesigned for the study area by the Natural Resources Conservation Service. As a result, more detailed information is available for analysis for the LCAVA project than during previous projects (e.g., Arthur et al., 2005). To determine the best representation of soil hydraulic conductivity and pedality in the aquifer vulnerability assessment, numerous data coverages were generated and evaluated for model input.

Countywide datasets representing soil hydraulic conductivity and soil pedality were developed for use as input into the LCAVA model. Multiple empirical values are reported in soil surveys representing various zones in each soil column underlying a particular soil polygon. Further, multiple columns may be reported for a single soil polygon. Because the model requires a single value for each soil polygon, two steps are used. First, representative values for each horizon in a column are combined using a sum of the weighted mean. Second, because multiple columns may be reported for a soil polygon, the sum values are averaged into a single value for each polygon. This is completed for both hydraulic conductivity and soil pedality. Figures 3 and 4 display the soil hydraulic conductivity and pedality evidential themes, respectively.

#### Recharge Potential

In Copeland et al. (1991), the area of the Brooksville Ridge in central Florida is defined as having higher recharge potential than adjacent areas. The Brooksville Ridge is chiefly composed of Undifferentiated Hawthorn Group sediments which are poorly to moderately consolidated clayey sands and silty clays (Scott et al., 2001). In Levy County, these sediments reach a maximum calculated thickness of 167 feet and can be discontinuous, deeply weathered and highly perforated by karst features.

In other areas of Florida, Hawthorn Group sediments form the Intermediate Confining Unit and normally provide an effective confining or semi-confining unit for the underlying FAS. In Levy County, however, these sediments are generally highly weathered, leaky, thin and intensely breached

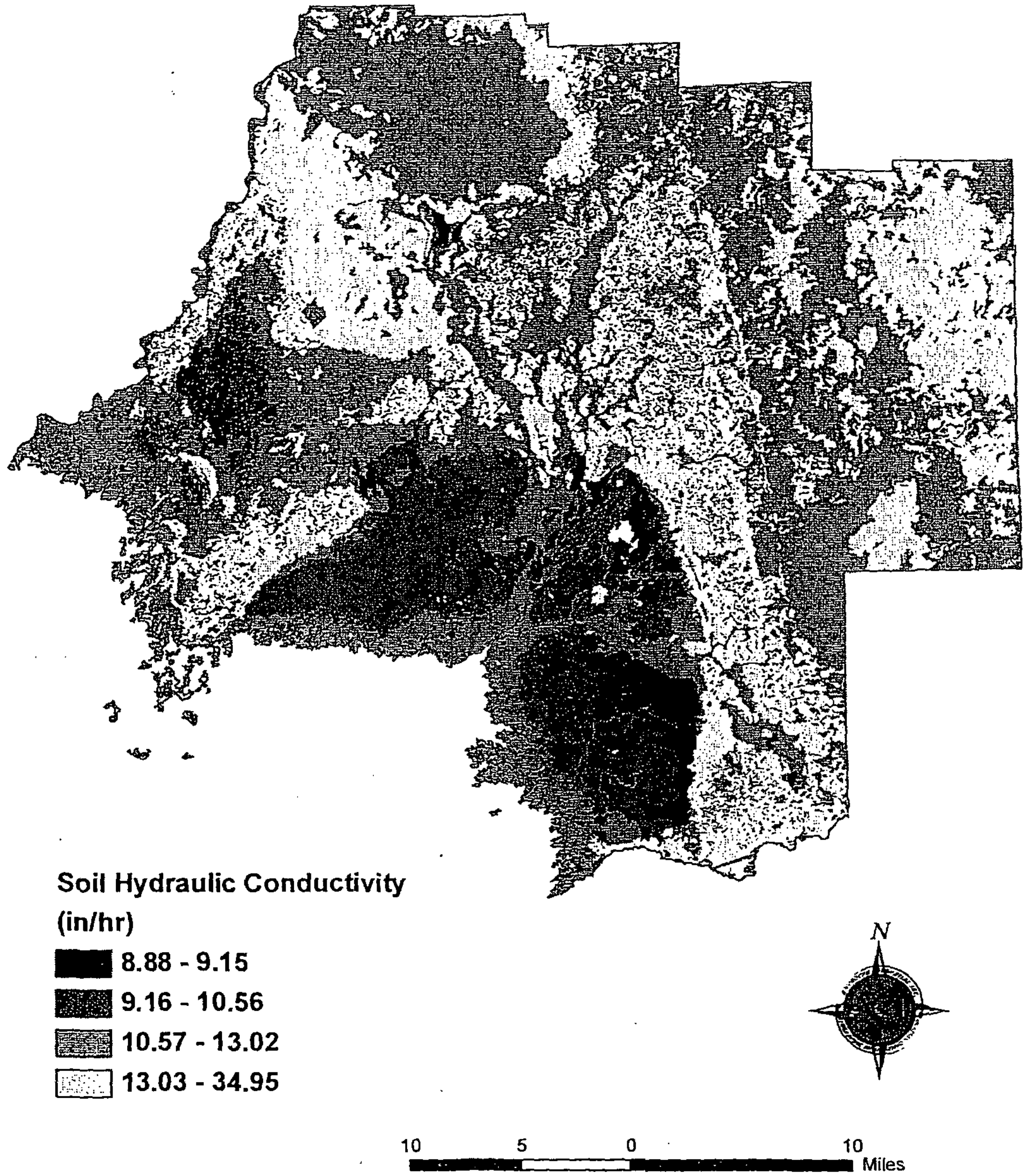


**Figure 3. Distribution of soil hydraulic conductivity values across the LCAVA study area. White areas represent 'no data' areas in the soil survey data or locations of water bodies.**

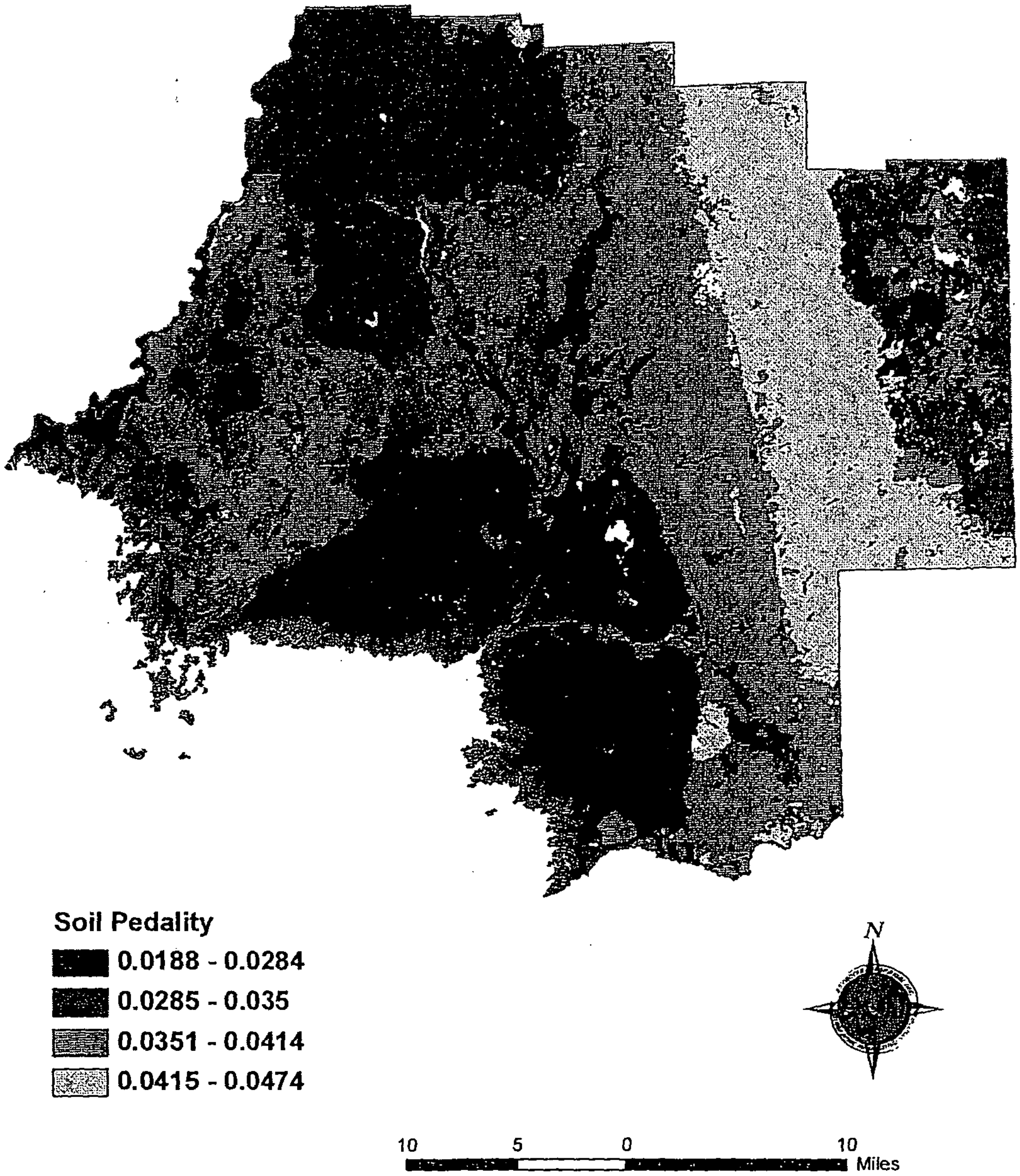


**Figure 4. Distribution of soil pedality values (unitless) across the LCAVA study area. White areas represent 'no data' areas in the soil survey data or locations of water bodies.**

by karst features. These factors combine to increase the recharge potential to the FAS in the study area where these sediments are present. Where recharge potential is high, aquifer vulnerability is increased.

Recharge potential values were calculated for the study area by subtracting the USGS 2000 potentiometric surface of the FAS (USGS, 2000) from land surface elevation derived from USGS 7.5" quadrangles. Resulting recharge potential values range from -18 ft to greater than 150 ft (relative to mean sea level). Negative values generally correspond to areas where the aquifer is estimated to be discharging while higher positive values are restricted to the more substantial hills located on the Brooksville Ridge.

Because the scale on which the potentiometric surface map was developed may not be appropriate for single-county scale analysis, categories of recharge potential were derived from the ranges of values calculated as described above. A preliminary weights of evidence analysis was completed on these empirical values to help guide category selection. This analysis indicated a very strong relationship between training points and recharge potential. Category breaks were then based on this preliminary weights of evidence analysis, and where the value of recharge potential is estimated at zero or less (i.e., potential discharge areas). Categories of recharge potential were ranked as displayed in Figure 5.

Use of recharge potential via this approach is restricted to areas of Florida where the FAS is not well confined (e.g., this layer may not be usable in areas which are also underlain by thicker, contiguous Intermediate Confining Unit sediments), and where there is not a laterally contiguous Surficial Aquifer System present.

### *Intermediate Confining Unit and Overburden Thickness Themes*

Aquifer confinement – either in the form of overburden overlying the FAS, or the ICU – is another critical layer in determining aquifer vulnerability. Where aquifer confinement is thick and the FAS is deeply buried, aquifer vulnerability is generally lower, whereas in areas of thin to absent confinement, the vulnerability of the FAS is generally higher.

In support of the FAVA Phase II project, the FGS developed GIS models of the surface of the FAS and surface of the ICU. The intent of these models was to allow the calculation of aquifer confinement thickness in various study areas. Surface models were developed using a dataset of borehole records supplemented with well gamma logs that contain descriptions of subsurface materials. AGI used these surfaces to calculate thickness of the ICU (Figure 6) and thickness of overburden overlying the FAS (Figure 7) in the study area. These two layers were tested for input in the model as described in *Sensitivity Analysis*.

### *Effective Karst Feature Theme*

Karst features, or sinkholes and depressions, can provide preferential pathways for movement of surface water into the underlying aquifer system and enhance an area's aquifer vulnerability where present. The closer an area is to a karst feature, the more vulnerable it may be considered. Closed topographic depressions extracted from U.S. Geological Survey 7.5-minute quadrangle maps served as the initial dataset from which to estimate karst features in the study area. To supplement these data, the FGS sinkhole database was included to identify karst features possibly not represented on USGS maps. These two data sources displayed in Figure 8 were combined and analyzed to develop an effective karst features evidential theme.

It is recognized that closed topographic depressions may or may not be true karst features, however, application of analytical processes to digital elevation maps and models to estimate karst has been

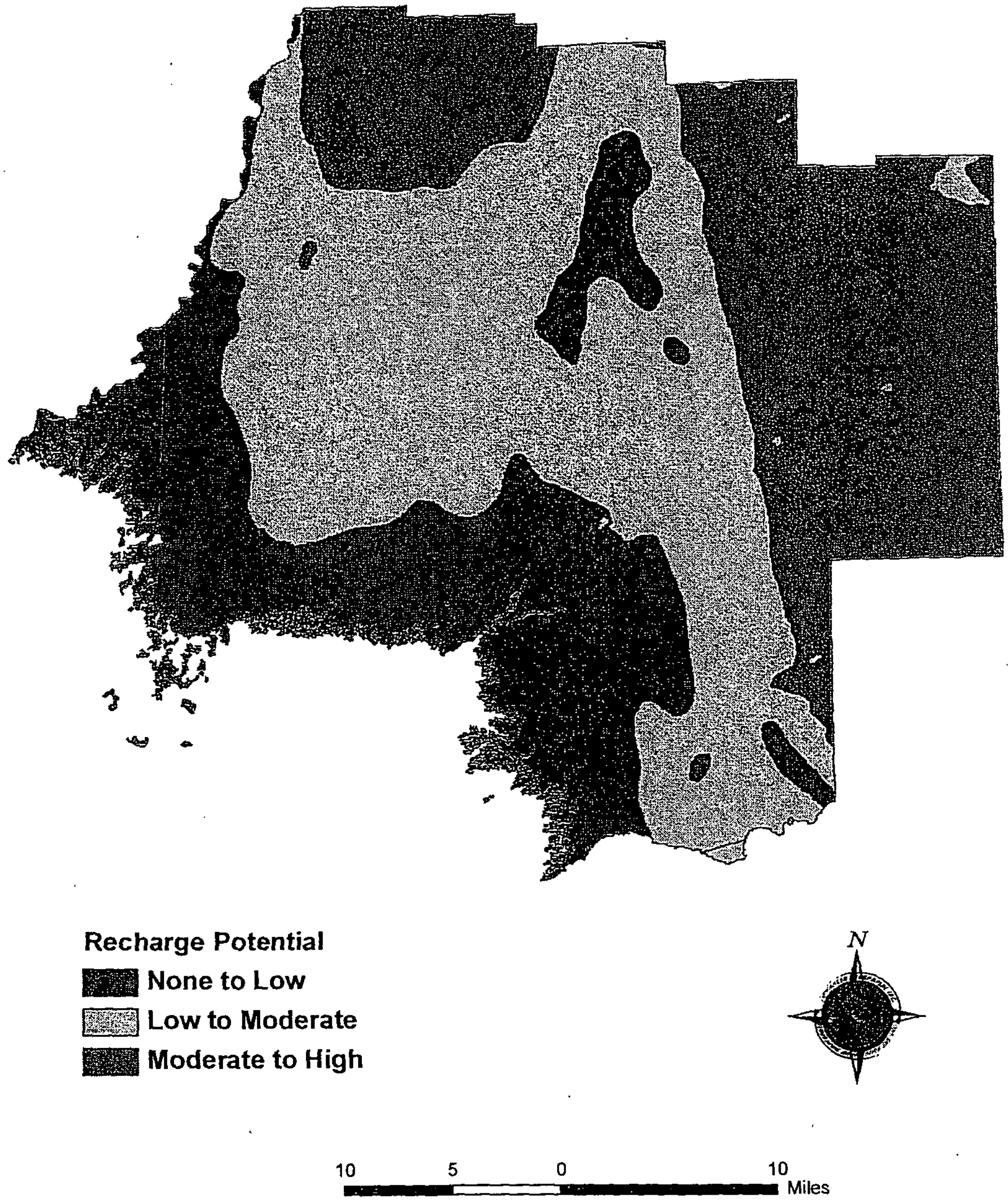


**Figure 5. Recharge potential estimated from FAS potentiometric surface data, land surface elevation and estimates developed for Copeland et al., (1991). Major lakes and water bodies were omitted for input into final model.**

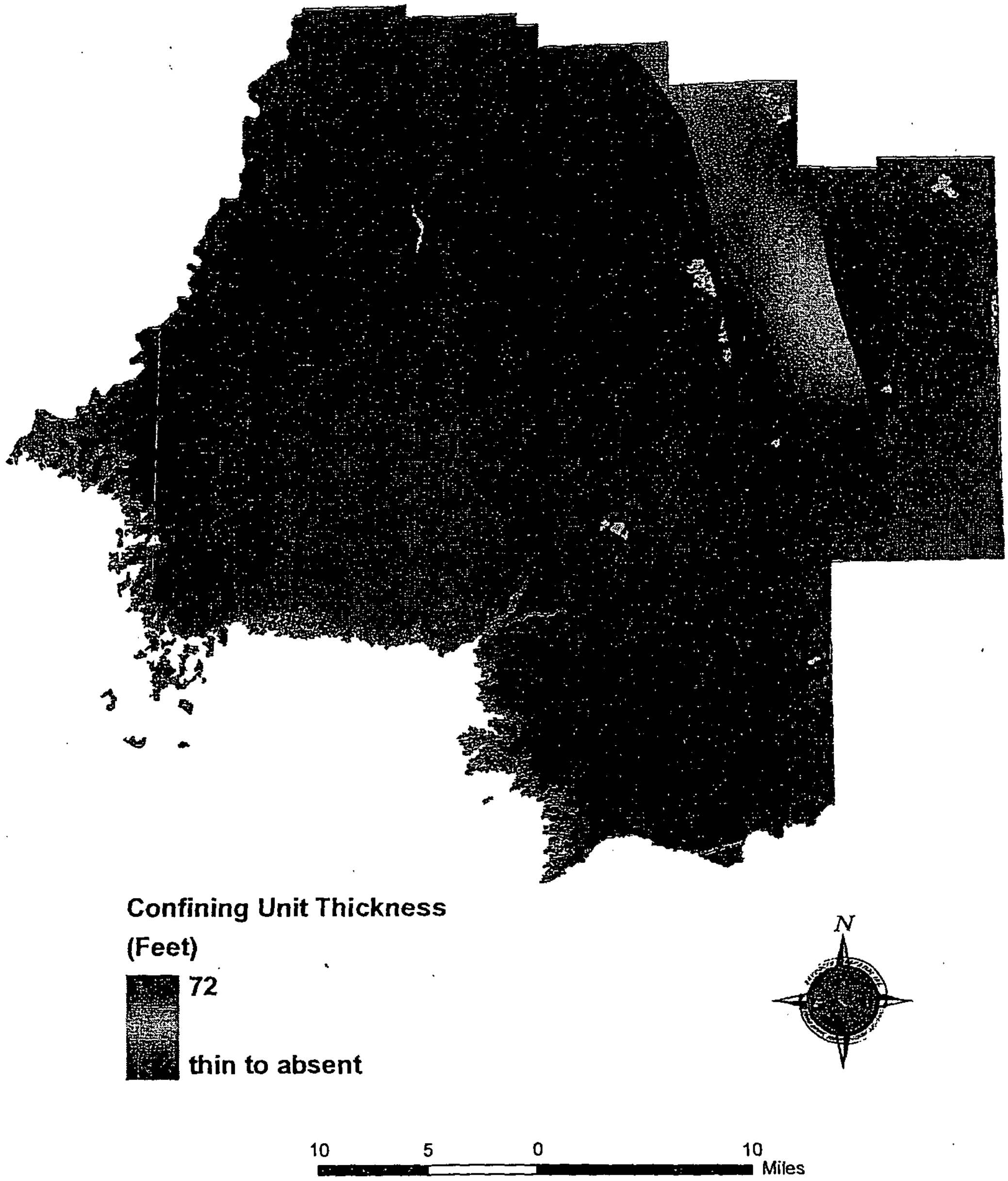


**Figure 6. Thickness of the ICU calculated by subtracting predicted surface of ICU from predicted surface of FAS as generated by FGS. Major lakes and water bodies were omitted for input into final model.**

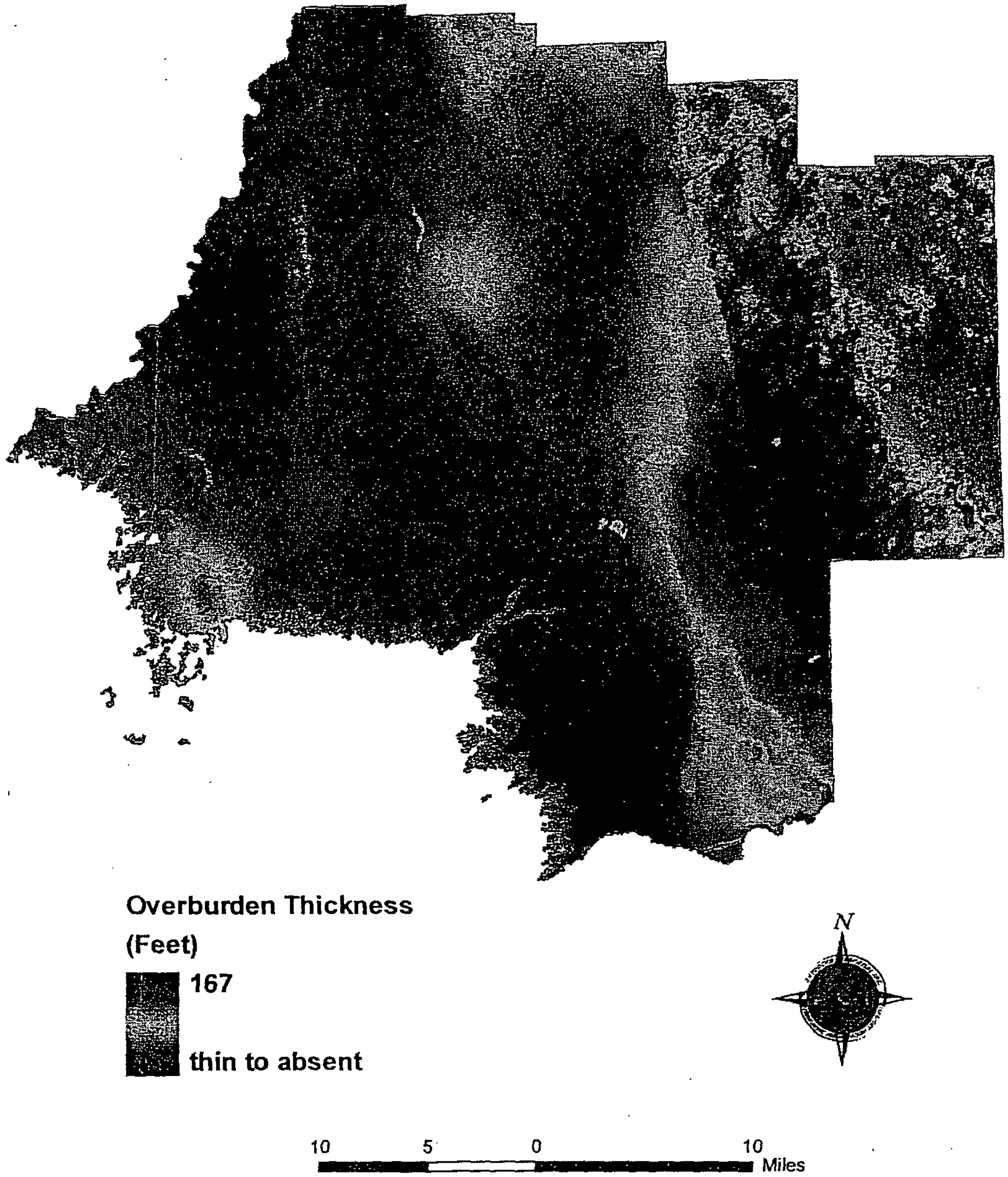


**Figure 7. Thickness of sediments overlying the FAS calculated by subtracting digital elevation data from predicted surface of FAS as generated by FGS. Major lakes and water bodies were omitted for input into final model.**

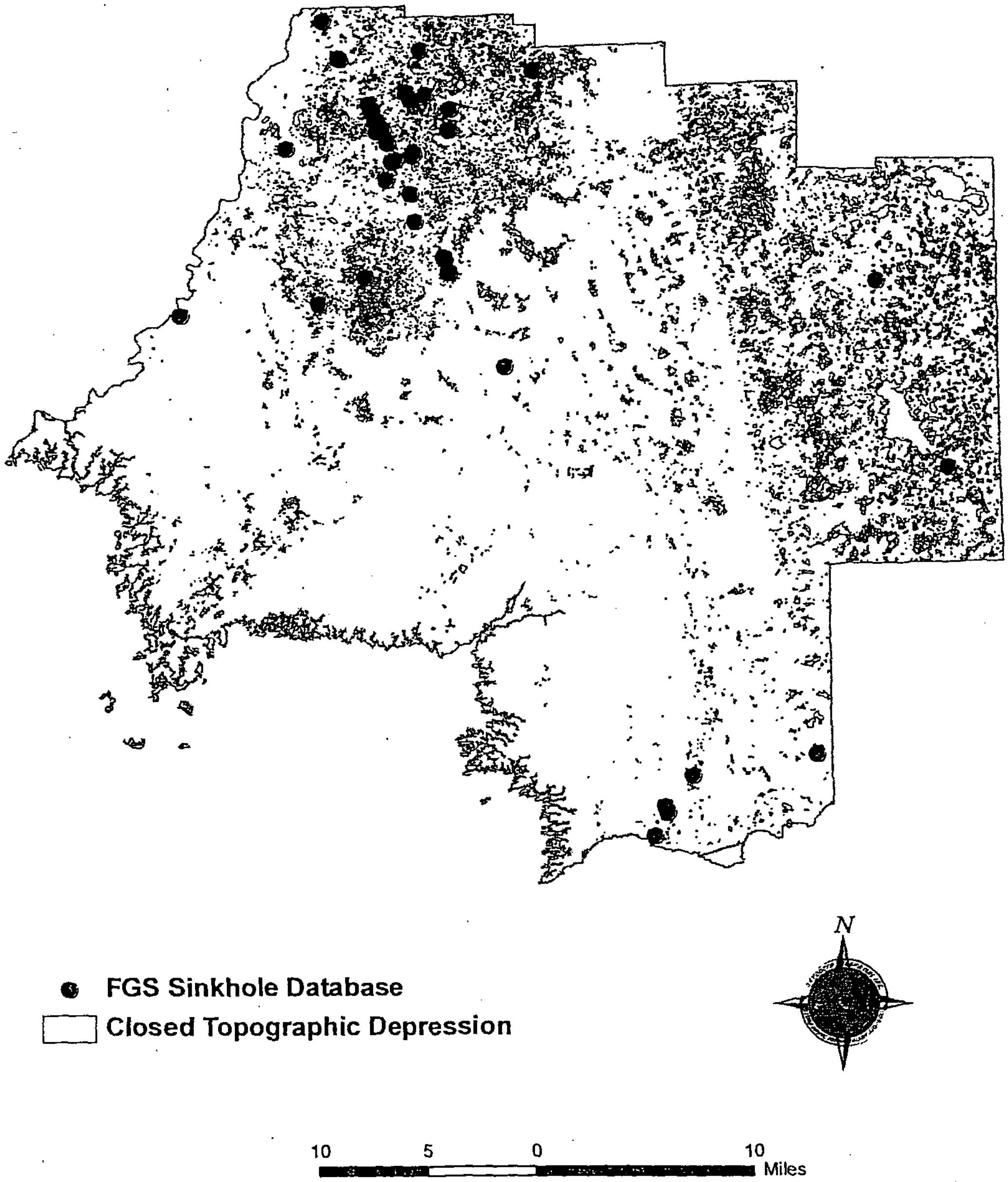


**Figure 8. All closed topographic depressions extracted from U.S. Geological Survey 7.5-minute topographic contour lines and sinkholes from the FGS sinkhole database.**

successfully completed in numerous projects (Baker et al., 2007; Arthur et al., 2005; Cichon et al., 2005; Baker et al., 2005; and Denizman, 2003). The most statistically significant and defensible method evaluated for this project is the circular index method described below.

#### *Circular index method*

Karst features, which form as the result of the dissolution of carbonate rocks and subsequent collapse of overlying material, are generally circular in nature. In contrast, non-karstic depressional features are common in near-shore modern terrains, relic dune terrains and other provinces, and tend to have a non-circular shape. To filter these features and other types of non-karst features in the study area, a circular index shape analysis (Denizman, 2003) was used to compare the roundness of depressional features to an ideal circle. The area of each closed depression was divided by the area of an ideal circle with the same perimeter as the depression. This resulted in a "roundness ratio" representing the degree of similarity between two such features. Several roundness ratio values were evaluated for use in the model; a value of 0.75 was found to be most suitable for this study area. Features with a roundness ratio of less than 0.75 were filtered out.

To avoid removal of nested karst features within larger, possibly karstic, but non-circular depressions, the circular index analysis was completed on five- and ten-foot topographic intervals within every topographic depression (depending on topographic map resolution). The results of this analysis were combined with the FGS sinkhole features to create an effective karst layer as displayed in Figure 9.

### *Sensitivity Analysis/Evidential Theme Generalization*

Sensitivity analysis allows decisions to be made about proposed evidential themes by evaluating each theme's association with training points – or aquifer vulnerability – and ultimately helps determine model input. For example, themes representing both soil pedality and soil hydraulic conductivity were developed to represent the impact of soils in the model; sensitivity analysis allows, through statistical analysis, determination of which of these two layers served as the most appropriate input representing soils for the final LCAVA analysis. Results of this process indicate that effective karst features, recharge potential, and soil pedality were the best suited evidential themes for use in final modeling.

Following sensitivity analysis and selection of evidential themes to be input into the LCAVA model, themes were generalized to assess which areas of the evidence share a greater association with locations of training points. During calculation of weights for each theme, a contrast value was calculated for each class of the theme by combining the positive and negative weights. Contrast is a measure of a theme's significance in predicting the location of training points and helps to determine the threshold or thresholds that maximize the spatial association between the evidential theme map pattern and the training point theme pattern (Bonham-Carter, 1994). Contrast and weights are described in more detail below in *Discussion*.

Contrast values were used to determine where to sub-divide evidential themes into generalized categories prior to final modeling. The simplest and most accepted method used to subdivide an evidential theme is to select the maximum contrast value as a threshold value to create binary generalized evidential themes. In other models, categorization of more than two classes may be justified (Arthur et al., 2005). For the LAVA project, a binary break was typically defined by the weights of evidence analysis for each evidential theme creating two spatial categories: one with stronger association with the training point theme and one with weaker association.

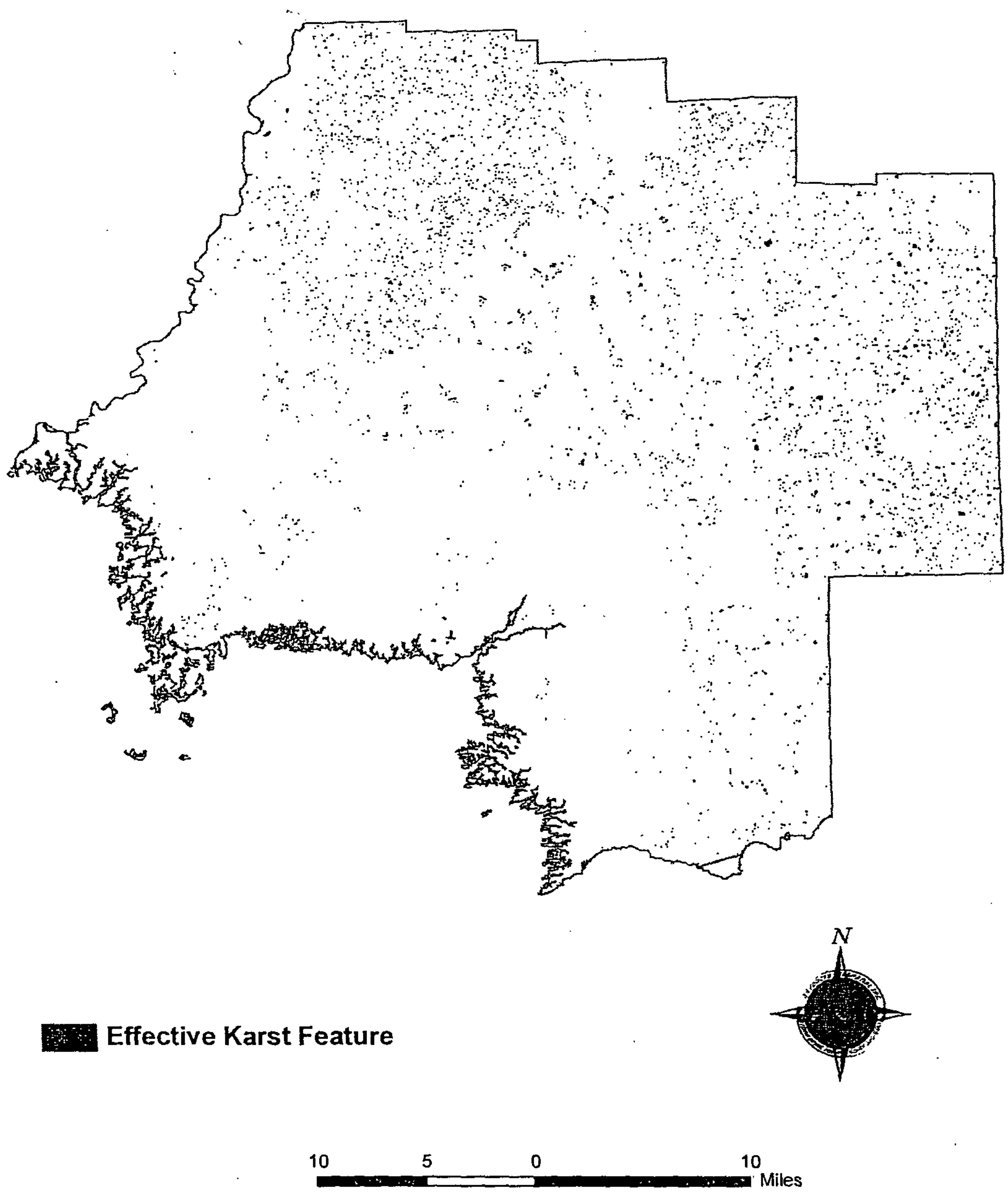


**Figure 9. Effective karst features resulting from circular index method applied to U.S. Geological Survey 7.5-minute topographical contour lines combined with sinkholes from the Florida Geological Survey sinkhole database.**

### *Soil Pedality/Soil Hydraulic Conductivity*

Weights calculated during sensitivity analysis for soil pedality were much stronger (i.e., had higher absolute value) than weights calculated for soil hydraulic conductivity. As a result, soil pedality was chosen as the better predictor of aquifer vulnerability because it shared the best association with training points.

Soil pedality, a unitless parameter, ranges from 0.0188 to 0.0474 across the study area. The analysis indicated that areas underlain by 0.0454 to 0.0474 were more associated with the training points, and therefore associated with higher aquifer vulnerability. Conversely, areas underlain by 0.0188 to 0.0453 were less associated with the training points, and therefore lower aquifer vulnerability. Based on this analysis, the evidential theme was generalized into two classes as displayed in Figure 10.

### *Intermediate Confining Unit / Overburden Thickness Themes*

Weights calculated during sensitivity analysis for the overburden thickness and ICU thickness indicated no association with training points. In fact, weights values were negative and revealed an inverse association between training points and aquifer confinement. Based on this lack of association, these layers were excluded from modeling.

### *Recharge Potential*

Recharge potential ranged from "none to low" to "moderate to high" across the study area. The analysis indicated that areas within the "moderate to high" potential recharge zone were more associated with the training points, and therefore with higher aquifer vulnerability. Conversely, areas in "none to low" and "low to moderate" recharge potential zones were less associated with the training points, and therefore lower aquifer vulnerability. Based on this analysis, the evidential theme was generalized into two classes as displayed in Figure 11.

### *Effective Karst Features*

As mentioned above, areas closer to an effective karst feature are normally associated with higher aquifer vulnerability. Based on this, features were buffered into 100-ft zones to allow for a proximity analysis (Figure 12). The analysis indicated that areas within 787 feet of a karst feature were more associated with the training points, and therefore with higher aquifer vulnerability. Conversely, areas greater than 787 feet from a karst feature were less associated with the training points, and therefore lower aquifer vulnerability. Based on this analysis, the evidential theme was generalized into two classes as displayed in Figure 13.

### ***Response Theme***

Using evidential themes representing effective karst, recharge potential, and soil pedality, weighted logistic regression was applied to generate a response theme, which is a GIS raster consisting of *posterior probability* values ranging from 0.00018 to 0.03156 across the study area. These probability values describe the relative favorability that a unit area of the model will contain a training point – i.e., a point of aquifer vulnerability as defined above in *Training Points* – with respect to the prior probability value of 0.0038. Prior probability is the probability that a training point will occupy a defined unit area within the study area, independent of evidential theme data. Probability values at the locations of 10 of the 11 training points are above the prior probability, indicating that this model is a strong predictor of training point locations. The final response theme is displayed in Figure 14.

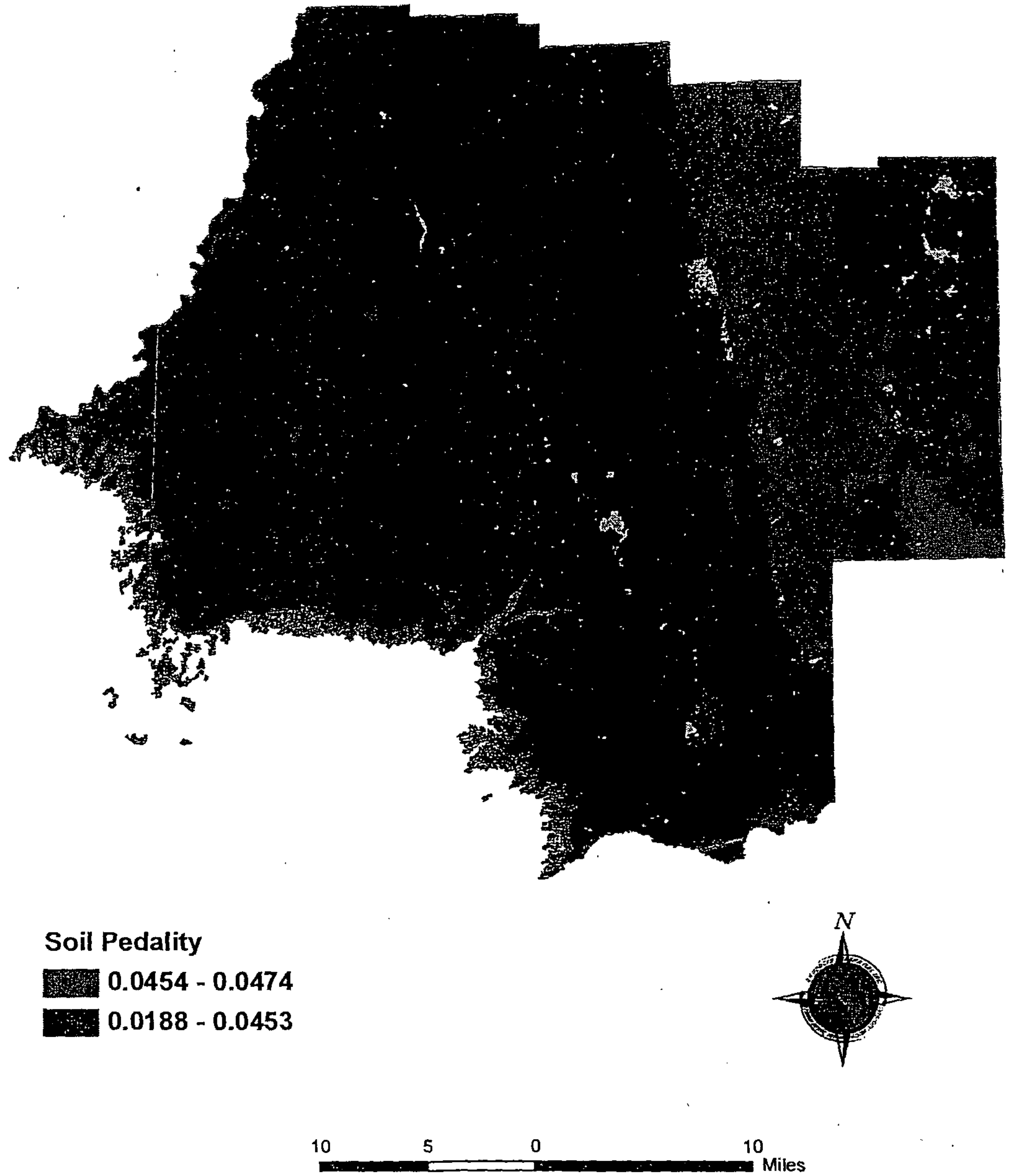


**Figure 10.** *Generalized soil pedality evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby aquifer vulnerability, whereas red areas share a stronger association with training points.*

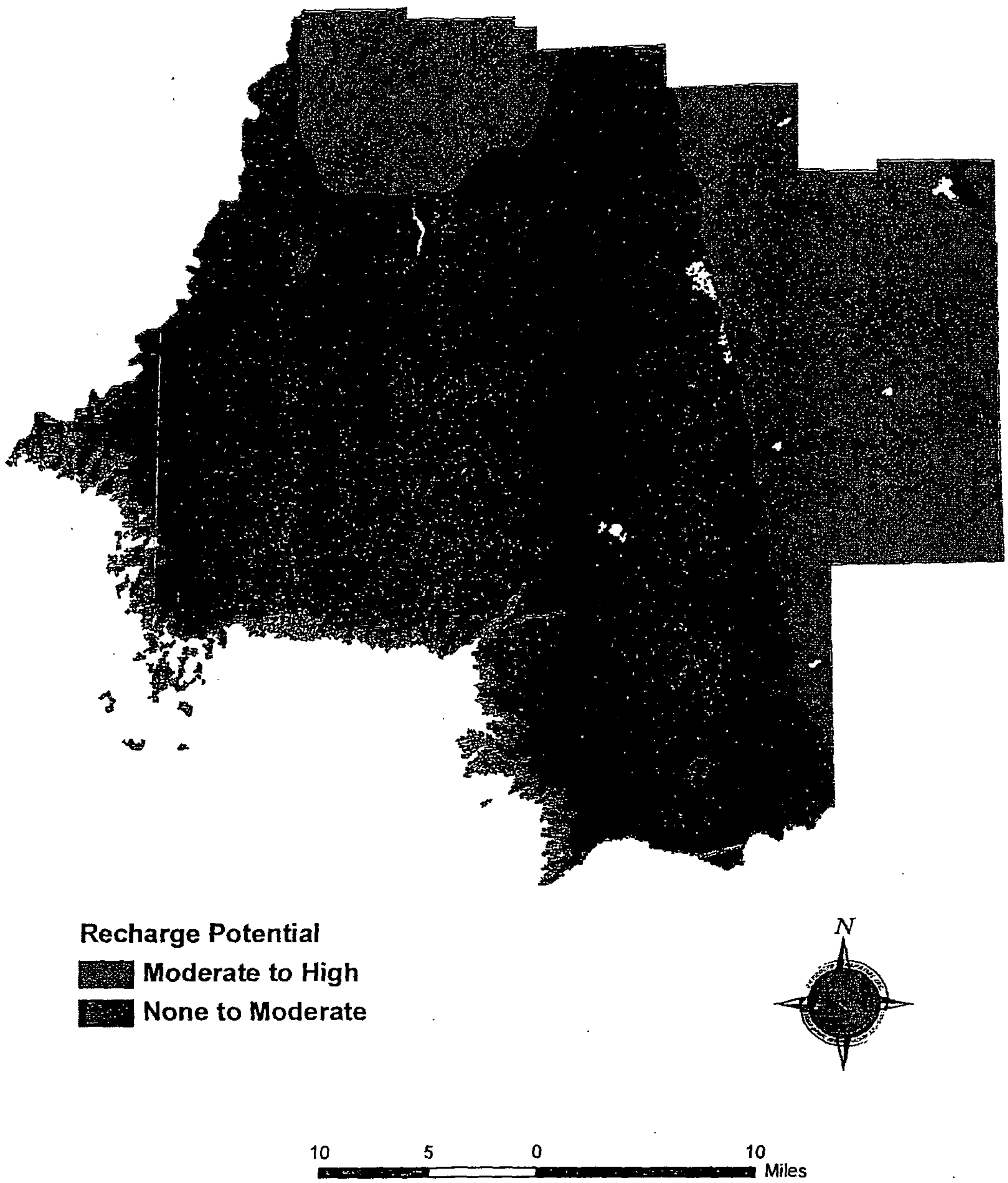


**Figure 11. Generalized recharge potential evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby aquifer vulnerability, whereas red areas share a stronger association with training points.**

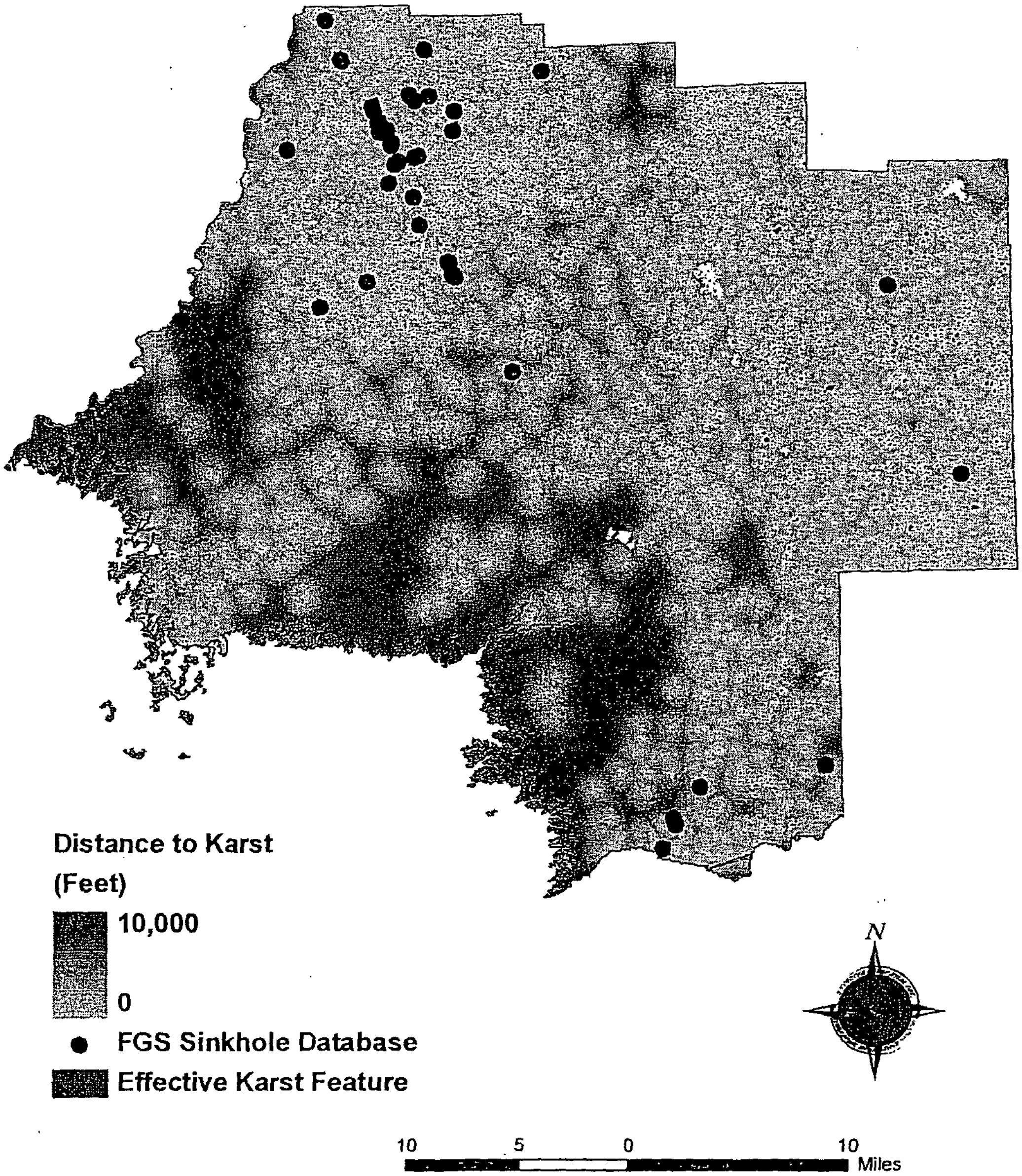


**Figure 12. Effective karst features evidential theme buffered into 100-ft zones for proximity analysis in the weights of evidence analysis.**

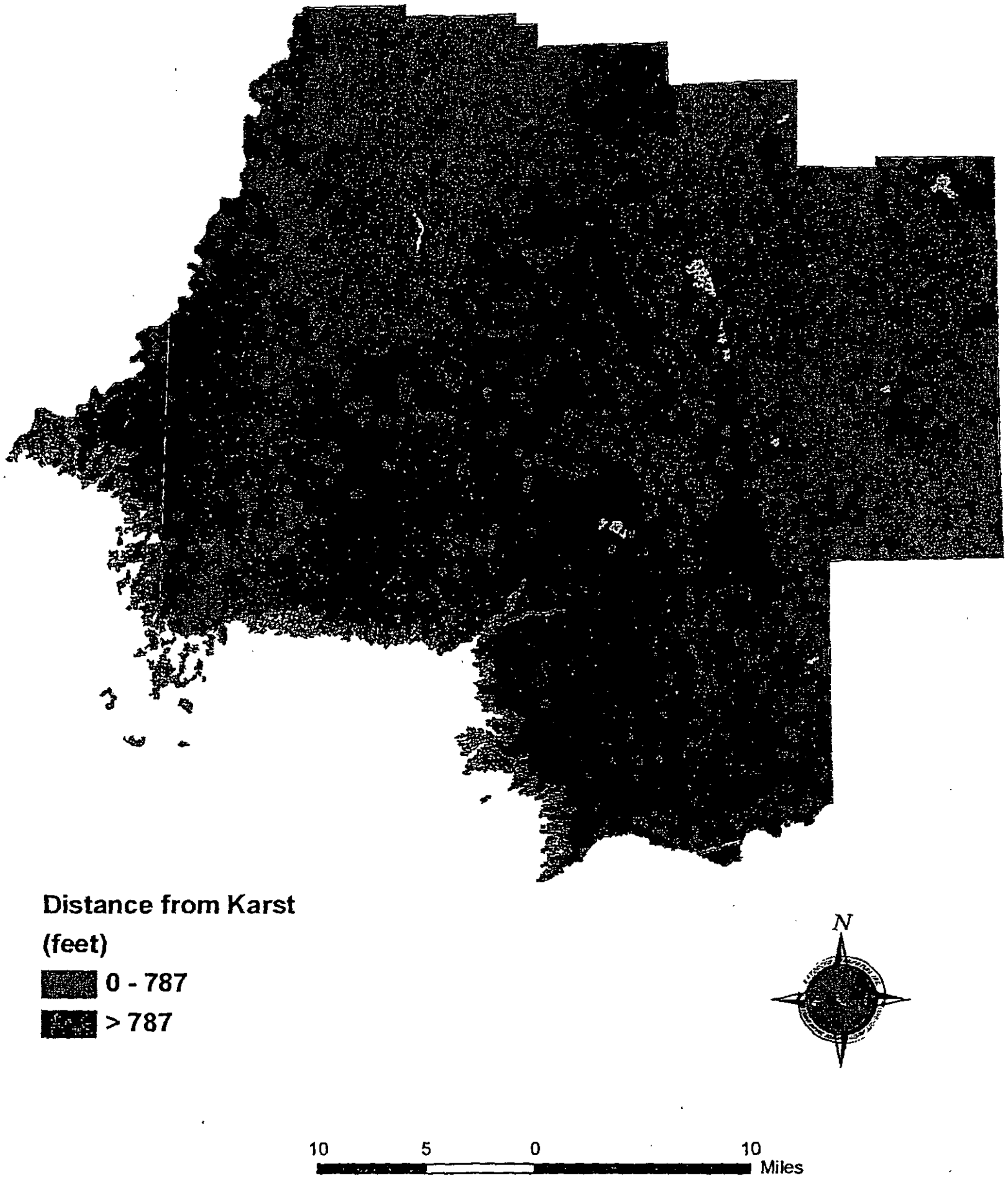


**Figure 13.** *Generalized effective karst feature evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby aquifer vulnerability, whereas red areas share a stronger association with training points.*

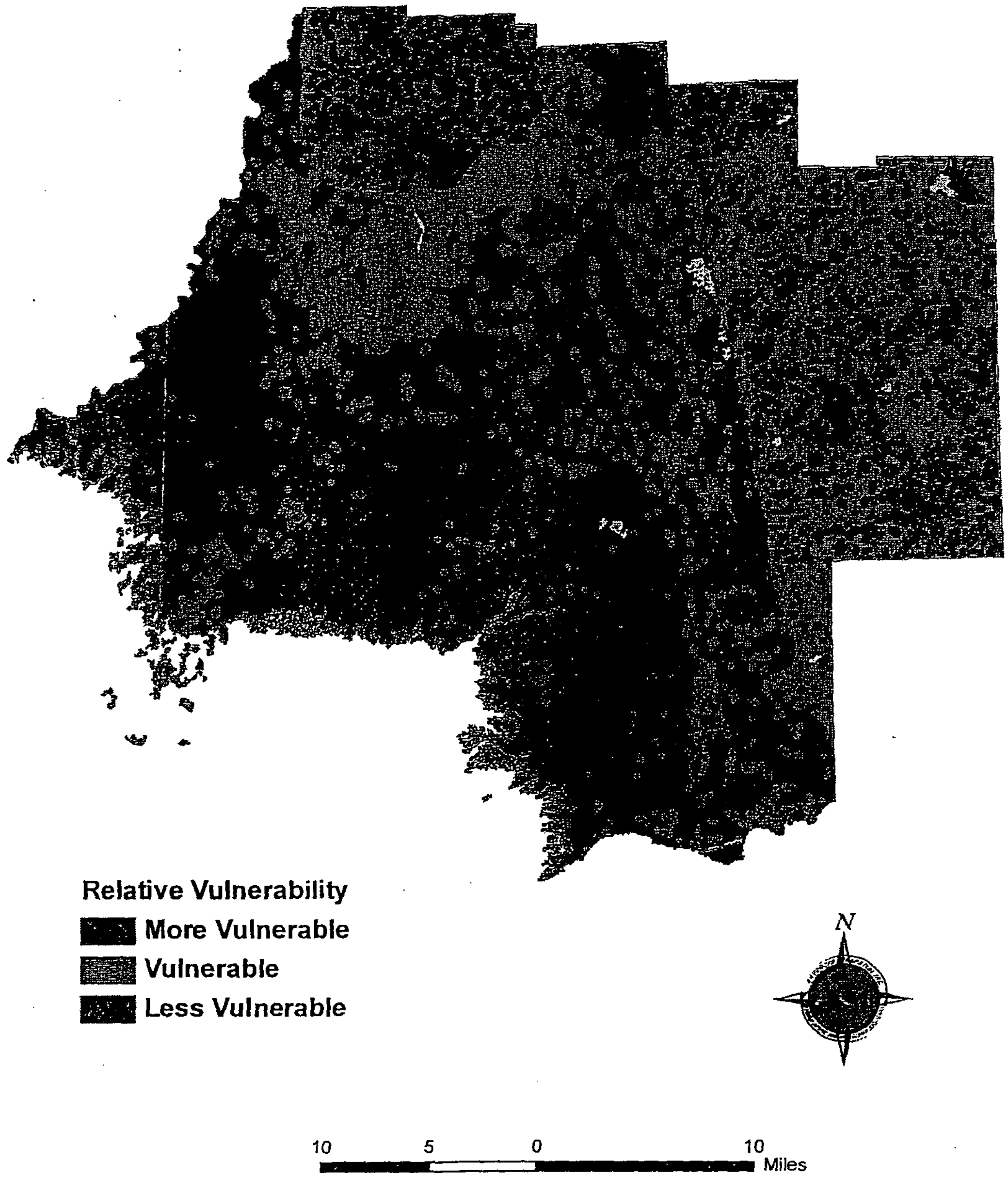


**Figure 14. Relative vulnerability map for the Levy County Aquifer Vulnerability Assessment project. Classes of vulnerability are based on calculated favorability of a unit area containing a training point, or a monitor well with water quality sample results indicative of vulnerability.**

The response theme was broken into classes of relative vulnerability based on the prior probability value and on inflections in a chart in which cumulative study area was plotted against posterior probability (Figure 15). Higher posterior probability values correspond with more vulnerable areas, as they essentially have a higher chance of containing vulnerability based on the definition of a training point. Conversely, lower posterior probability values correspond to less vulnerable areas as they essentially have a lower chance of containing vulnerability based on the definition of a training point.

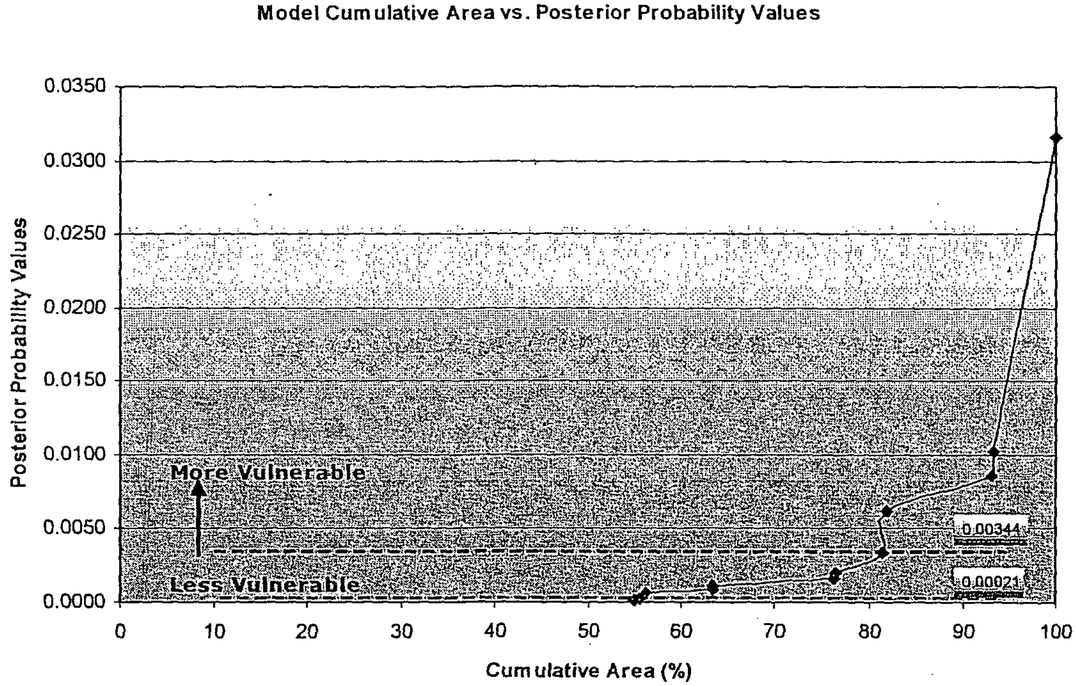


**Figure 15. Vulnerability class breaks are defined by selecting where a significant increase in probability and area are observed.**

As described in *Introduction*, the LCAVA model was based on the modeling technique used in the FAVA project. The FAVA project identified relative vulnerability of Florida's principal aquifer systems broken into three classes: more vulnerable, vulnerable and less vulnerable zones. This naming technique was applied to the LCAVA results to define the relative vulnerability classes.

As expected, the LCAVA model response theme indicates that the areas of highest vulnerability are associated with areas of dense effective karst-features, moderate-to-high recharge potential and higher soil pedality. Conversely, areas of lowest vulnerability are determined by sparse karst-feature distribution, lower recharge potential and lower soil pedality values.

### *Interpretation of Results in Context of FAVA*

Results of the LCAVA project have allowed delineation of new and unique zones of relative vulnerability for the FAS in Levy County, based on the county-specific model boundary used, inclusion of a layer estimating recharge potential, incorporation of most recent soils data, a new training point set, and application of recently-developed approaches for karst estimation in a GIS. These new results, though refined and highly detailed, do not replace results of previous studies. In other words, the FDEP's regional FAVA results (Figure 16; Arthur et al., 2005) for the FAS

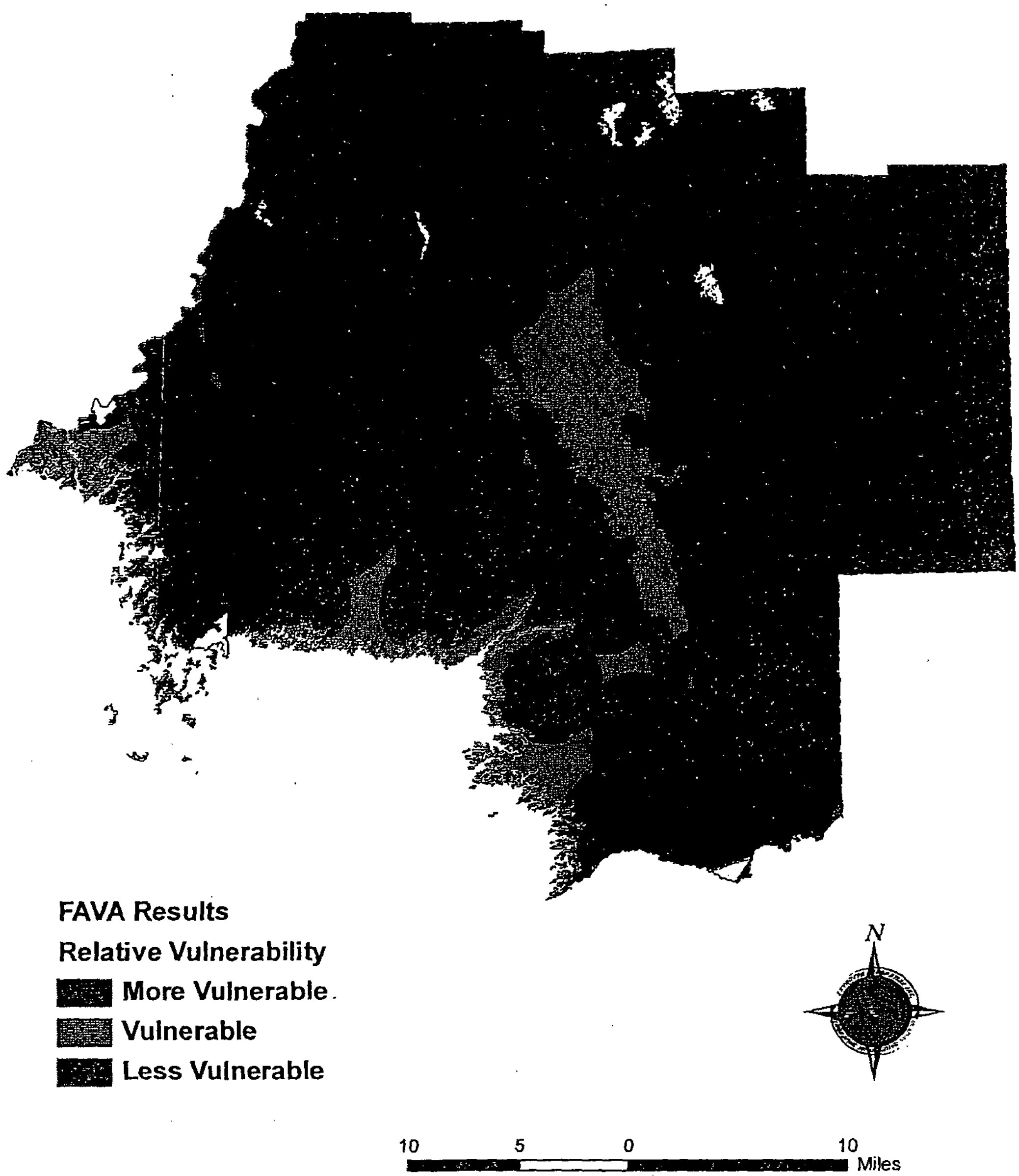


**Figure 16. Results of the Florida Aquifer Vulnerability Assessment project (Arthur et al., 2005) for the FAS in Levy County. The LCAVA model relative vulnerability zones, while based on more refined data than the FAVA project, occur within the context of this regional model.**

indicate that the Levy County study area occurs in primarily a "more vulnerable" zone relative to other areas in Florida; as a result the new LCAVA model output should be interpreted in the context of this major regional project. The new zones delineated in the LCAVA project are unique to the LCAVA study area, and reveal more detailed information regarding aquifer vulnerability within the regional "more vulnerable", and "vulnerable" zones identified in the FAVA project.

## DISCUSSION

Prior to discussion of weights calculations during model execution, two components of a weights of evidence analysis are described to assist in interpretation of LCAVA model results: *Conditional Independence* and *Model Confidence.*

### *Conditional Independence*

Conditional independence is a measure of the degree that evidential themes are affecting each other due to similarities between themes. Evidential themes are considered independent of each other if the conditional independence value is around 1.00, and conditional independence values within the range of 1.00 ± 0.15 generally indicate limited to no dependence among evidential themes (Bonham-Carter, 1994). Values significantly outside this range can inflate posterior probabilities resulting in unreliable response themes.

Conditional independence was calculated at 0.32 for the LCAVA project indicating that evidential themes had a high degree of conditional dependence. Because of the interrelated origin of some natural features controlling aquifer vulnerability (e.g., thin aquifer confinement/density of karst), some interdependence between evidential themes is expected. This has occurred in the past in similar projects; for example, conditional independence calculated for the FAS model in the FAVA Phase I project also indicated evidential themes had a high degree of interdependence (Arthur et al., 2005).

### *Weighted Logistic Regression*

The weighted logistic regression method was employed to resolve a conditional independence issue in the FAVA Phase I project. The benefit of this method is it avoids the bias caused by combining datasets that are conditionally dependent and can be used to account for the inflated probabilities associated with conditional independence problems (Agterberg et al., 1993, and Bonham-Carter, 1994).

Weights of evidence models that rely on logistic regression to generate final model output do not differ greatly from standard weights of evidence model results. The primary difference is that posterior probability values can be inflated when conditional independence values fall significantly outside the acceptable range discussed above. Overall, the patterns of the response themes are extremely similar (Mihalasky and Moyer, 2004).

### *Model Confidence*

During model execution confidence values are calculated both for each generalized evidential theme and for the final response theme. Confidence values approximately correspond to the statistical levels of significance listed in Table 2.

**Table 2. Test values calculated in weights of evidence and their respective studentized T values expressed as level of significance in percentages.**

| Studentized T Value | Test Value |
|---|---|
| 99.5% | 2.576 |
| 99% | 2.326 |
| 97.5% | 1.960 |
| 95% | 1.645 |
| 90% | 1.282 |
| 80% | 0.842 |
| 75% | 0.674 |
| 70% | 0.542 |
| 60% | 0.253 |

Confidence of the evidential theme equals the contrast divided by the standard deviation (a student T-test) for a given evidential theme and provides a useful measure of significance of the contrast due to the uncertainties of the weights and areas of possible missing data (Raines, 1999). A confidence value of 2.9432 corresponds to a greater than 99.5% test value – or level of significance – and was the minimum calculated confidence level for LCAVA project evidential themes (see Table 3 below for evidential theme confidence values).

Confidence is also calculated for a response theme by dividing the theme's posterior probability by its total uncertainty (standard deviation). A confidence map can be generated based on these calculations. The confidence map for the LCAVA response theme is displayed in Figure 17. Areas with high posterior probability values typically correspond to higher confidence values and as a result have a higher level of certainty with respect to predicting aquifer vulnerability.

### *Weights Calculations*

Table 3 displays evidential themes used in the LCAVA model, weights calculated for each theme, along with contrast and confidence values. Positive weights indicate areas where training points were likely to occur, while negative weights indicate areas where training points were not likely to occur. The contrast column is a combination of the highest and lowest weights (positive weight – negative weight) and is a measure of how well the generalized evidential themes predict training points. A positive contrast that is significant, based on its confidence, suggests that a generalized evidential theme is a useful predictor.

**Table 3. Weights of evidence final output table listing weights calculated for each evidential theme and their associated contrast and confidence values of the evidential themes.**

| Evidential Theme | W1 | W2 | Contrast | Confidence |
|---|---|---|---|---|
| Recharge Potential | 1.1000 | -2.0375 | 3.1375 | 2.9893 |
| Effective Karst Features | 1.0665 | -2.0226 | 3.0892 | 2.9432 |
| Soil Pedality | 1.6199 | -0.8770 | 2.4969 | 3.9678 |

Because negative weights (W2) values for recharge potential and effective karst themes are stronger (have greater absolute values) than the positive weights (W1), these two evidential themes are better predictors of where training points were *less* likely to occur. In contrast, soil pedality is a better predictor of where training points are *more* likely to occur, as W1 is stronger than W2.

Table 4 also displays evidential themes used in the LCAVA model and a coefficient for each evidential theme, which, like the weights of evidence table, indicates relative importance of each evidential theme in determining the posterior probability of the response theme (Mihalasky and Moyer, 2004). The higher the absolute value of the coefficient, the better predictor the associated evidential theme is of training points, or aquifer vulnerability.

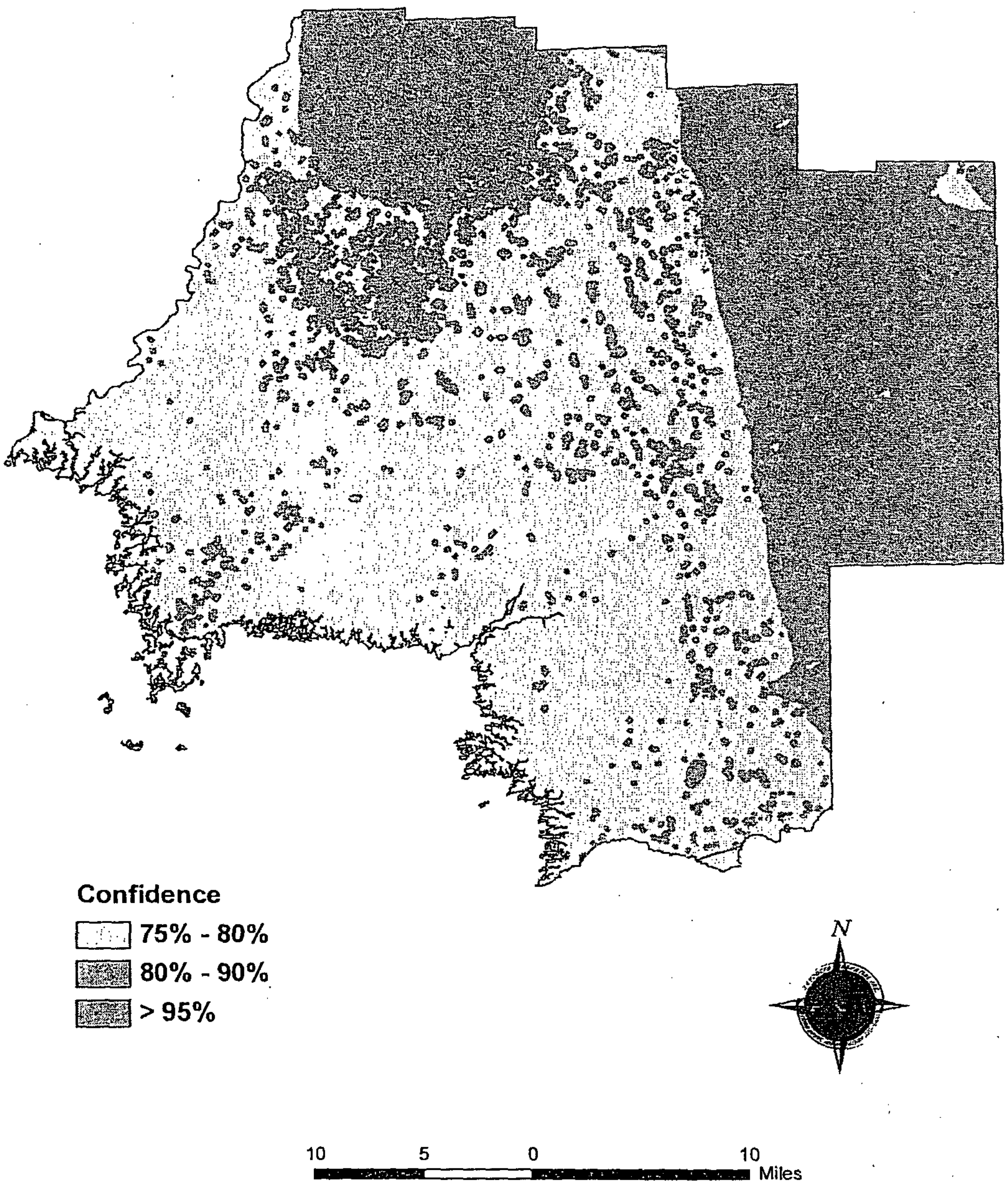


**Figure 17. Confidence map for the LCAVA model calculated by dividing the posterior probability values by the total uncertainty for each class to give an estimate of how well specific areas of the model are predicted.**

**Table 4. Weighted logistic regression final output table listing coefficients calculated for each evidential theme.**

| Evidential Theme | Coefficient |
|---|---|
| Effective Karst Features | -2.245824 |
| Recharge Potential | -1.654336 |
| Soil Pedality | -1.317255 |

Based on coefficient values, the effective karst features theme has the strongest coefficient (highest absolute value) and is the primary determinant in predicting areas of vulnerability in the LCAVA model.

### *Validation*

The weights of evidence approach, because it relies on a set of training points, which by definition are known sites of vulnerability, is essentially self-validated. Moreover, the location of 10 of 11 training points in "more vulnerable" zones indicates that the LCAVA model is a strong predictor of aquifer vulnerability based on the definition of a training point. Further strengthening the results were the evaluation of a minimum confidence threshold for evidential themes, and generation of a confidence map of the response theme. In addition to these exercises, and in the style of previous aquifer vulnerability assessments (Cichon et al., 2005; Baker et al., 2005; Arthur et al., 2005), additional validation techniques were applied to the LCAVA model to further strengthen its defensibility, and, ultimately, its utility: (1) comparison of dissolved nitrogen values with vulnerable zones of the response theme; (2) generation of a test response theme based on a subset of training points and comparison of points not used in subset to model results; and (3) comparison of dissolved oxygen values to posterior probability and evaluation of an associated trend.

#### *Dissolved Nitrogen Data*

Perhaps the most rigorous validation exercise used to evaluate quality of model-generated output is to compare predicted model values with independent test values not used in the model. For the LCAVA model, this was accomplished by comparison of a separate well dataset based on dissolved nitrogen. As mentioned above in *Training Point Theme*, dissolved nitrogen is indicative of aquifer vulnerability, but is independent of dissolved oxygen. Applying the methodology described in *Training Point Theme* to dissolved nitrogen data (obtained from the same data sources as dissolved oxygen data) resulted in a dissolved nitrogen dataset of 13 wells each indicative of aquifer vulnerability.

These 13 points were evaluated against posterior probability values of the LCAVA model output. Extracting the value of posterior probability from the dissolved oxygen response theme for the location of each of the 13 dissolved nitrogen training points revealed that 11 of the 13 dissolved nitrogen training points occur in areas of the dissolved oxygen model with predicted probability values higher than the prior probability value. In other words, 85% of the dissolved nitrogen wells were located in areas predicted to have a greater than chance probability of containing a training point. Based on this test, the dissolved oxygen model is not only a good predictor of vulnerability as defined by the training point theme, it is also a good predictor of the location of an independent parameter also representing aquifer vulnerability. Figure 18 displays dissolved nitrogen data points plotted on the dissolved oxygen response theme.

#### *Subset Response Theme*

Another meaningful validation exercise similar to the exercise above is to use the existing training point dataset to develop two subsets: one to generate a test response theme, and one to validate output from this test response theme. Results from this exercise helped to further assess whether the dissolved oxygen training points are reasonable predictors of aquifer vulnerability.

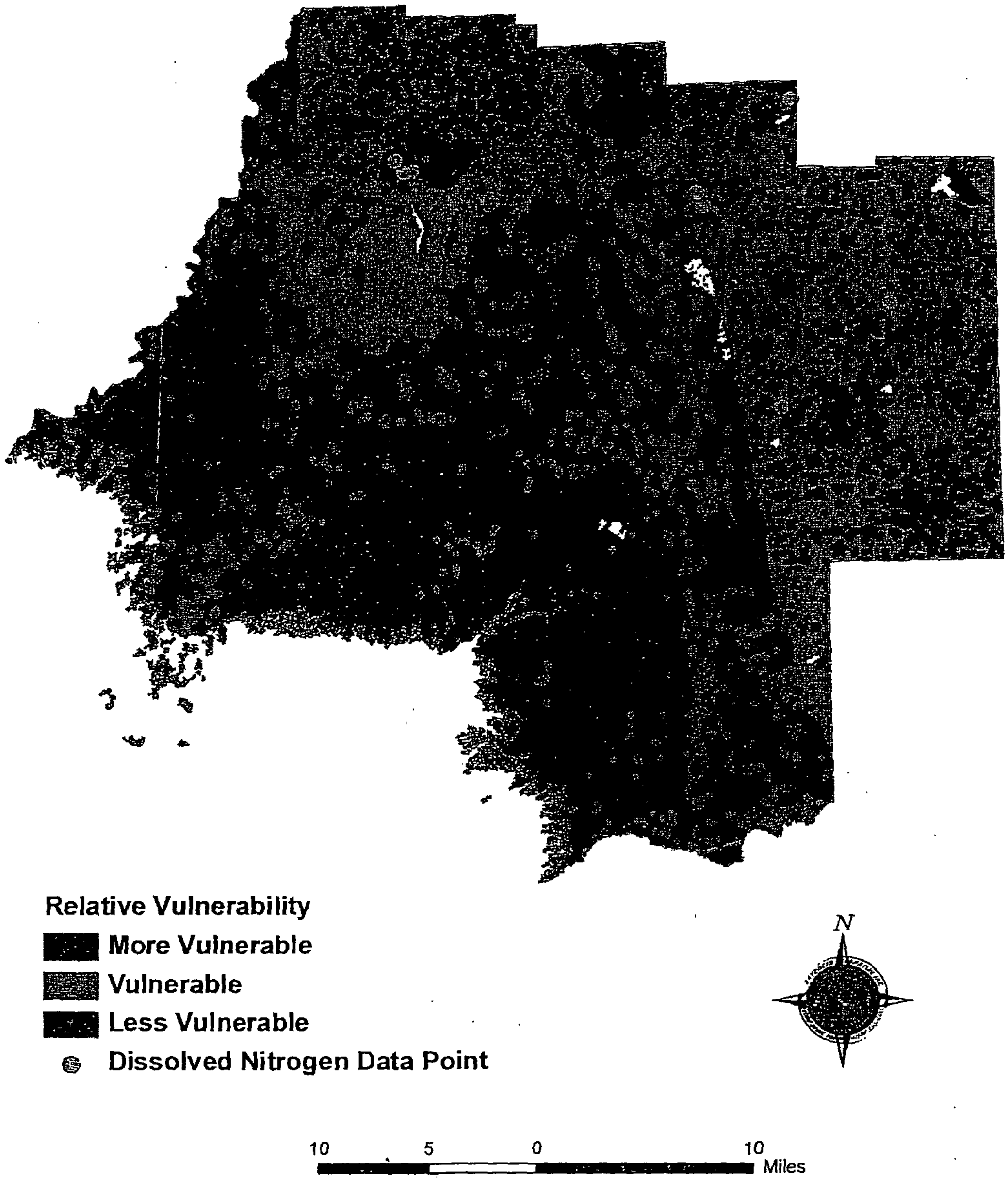


**Figure 18. Dissolved nitrogen validation training points plotted in the dissolved oxygen response theme. Comparison reveals 11 of 13 wells (85%) of the independent water quality dataset are located in "more vulnerable" areas.**

vulnerability. Additionally, model results do not account for human activities at land surface, take into consideration contaminant types, or estimate ground-water flow paths or fate/transport of chemical constituents.

### *Confidence Map*

As mentioned above, a confidence map of the model's posterior probability values can be calculated by dividing the posterior probability by its standard deviation. This essentially applies an informal student T-test (as in Table 2) to the posterior probability values. The higher the confidence values, the greater the certainty is with regard to the posterior probability. This map essentially indicates the degree of confidence to which the posterior probabilities are meaningful and should be referenced when interpreting and implementing the model results. In other words, the confidence map should be used to help guide implementation of the vulnerability map as it reveals the confidence level associated with each vulnerability class (Mihasky and Moyer, 2004).

### *Surface Water Areas*

In addition to large surface-water bodies omitted from the analysis, there are many other surface-water features which were not removed. Many of these features may represent areas of ground-water discharge; however, these discharging surface waters are not part of the aquifer, although they originate from it. Accordingly, the LCAVA model is not intended to be used to assess contamination potential of surface waters, though the discharging surface waters are highly vulnerable to contamination.

### *Recommendations on Scale of Use*

Use of highly detailed evidential theme data as model input results in highly resolute model output as can be seen in the model response theme. These resolute features are reflections of real data used as input; however, the final maps should not be applied to very large scales such as to compare adjacent small parcels. The following recommendations are made in recognition of the need for these maps to be applied to regulation and decisions made at the parcel scale.

LCAVA model output is, in a sense, as accurate as the most detailed input layer, and as inaccurate as the least detailed layer. Wells used to define aquifer confinement thickness represent an area up to 28 square miles ($mi^2$), for example; on the other hand, soils polygonal data represent an area as small as 19,375 $ft^2$.

Reports on past projects recommended that model results be applied on a local scale of greater than or equal to approximately 1.0 $mi^2$ for statewide studies (Arthur et al., 2005: Florida Aquifer Vulnerability Assessment) or approximately 0.75 $mi^2$ for localized studies (Cichon et al., 2005: Wekiva Aquifer Vulnerability Assessment; Baker et al., 2007: Marion County Aquifer Vulnerability Assessment). Based on similarities to larger-scale projects, AGI recommends that the LCAVA model output be used for implementation on the order of greater than 0.75 $mi^2$, or an area of approximately 480 acres or greater. In other words, when applying model results to compare vulnerability zones, it is recommended that the user refrain from making decisions, comparing parcels, or relative vulnerability zones within a 480 acre area, or 4500-ft by 4500-ft view window. Application of model results on a less resolute scale, or simply, a more "zoomed-out" view than the 4,500-ft x 4,500-ft view window is recommended.

Every raster cell of the model output coverage has significance per the model input as discussed above. However, it is important to note that aquifer vulnerability assessments are predictive models and no assumptions are made that all input layers are accurate, precise or complete at a single-raster cell scale. Ultimately, accuracy of the maps does not allow for evaluation of aquifer vulnerability at a specific parcel or site location. It is the responsibility of the end users of the LCAVA model output to determine specific and appropriate applications of these maps. In no instance should use of aquifer vulnerability assessment results substitute for a detailed, site-specific hydrogeological analysis.

## CONCLUSION

As demands for fresh ground water from the FAS underlying Levy County increase resulting from continued population growth, identification of zones of relative vulnerability becomes an increasingly important tool for implementation of a successful ground-water protection and management program. The results of the LCAVA project provide a science-based, water-resource management tool allowing for a pro-active approach to protection of the FAS, and, as a result, have the potential to increase the value of protection efforts. Model results will enable improved decisions to be made about aquifer vulnerability based on the input selected, including focused protection of sensitive areas such as springsheds and ground-water recharge areas.

The results of the LCAVA vulnerability model are useful for development and implementation of ground-water protection measures; however, the vulnerability output map included in this report should not be viewed as a static evaluation of the vulnerability of the FAS. Because the assessments are based on snapshots of best-available data, the results are static representations; however, a benefit of this methodology is the flexibility to easily update the response themes as more refined or new data becomes available. In other words, as the scientific body of knowledge grows regarding hydrogeologic systems, this methodology allows the ongoing incorporation and update of datasets to modernize vulnerability assessments thereby enabling end users to better meet their objectives of protecting these sensitive resources. The weights of evidence modeling approach to aquifer vulnerability is a highly adaptable and useful tool for implementing ongoing protection of Florida's vulnerable ground-water resources.

## QUALIFICATIONS

### *Disclaimer and Funding Source*

Maps generated as part of this project were developed by Advanced GeoSpatial Inc. (AGI) to provide the Florida Department of Environmental Protection (FDEP) with a ground-water resource management and protection tool to carry out agency responsibilities related to natural resource management and protection regarding the Floridan Aquifer System. Although efforts were made to ensure information in these maps is accurate and useful, neither FDEP nor AGI assumes responsibility for errors in the information and does not guarantee that the data are free from errors or inaccuracies. Similarly, AGI and FDEP assume no responsibility for consequences of inappropriate uses or interpretations of the data on these maps. Accordingly, these maps are distributed on an "as is" basis and the user assumes all risk as to their quality, results obtained from their use, and performance of the data. AGI and FDEP further make no warranties, either expressed or implied as to any other matter whatsoever, including, without limitation, the condition of the product, or its suitability for any particular purpose. The burden for determining suitability for use lies entirely with the end user. In no event shall AGI or FDEP, or their respective employees have any liability whatsoever for payment of any consequential, incidental, indirect, special, or tort damages of any kind, including, but not limited to, any loss of profits arising out of use of or reliance on the project results. AGI and FDEP bear no responsibility to inform users of any changes made to this data. Anyone using this data is advised that resolution implied by the data may far exceed actual accuracy and precision. Because this data was developed and collected with FDEP funding, no proprietary rights may be attached to it in whole or in part, nor may it be sold to FDEP or other government agency as part of any procurement of products or services.

The FAVA Phase II project and the preparation of this document were funded in part by a Section 106 Water Pollution Control Program grant from the U.S. Environmental Protection Agency (US EPA) through a contract with the Florida Geological Survey, Division of Resource Assessment and Management of the Florida Department of Environmental Protection. The total cost of the FAVA Phase II project was $234,899, of which $25,000 or 11% was provided by the US EPA.

### *Ownership of Documents and Other Materials*

This project represents significant effort and resources on both the part of FDEP and AGI to establish peer-reviewed, credible and defensible aquifer vulnerability model results. Unauthorized changes to results can have far reaching implications including confusing end users with multiple model results, and discrediting validity and defensibility of original results.

A main goal of the project is to maintain the integrity and defensibility of the final model output by preserving its data-driven characteristics. Modification or alteration of the model or its output can only be executed by trained professionals experienced with the project and with weights of evidence.

To protect both FDEP and AGI from potential misuse or unauthorized modification of the project results, all input and output results of aquifer vulnerability assessments, and the aquifer vulnerability assessment models, along with project documents, reports, drawings, estimates, programs, manuals, specifications, and all goods or products, including intellectual property and rights thereto, created under this project or developed in connection with this project will be and will jointly remain the property of FDEP and AGI.

For additional information regarding this project, please refer to the associated 24" x 36" interpretive poster of the same title as this report, and/or the GIS project data and associated metadata. At the time of this report, these GIS files may be accessed using ArcMap™, version 9.x.

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## WEIGHTS OF EVIDENCE GLOSSARY

Conditional Independence – Occurs when an evidential theme does not affect the probability of another evidential theme. Evidential themes are considered independent of each other if the conditional independence value calculated is within the range 1.00 ± 0.15 (Bonham-Carter, 1994). Values that significantly deviate from this range can inflate the posterior probabilities resulting in unreliable response themes.

Confidence of Evidential Theme – Contrast divided by its estimated standard deviation; provides a useful measure of significance of the contrast.

Confidence of Posterior Probability – A measure based on the ratio of posterior probability to its estimated standard deviation.

Contrast – W+ minus W- (see weights), which is an overall measure of the spatial association (correlation) of an evidential theme with the training points.

Data Driven – refers to a modeling process in which decisions made in regard to modeling input are driven by empirical data. Examples include the weights of evidence approach or logistic regression approach as in the FDEP's FAVA project (Arthur et al., 2005).

Evidential Theme – A set of continuous spatial data that is associated with the location and distribution of known occurrences (i.e., training points); these map data layers are used as predictors of vulnerability.

Expert Driven – a scientific approach which relies on the expertise and knowledge of one or more specialists to drive decisions in a modeling project. An example is the EPA's index ranking method known as "DRASTIC".

Posterior Probability – The probability that a unit cell contains a training point after consideration of the evidential themes. This measurement changes from location to location depending on the values of the evidence.

Prior Probability – The probability that a unit cell contains a training point before considering the evidential themes. It is a constant value over the study area equal to the training point density (total number of training points divided by total study area in unit cells).

Response Theme – An output map that displays the probability that a unit area would contain a training point, estimated by the combined weights of the evidential themes. The output is displayed in classes of relative aquifer vulnerability or favorability to contamination (i.e., this area is more vulnerable than that area). The response theme is the relative vulnerability map.

Spatial Data – Information about the location and shape of, and relationships among, geographic features, usually stored as coordinates and topology.

Training Points – A set of locations (points) reflecting a parameter used to calculate weights for each evidential theme, one weight per class, using the overlap relationships between points and the various classes. In an aquifer vulnerability assessment, training points are wells with one or more water quality parameters indicative of relatively higher recharge which is an estimate of relative vulnerability.

Weights – A measure of an evidential-theme class. A weight is calculated for each theme class. For binary themes, these are often labeled as W+ and W-. For multiclass themes, each class can also be described by a W+ and W- pair, assuming presence/absence of this class versus all other classes. Positive weights indicate that more points occur on the class than due to chance, and the inverse for negative weights. The weight for missing data is zero. Weights are approximately equal to the proportion of training points on a theme class divided by the proportion of the study area occupied by theme class, approaching this value for an infinitely small unit cell.

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