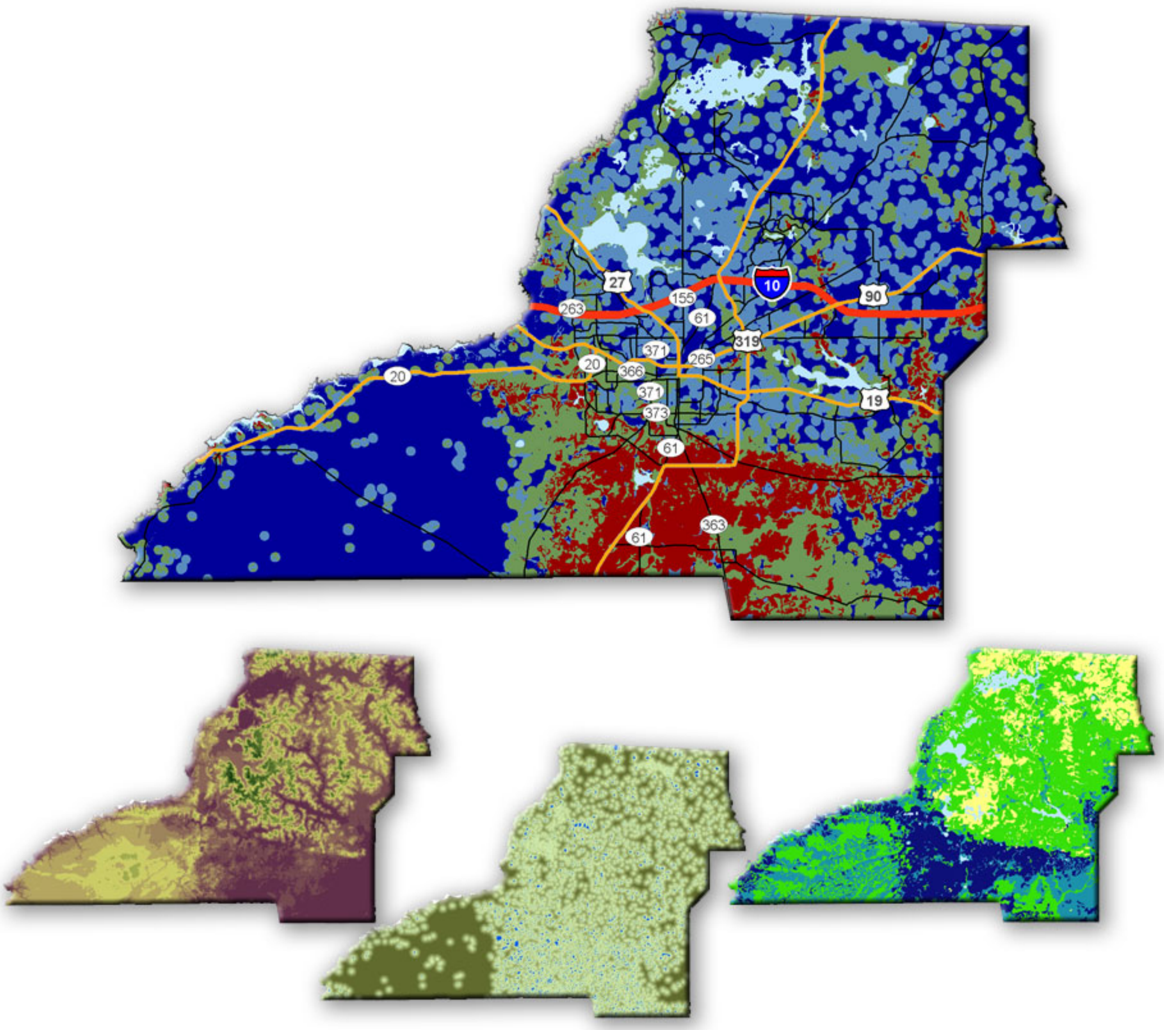
THE LEON COUNTY AQUIFER VULNERABILITY ASSESSMENT

A Ground-Water Protection and Management Tool



Prepared for the Leon County Board of County Commissioners by Advanced GeoSpatial Inc. in fulfillment of BC-06-21-06-53

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THE LEON COUNTY AQUIFER VULNERABILITY ASSESSMENT

Prepared For:
The Leon County Board of County Commissioners
In fulfillment of Leon County Project No. BC-06-21-06-53

Prepared by

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July 2007

PROFESSIONAL GEOLOGIST CERTIFICATION

I, Alan E. Baker, P.G., no. 2324, have read and agree with the findings in this report titled THE LEON 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

July 19, 2007
Date

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Special Note: 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 either ESRI®’s ArcReader or ArcMap™, version 9.x.

EXECUTIVE SUMMARY

The primary purpose of the Leon County Aquifer Vulnerability Assessment (LAVA) project is to provide a science-based, water-resource management tool to help minimize adverse impacts on ground-water quality, including focused protection of sensitive areas like springsheds and ground-water recharge zones. The LAVA model results are intended to have many uses, and include: (1) augmenting development of wastewater and infrastructure management guidelines; (2) establishing best management practices for land use and other practices; (3) prioritizing sensitive land acquisition for conservation; and (4) helping identify potential areas of concern for potable well contamination and directing water quality sampling. In addition, model results are also intended to be combined with other map overlays and datasets to help develop derivative tools such as aquifer protection zone maps.

Located mainly on the Woodville Karst Region, Leon County is underlain by thick and very permeable limestone layers and other carbonate rocks which make up the Floridan Aquifer System (Pratt et al., 1996). Sinkholes, swallets, river rises, springs and their springsheds and other karst features are common throughout the area. This includes such recognized features as Natural Bridge Spring, Horn Spring, St. Marks River Rise and the Leon Sinks Geological Area. These karst features can enhance the hydrologic interactions between land surface and the underlying Floridan Aquifer System. This can result in a system which is highly sensitive to activities occurring at land surface.

Leon County's residents rely heavily on the Floridan Aquifer System, which is the most important source of fresh water in Leon County. Identifying areas of Leon County where the Floridan Aquifer System is more vulnerable to contamination is a critical component of a comprehensive ground-water management program. Aquifer vulnerability modeling allows for a pro-active approach to achieve such protection, and can save significant time and greatly increase the value of protection efforts.

The modeling process used for the LAVA project is known as "weights of evidence", and is based in a geographic information system (GIS). A main benefit of applying this technique in the LAVA project is that model output depends on training sites resulting in self-validated model output. Training sites are simply ground-water wells with water quality that indicates a good connection between the aquifer and land surface. In other words, training sites indicate where aquifer vulnerability is occurring.

The LAVA model generation involved associating training site locations with data layers that represent the natural conditions controlling aquifer vulnerability. For example, data layers that control aquifer vulnerability in Leon County include the presence of sinkholes and other karst features, the thickness of protective material overlying the Floridan Aquifer System, and how effectively water can move through the soil horizon. Highly detailed elevation data was also used to help estimate and measure input layers in a GIS. The LAVA project takes advantage of local scale data and provides a very usable end product for planners, developers, and regulators working on the local level to develop solutions to water resource issues.

The finished output for the LAVA project consists of a probability map displaying zones of relative aquifer vulnerability across the Leon County study area. The model's output map indicates that the areas of highest aquifer vulnerability are generally associated with areas (1) where the thickness of protective material is thin to absent, (2) where there are numerous sinkholes and other karst features, and (3) where water more readily moves through the soil horizon.

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INTRODUCTION

The Floridan Aquifer System is the most important and prolific source of fresh water in Leon County. According to the Northwest Florida Water Management District, permitted ground-water use from the Floridan Aquifer System in Leon County exceeds 97 million gallons of water per day for public supply, agriculture, and other uses. In addition to this amount, there are over 8,000 self-supply wells tapping the Floridan Aquifer System in Leon County providing fresh water to homeowners (NWFWMD personal communication, 2007). Leon County's 245,625 residents (U.S. Census Bureau, 2005) rely almost exclusively on the Floridan Aquifer System for their fresh water needs.

Leon County lies mainly within the Woodville Karst Region and is underlain by thick and highly permeable carbonate rocks which comprise the Floridan Aquifer System (Pratt et al., 1996). Sediments overlying this aquifer system vary from moderately thick in the western part of the county to thin and breached by sinkholes in other parts of the county. Karst features characterize the area and include sinkholes, swallets, river rises, and springs and their springsheds. These features all represent surface connections or interactions with the underlying aquifer system, and include Natural Bridge Spring, Horn Spring, St. Marks River Rise and the Leon Sinks Geological Area (Scott et al., 2004). This complex and highly integrated surface and ground-water environment can be very sensitive to activities occurring at land surface.

Identifying areas of Leon 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 the Leon County study area. 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:

- Wellhead protection
- Source-water protection
- Land-use planning
- Environmental protection
- Sensitive land acquisition

Project Objective

Leon County contracted with Advanced GeoSpatial Inc. (AGI) in September of 2006 to develop the Leon County Aquifer Vulnerability Assessment (LAVA) model characterizing the natural (or intrinsic) vulnerability of the Floridan Aquifer System (FAS). The primary purpose of this project is to provide Leon 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 Leon

County to make improved decisions about aquifer vulnerability 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, for use in planning or regulation. 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 Florida Department of Environmental Protection (FDEP) in the Florida Aquifer Vulnerability Assessment (FAVA) 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 was employed in FDEP’s FAVA project (for detailed information please refer to Arthur et al., 2005). Use of this method 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 this methodology; project-specific and more detailed information is presented in *Project Results*.

Weights of Evidence

Weights of evidence methodology was used in the LAVA project to develop an aquifer vulnerability assessment model of the FAS. The modeling technique is based in a geographic information system (GIS) and is executed using Arc Spatial Data Modeler (Arc-SDM), an extension to ESRI’s ArcGIS software package. For more information on weights of evidence please refer to Arthur et al. (2005), Kemp et al. (2001), Raines et al. (2000), and Bonham-Carter (1994). Primary benefits of applying the weights of evidence technique to the LAVA project are that it is a data-driven method, rather than an expert-driven method, and model generation is dependent upon a training dataset resulting in self-validated model output.

Data Acquisition and Development

The initial phase of any aquifer vulnerability 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 Pedality

Vulnerability Modeling

Upon completion of the development and adaptation of the necessary data coverages for the vulnerability assessment, the modeling phase using weights of evidence is initiated to generate aquifer vulnerability response themes, which are expressed as probability 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. The Leon County political boundary served as the model study area for the LAVA 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 nitrogen or dissolved oxygen analytical concentrations can be 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. Based on these calculations, 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 is a probability map, and for LAVA is displayed in classes of relative vulnerability for the FAS in Leon 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 the results. Sensitivity analysis was applied during development of each evidential theme and validation exercises were applied to model results to assess strength and confidence.

LAVA Technical Advisory Committee

An advisory committee was formed to provide technical review and support during the development of the LAVA project and consisted of professionals in water resource, planning, engineering, hydrogeologic and other environmental fields. Members participated in three workshop meetings, provided technical review of model progress and the final results and report. Members and their organization are listed in Table 1 below.

Table 1. LAVA Technical Advisory Committee members.

Name	Organization
Rick Copeland, Ph.D., P.G.	Florida Geological Survey/FDEP
Linda Clemens, P.G.	Florida Department of Environmental Protection
Tony Countryman, P.G.	Northwest Florida Water Management District
Jay L. Johnson, GISP	Tallahassee/Leon County Interlocal GIS
Koren Taylor, P.G	City of Tallahassee Aquifer Protection
Timothy J. Hazlett, Ph.D.	Hazlett-Kincaid Inc.

In addition to the advisory committee members listed above, other representatives of Leon County and City of Tallahassee government participated in meetings. They are: John Kraynak and Tom Ballentine of Leon County Growth and Environmental Management, Walt Loomis of Tallahassee Water Quality Division. Kristen Andersen of Tallahassee/Leon County Planning Department managed the LAVA contract.

PROJECT RESULTS

Study Area

The political boundary of Leon County was used as the LAVA model study area extent (Figure 1). For development of some input layers, data from outside the county boundaries was used. Because of the sizes of some polygons representing soil data and because the Leon County LIDAR-derived digital elevation model (DEM) was used to develop model input, a grid cell size of 400 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 LAVA analysis, training points are ground-water wells tapping the FAS with water quality data indicative of high recharge. Naturally occurring nitrogen and oxygen 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 the ground-water system, they are good indicators of aquifer vulnerability (Arthur et al., 2007).

Water quality data sources explored for the LAVA project included the FDEP background water quality network, FDEP STATUS network, Northwest Florida Water Management District (NWFWMD), and the City of Tallahassee. From these data sources, 74 wells measured for dissolved nitrogen and oxygen were identified as being potential candidates for training points.

Test modeling and analysis of the training point datasets revealed an atypical trend in the distribution and values of dissolved oxygen across the Leon County study area when compared to similar hydrogeologic investigations (Baker et al., 2007; Cichon et al., 2005; Baker et al., 2005; Arthur et al., 2005). Further, applying a dissolved oxygen training point dataset in the testing model phase of the project indicated that patterns in the evidential themes were not consistent when compared with results of similar projects. It falls beyond the scope of the LAVA project to further investigate this atypical dissolved oxygen trend and determine its source or origin.

Previous aquifer vulnerability assessment projects have relied on nitrogen data as a primary training point theme. For example, dissolved nitrogen was used with success in the Florida Aquifer Vulnerability Assessment project to model the vulnerability of all three of Florida's major aquifer systems: the FAS, the Surficial Aquifer System and the Intermediate Aquifer System (Arthur et al., 2005). Sensitivity analysis and test modeling in the LAVA project revealed that dissolved nitrogen values serve as a more statistically valid training point dataset for this study area.

As mentioned above, 74 wells were identified that were measured for dissolved nitrogen. Statistical analyses revealed that five wells were considered statistical outliers. The upper 25^{th} percentile of the remaining set – or all wells with median dissolved nitrogen values greater than 0.41 milligrams per liter (mg/L) – served as the training point theme and consisted of 18 wells. Figure 2 displays the distribution of water wells used to derive training points and the resulting training point theme across the study area.

In the weights of evidence model, training points are used to calculate prior probability, weights for each evidential theme, and posterior probability of the response theme (see Glossary for more information). 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 any evidential theme data. The prior probability value, a unitless parameter, for the LAVA model is 0.0103. 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. Factors considered for the LAVA project include karst features, thickness of aquifer confinement, soil hydraulic conductivity and soil pedality. In an effort to take advantage of recently-collected data and the most resolute data available, such as LIDAR-derived DEM and recently constructed wells, new data coverages not previously available were developed representing aquifer confinement and karst features. Further, datasets representing soils were adapted from existing data for use in the LAVA model and now represent previously unavailable countywide datasets

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 LAVA 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 LAVA using the pedality point method developed by Lin et al. (1999).

In 2006, Leon 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 LAVA 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 to determine best model input.

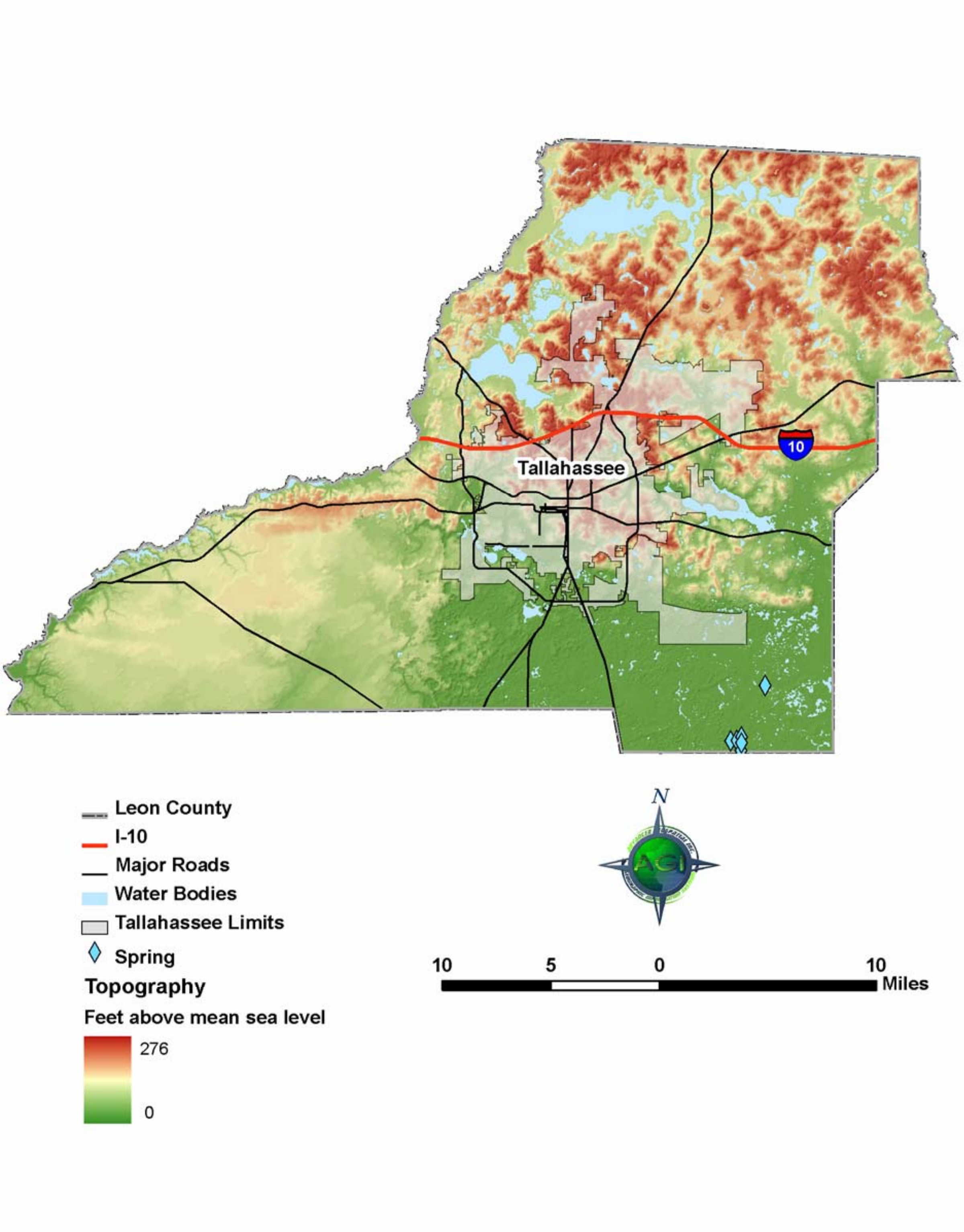

Figure 1. Leon County Aquifer Vulnerability Assessment project study area corresponds to the County's political boundary.

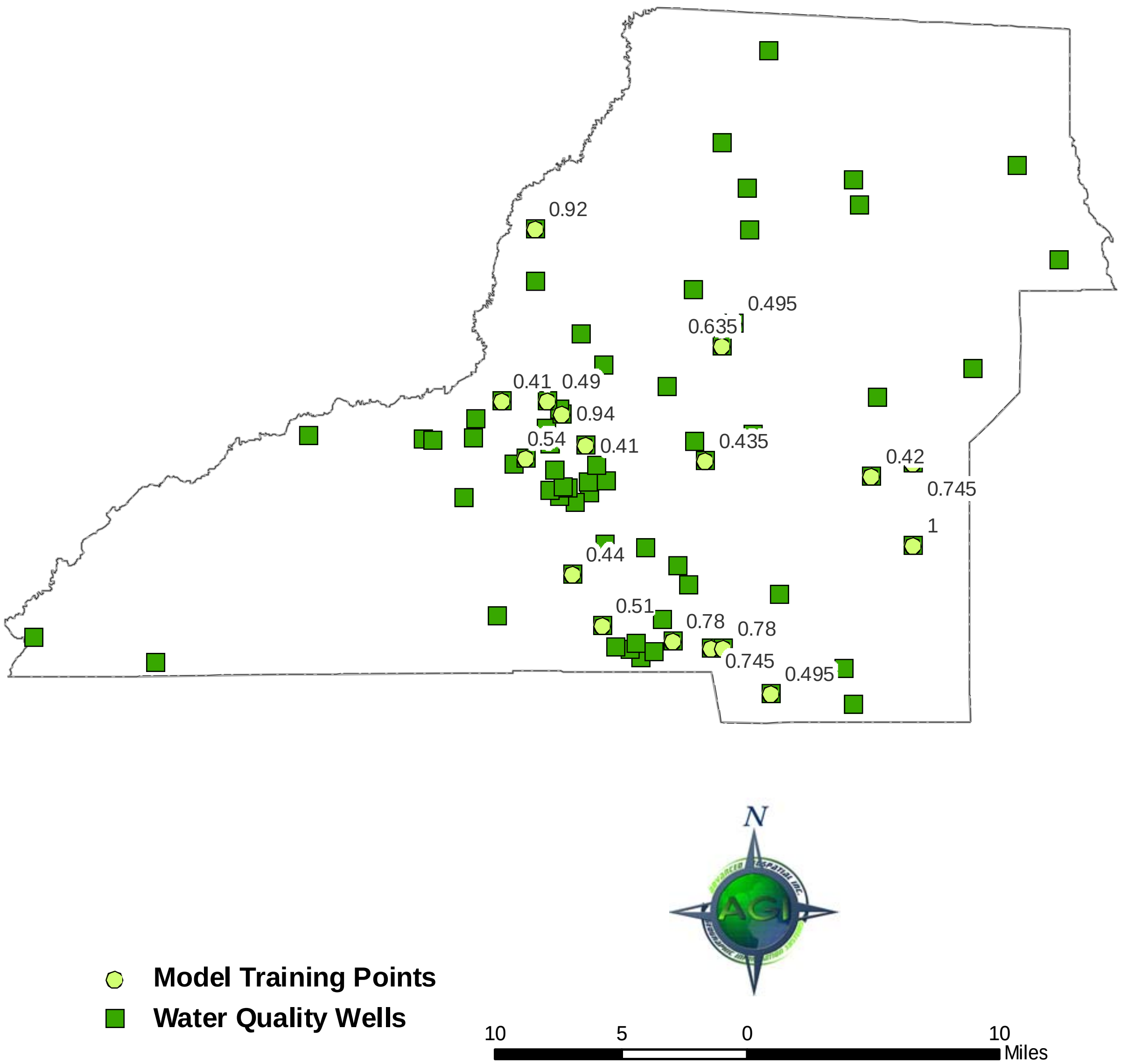

Figure 2. Location of all wells measured for dissolved nitrogen, and locations of wells with median dissolved nitrogen values higher than 0.41 mg/L which comprise training point dataset.

Countywide datasets representing soil hydraulic conductivity and soil pedality were developed for use as input into the LAVA 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.

Intermediate Confining Unit / Overburden Thickness Themes

Aquifer confinement – either in the form of overburden on the FAS (surface of limestone to land surface), or the Intermediate Confining Unit (ICU) – is another critical layer in determining aquifer vulnerability. The rate water moves through the confining units overlying an aquifer, or conductivity, is an important measure of degree of confinement. However, reliable data representing conductivity is limited across the study area, while detailed information regarding thickness of confinement is generally more readily available in borehole and gamma logs from wells. Where aquifer confinement is thick and the FAS is deeply buried, aquifer vulnerability is lower, whereas in areas of thin to absent confinement, the vulnerability of the FAS is generally higher.

As part of the LAVA project, AGI developed models of both overburden on the FAS, and the ICU using a dataset of borehole records combined with well gamma logs that contain descriptions of subsurface materials. Sources of these datasets included the Florida Geological Survey and NWFWMD. Data points were analyzed to identify potential statistical outliers and erroneous data points. Because the ICU is discontinuous across the study area, it was necessary to estimate the areas where the ICU was absent. Data points were used in conjunction with the State of Florida geologic map (Scott et al., 2001), the Leon County DEM, and extents used in previous works (Arthur et al., 2005; Arthur et al., 2007) to estimate the areal extent of the ICU. The well dataset and areal extent of ICU are identified in Figure 5.

The point dataset was then used to predict two hydrostratigraphic surfaces: top of FAS (Figure 6) and top of ICU (Figure 7). Ordinary kriging was selected as the surface prediction method because of its flexibility and data exploration options. A sensitivity analysis was completed to determine the best modeling protocol for creating surfaces. These surfaces were combined with DEM data to resolve areas where the prediction technique estimated values above land surface. Resulting surfaces were used to calculate thickness of the ICU (Figure 8) and thickness of material overlying the FAS (Figure 9). 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 ground 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 the county’s DEM served as the initial dataset from which to estimate effective karst features in the study area. It is recognized that closed topographic depressions may or may not be true karst features. For example, storm water ponds are by definition closed depressions, yet they are not karstic in origin; depending on pond construction and treatment objectives they may or may not represent preferential vertical flow pathways. In addition, some karst features may not be represented in the closed depressions data. For example, some karst features known as solution pipes offer direct pathways to the FAS and are typically very small in size, possibly below the feature size threshold restrictions applied in this project.

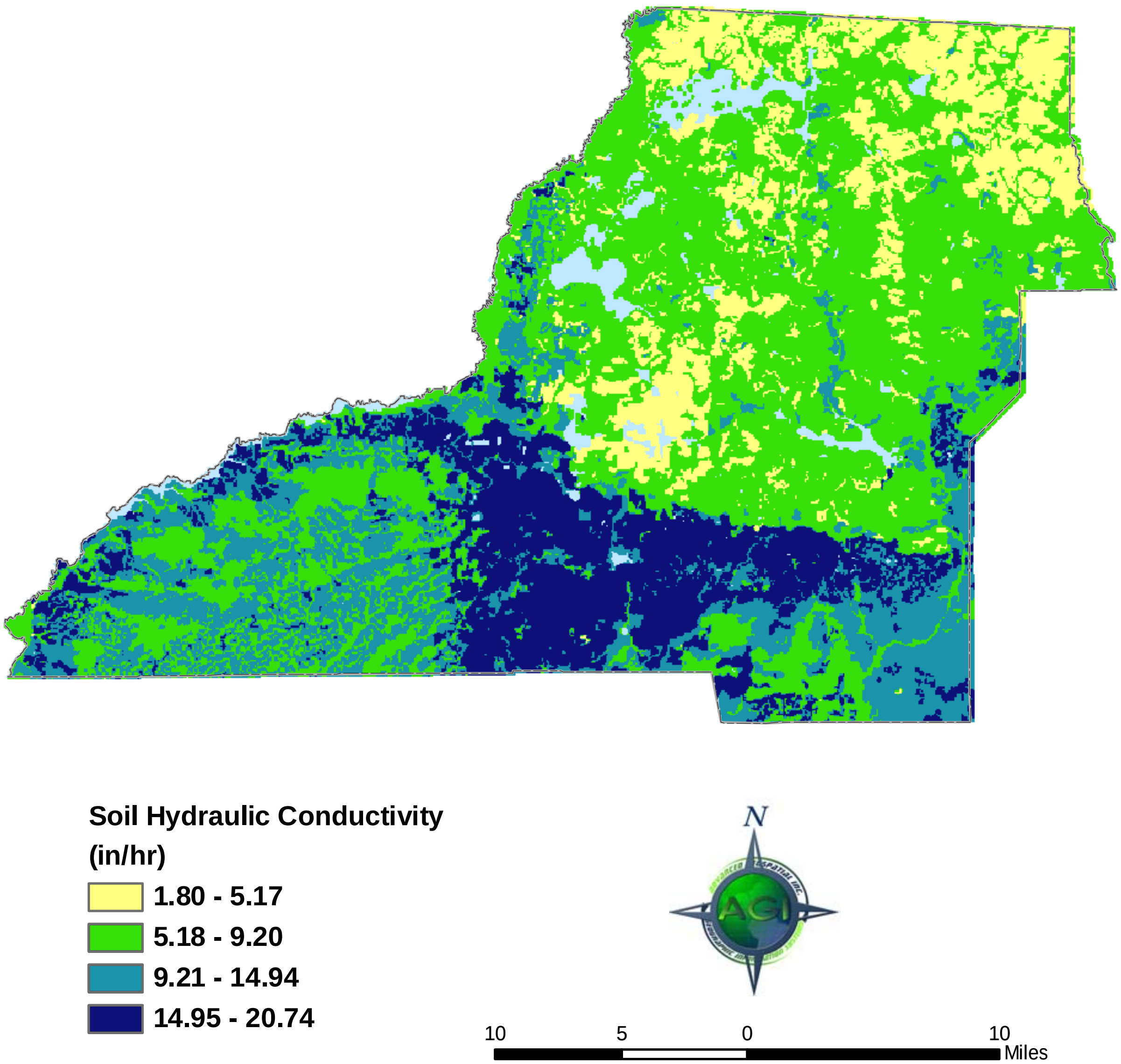

Figure 3. Distribution of soil hydraulic conductivity values across the LAVA study area.

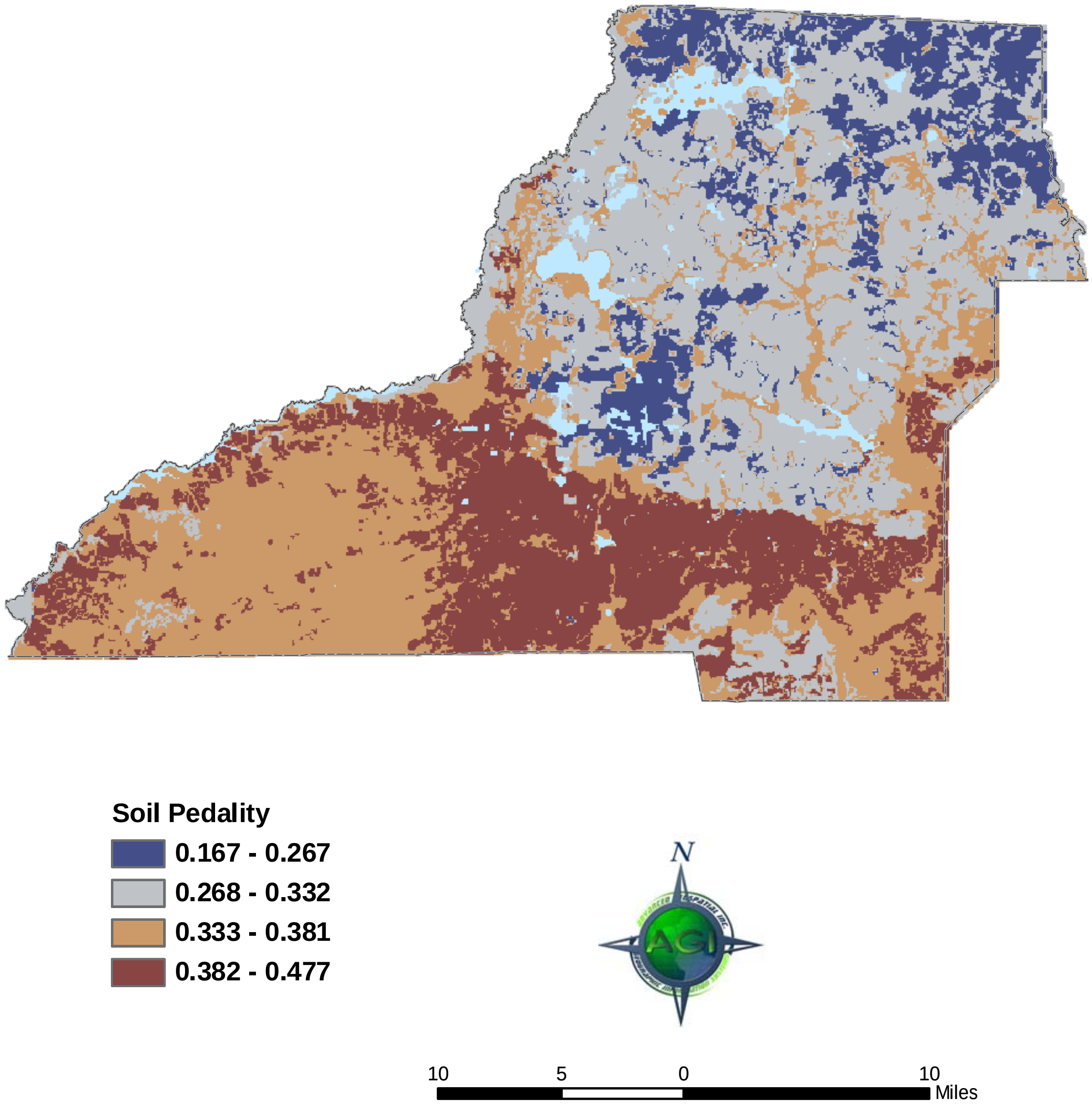

Figure 4. Distribution of soil pedality values (unitless) across the LAVA study area.

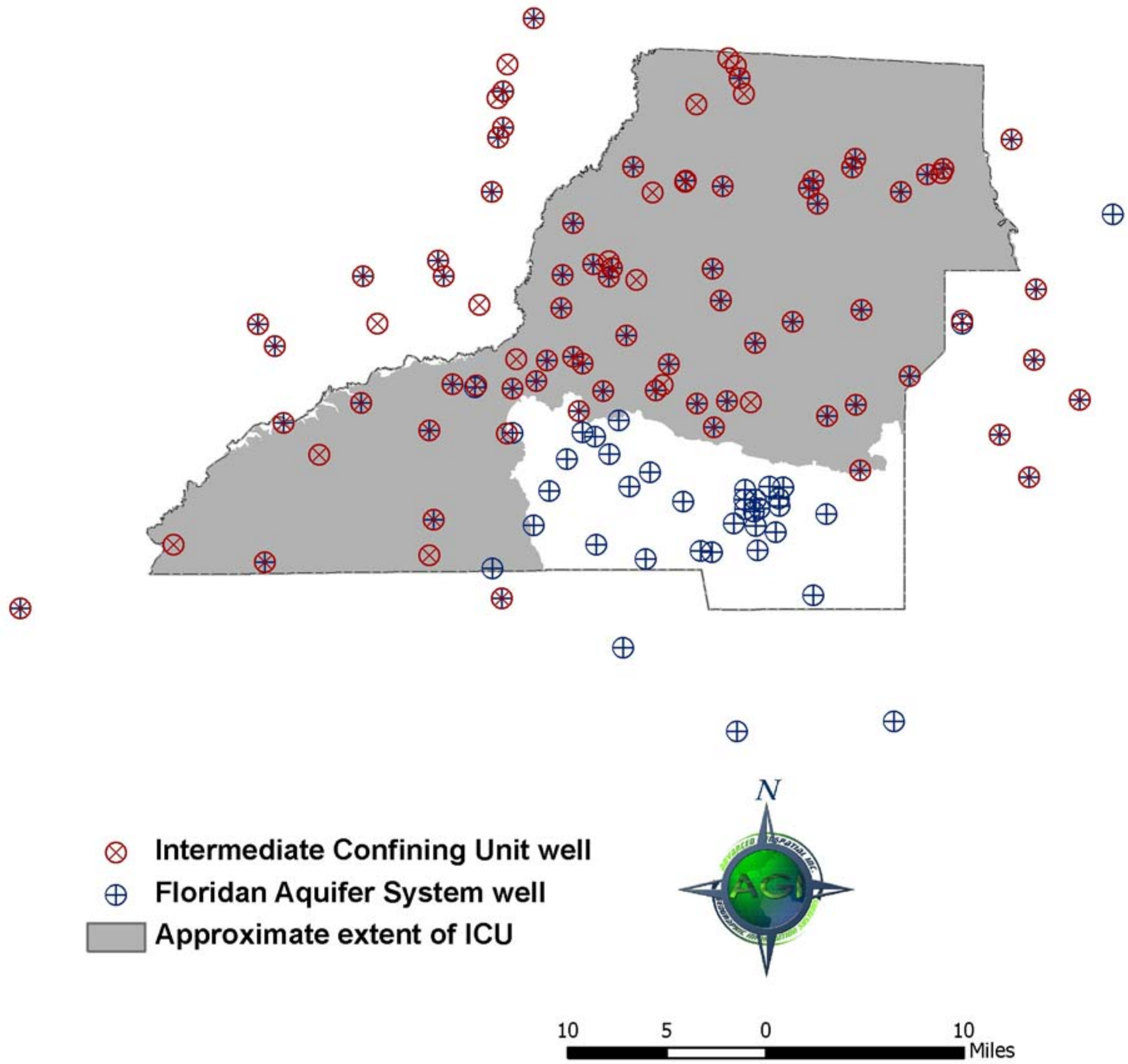

Figure 5. Data points used to develop surfaces representing the FAS and ICU surfaces. Overlapping points represent wells containing information about both the FAS and ICU.

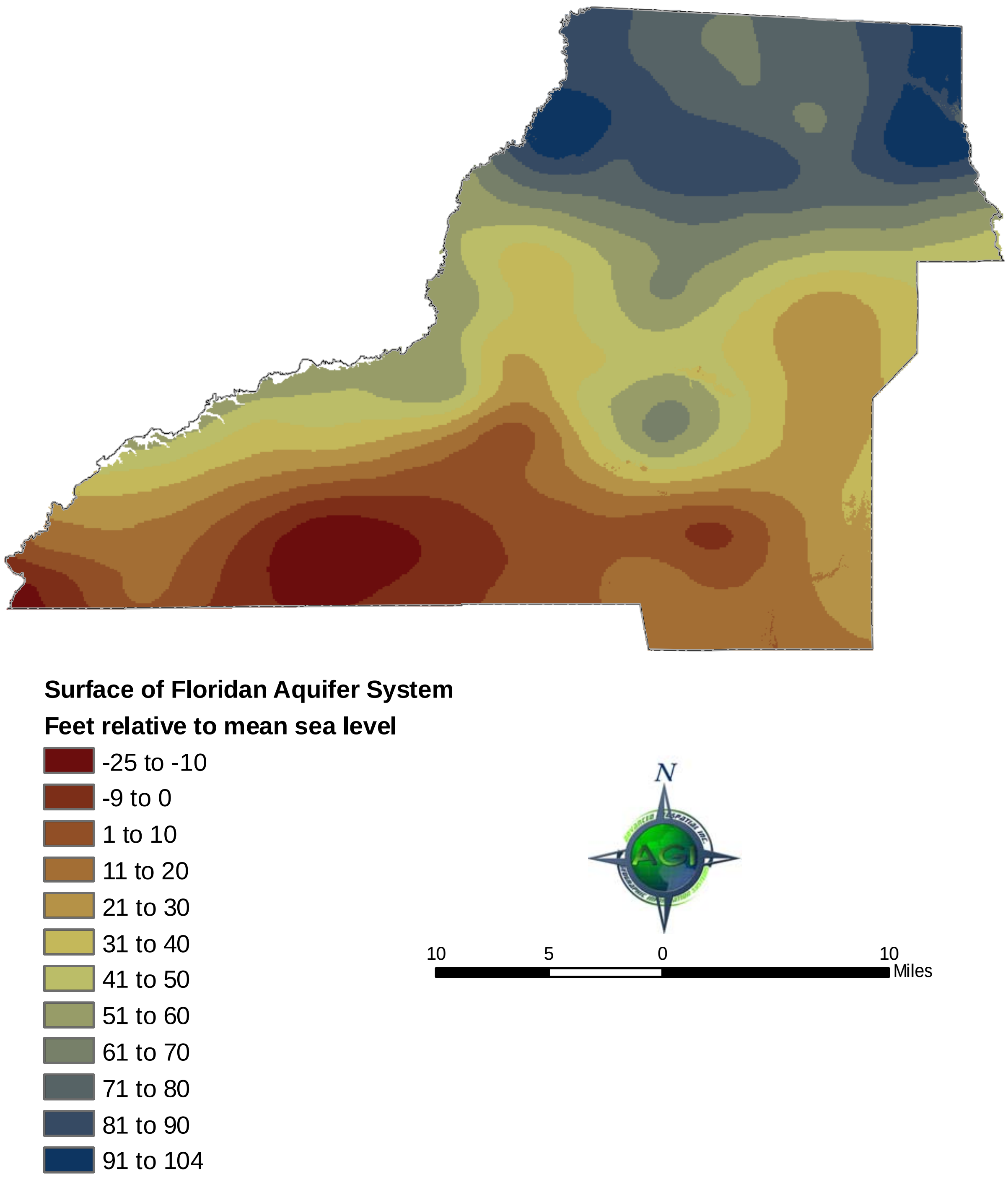

Figure 6. Predicted surface of the FAS in Leon County.

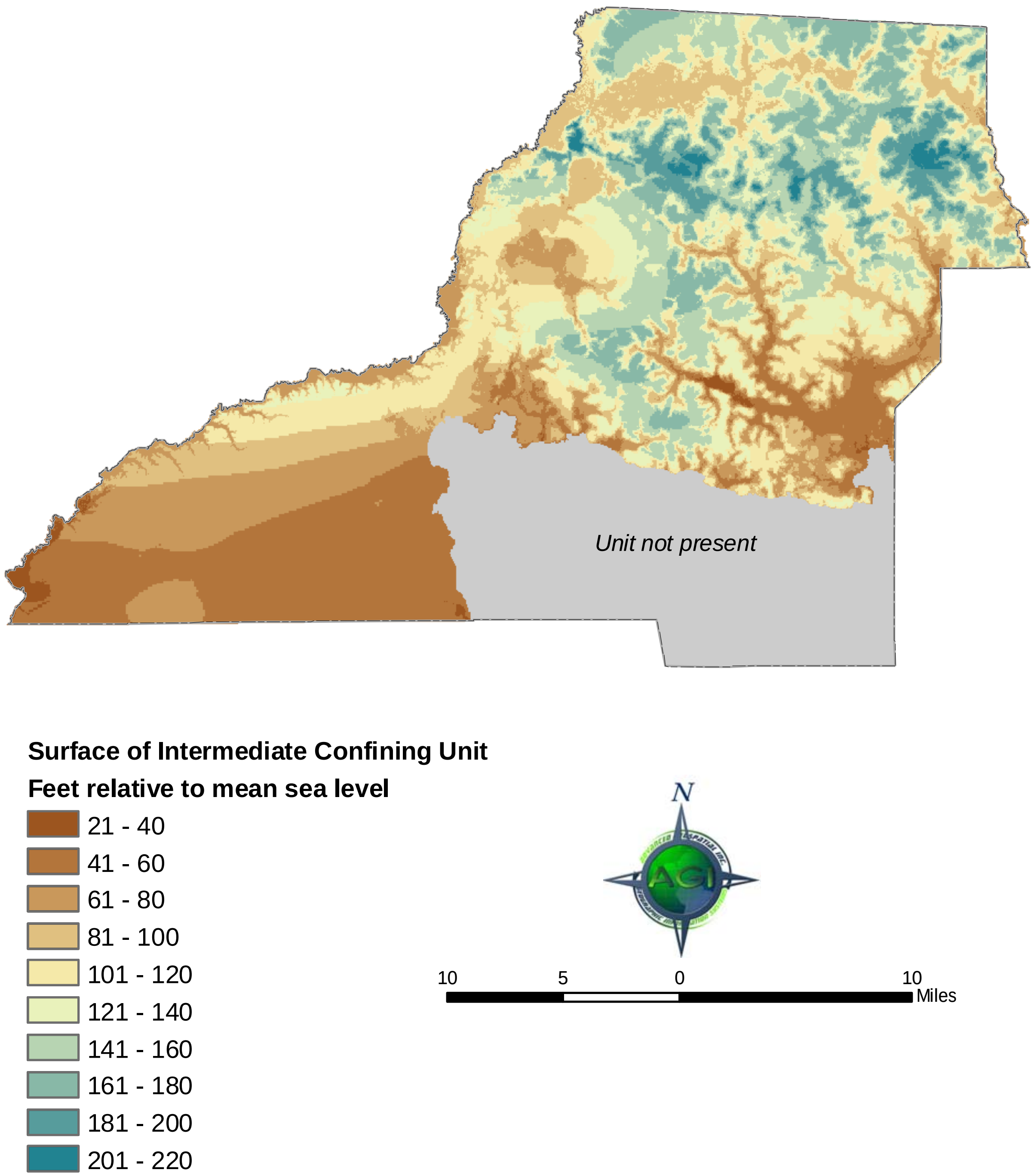

Figure 7. Predicted surface of the ICU in Leon County. Extent of unit based on well borings, gamma logs, and digital elevation model.

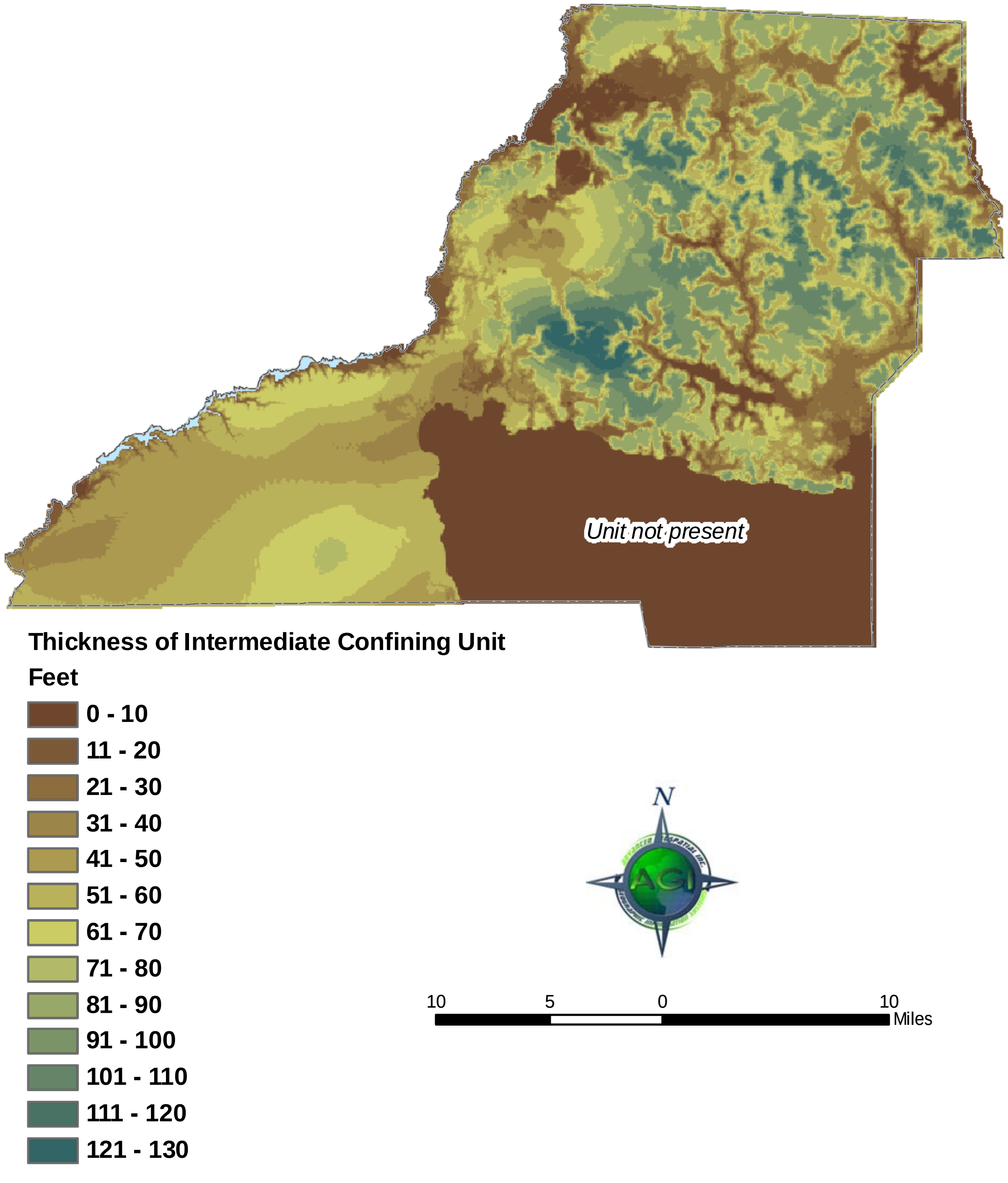

Figure 8. Thickness of the ICU calculated by subtracting predicted surface of ICU (Figure 7) from predicted surface of FAS (Figure 6).

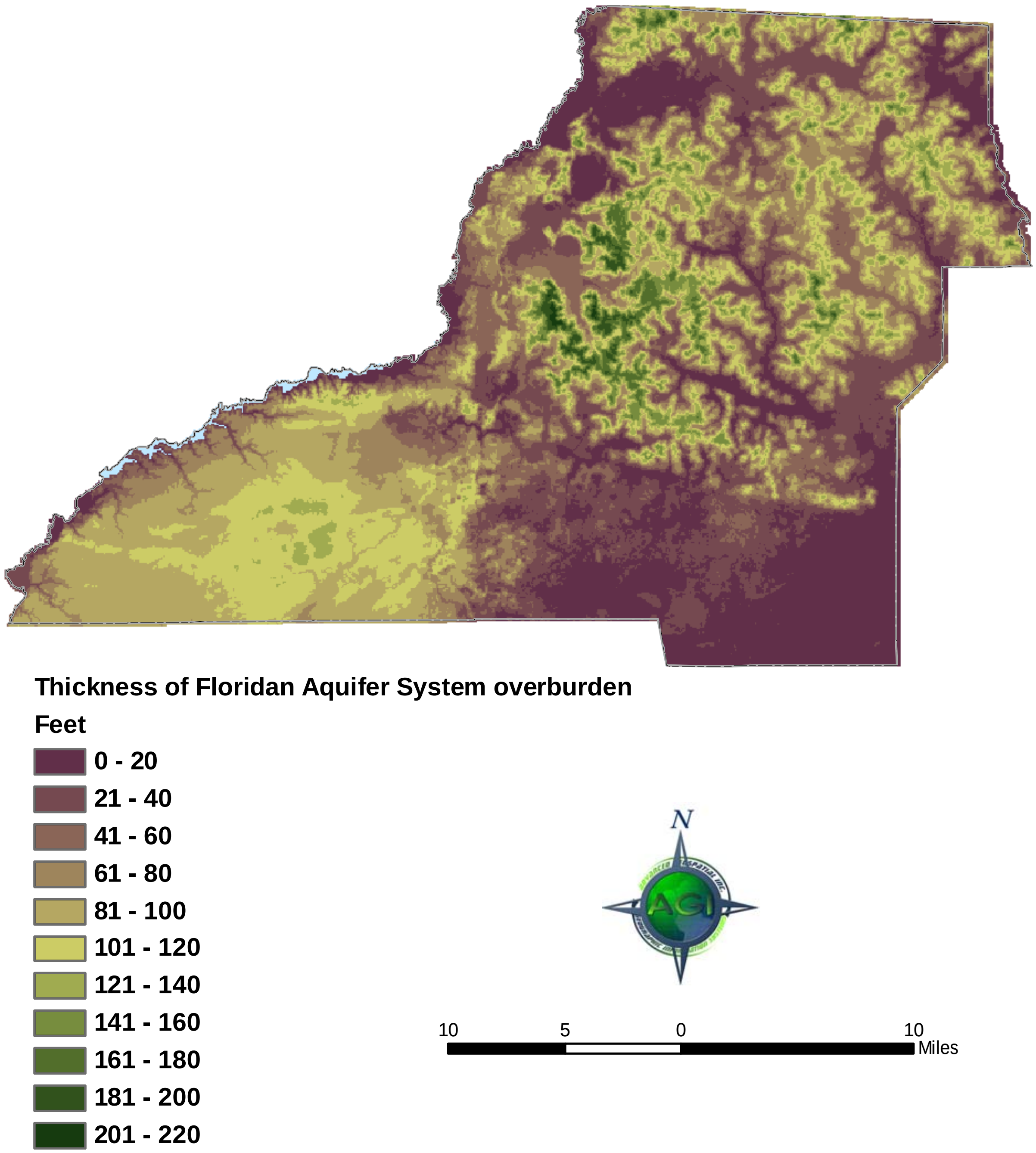

Figure 9. Thickness of sediments overlying the FAS calculated by subtracting digital elevation data (DEM) from predicted surface of FAS (Figure 6).

In lieu of an exhaustive field-karst survey, applying GIS techniques to closed topographic depressions results in a defensible method for estimating karst in the county. Application of analytical processes to digital elevation maps and models to estimate karst has been successfully completed in numerous projects (Arthur et al., 2005, Cichon et al., 2005, Baker et al., 2005, and Denizman, 2003).

Leon County staff supported the LAVA project by completing a majority of the work required for development of the karst evidential theme through the Tallahassee-Leon County Interlocal GIS. The following analyses were applied to the county's DEM to develop an *effective karst features* evidential theme for model input. Several of these analytical processes filter out features which are considered to have little or no impact on the underlying aquifer system, and which may not be true karst features.

DEM reconditioning

The first step in creating the effective karst feature theme was to "burn" the county's Environmentally Sensitive Areas (ESA) watercourse network into the standard 20-ft resolution DEM. This process lowered elevations in the DEM along the watercourse routes to enforce known surface flow paths that might otherwise be obscured. The relatively small vertical relief within many areas of the county and the noise inherent in the LIDAR-derived DEM both contribute to the formation of false pits or sinks within the DEM in the vicinity of watercourses. ArcHydro's DEM Reconditioning tool was used to perform this operation; this tool uses the AGREE method, which is a refinement of traditional DEM reconditioning techniques (Hellweger, 1997).

DEM filling and closed depression identification

Next the reconditioned DEM was filled using ArcInfo Workstation's GRID: FILL function with no z-limit. This process completely filled the surface until no internal sinks remained. In order to identify all closed depressions the filled surface was then subtracted from the unfilled surface, which resulted in a raster layer representing all closed depressions and their depths (Figure 10).

Feature size and depth restriction

LIDAR data reveals highly resolved and detailed information about an area's surface elevation, including the characterization of very small or shallow depressional features. These minor features are real, but may not be karstic in nature. Use of a 20-ft resolution DEM to develop a coverage of closed topographic depressions greatly reduces the number of these minor depressional features by averaging elevation values within each 20-ft grid cell. To further eliminate minor, potentially non-karstic features, a statistical process, "Focal Majority", was applied to the data. This process evaluated the presence or absence of depression values in a floating window three grid cells by three grid cells (60 ft by 60 ft) centered on each cell in the raster. The central grid cell in windows including four or fewer depression values (code = 0) was reclassified as non-depressional and the central cell in windows containing five or more depression values (code = 1) was reclassified as depressional. Subsequent to the "Focal Majority" process, an "Expand" process was applied to ameliorate the effects of edge erosion inherent in the "Focal Majority" process. The net effect of this statistical processing was to eliminate isolated depression features of less than 1,600 ft^2, to eliminate thin isolated linear features, and to eliminate "tails" extending from larger preserved features (Figure 11). A depth restriction was also applied to exclude features with a maximum fill depth of three feet or less.

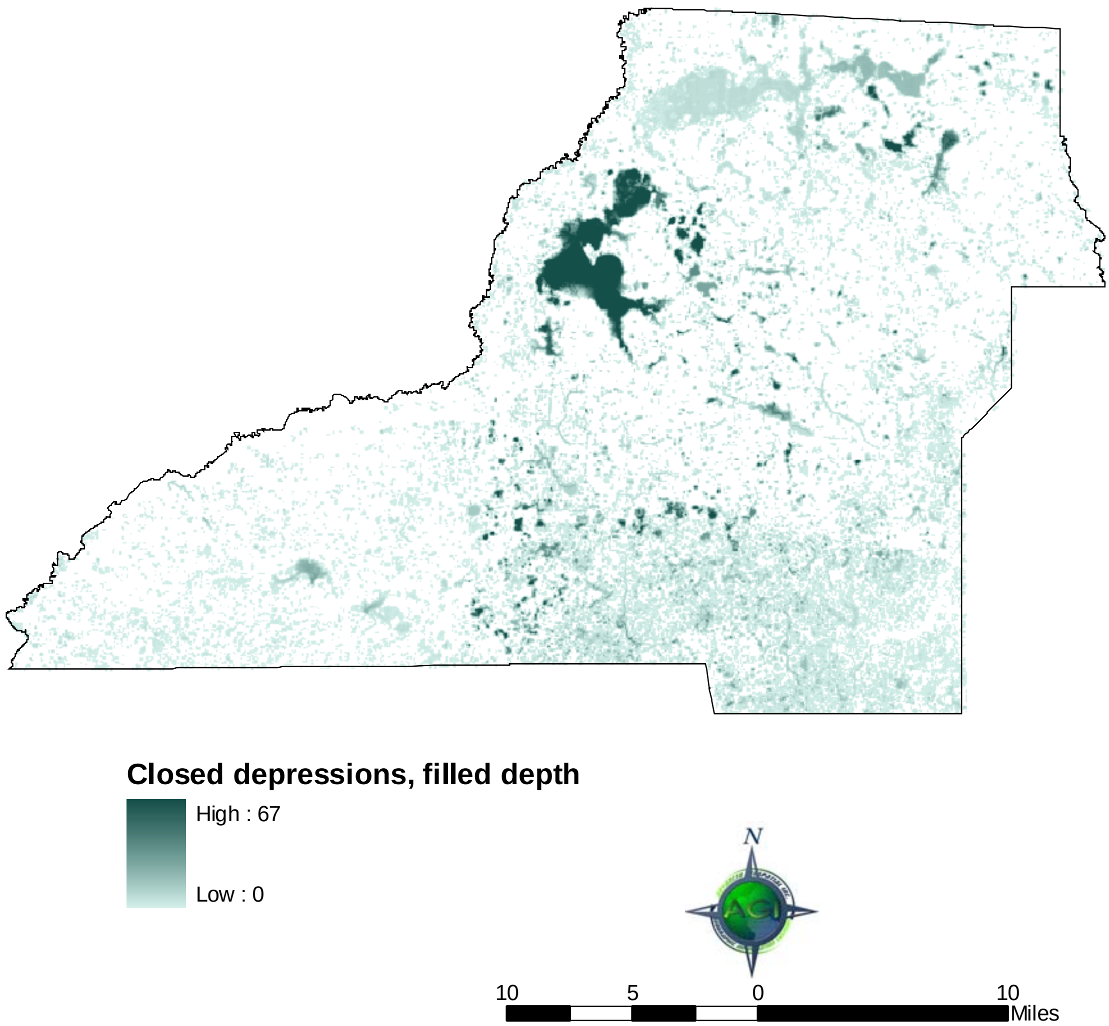

Figure 10. All closed topographic depressions and fill depths extracted from the Leon County 20-foot LIDAR digital elevation model (DEM).

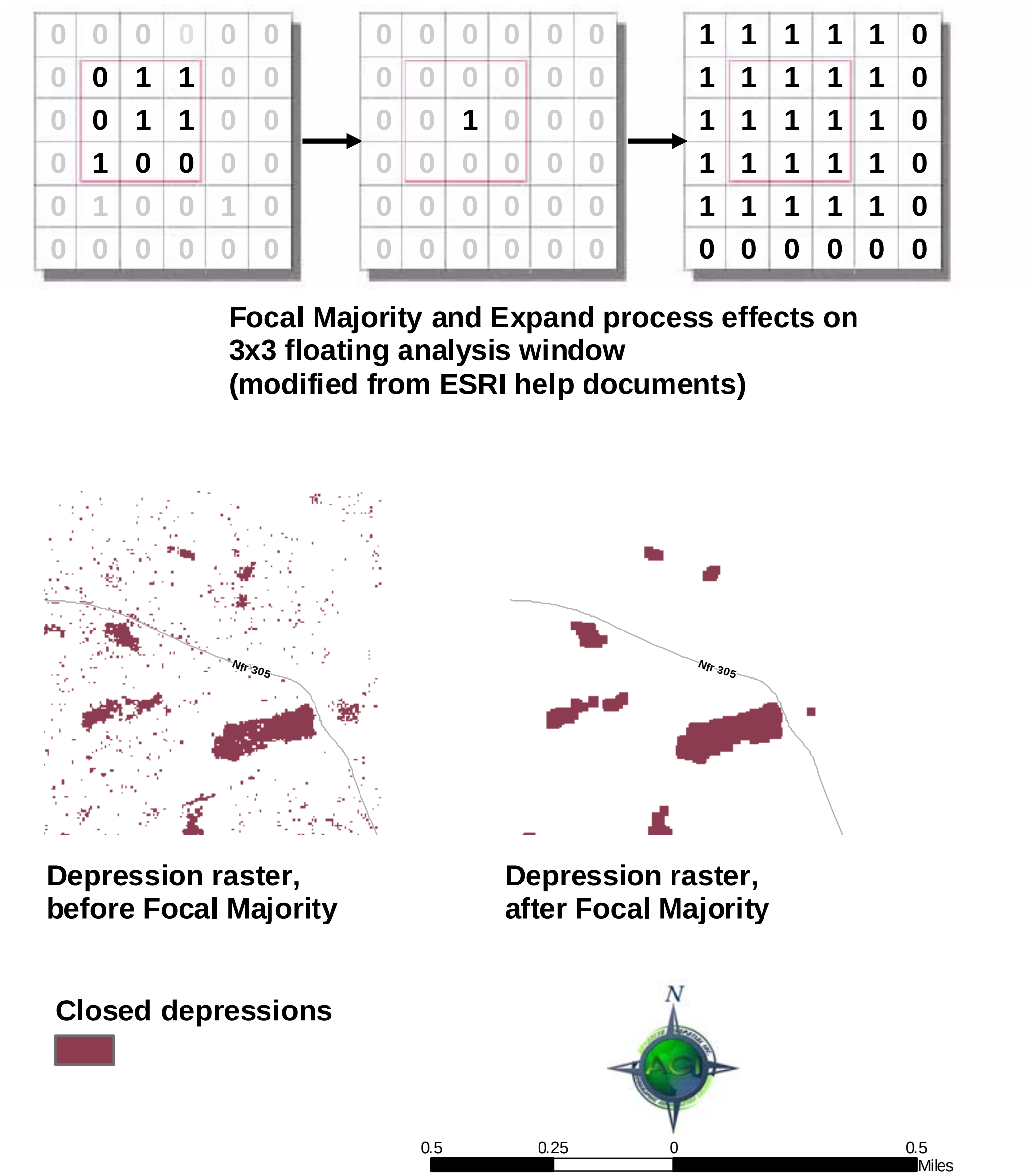

Figure 11. Focal Majority processing.

Nested features

It is not uncommon in karst terrains for karst features to be nested (Figure 12). To avoid removal of nested karst features within larger, possibly karstic, but non-circular depressions, the raster data was reclassified on a five-foot interval, and the depressions produced by these "slices" were converted to vector features. The resulting polygons were merged into a seamless polygon layer that preserves the footprint of both nested and non-nested closed depressions.

Circular index method

Karst features form as the result of the dissolution of carbonate material and subsequent collapse of overlying material, and 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 0.4 was found to be most suitable for this study area. Features with a roundness ratio of less than 0.4 were filtered out. This last process produces the final effective karst evidential theme as displayed in Figure 13.

Sensitivity Analysis/Evidential Theme Generalization

Following sensitivity analysis and selection of evidential themes to be input into the LAVA 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.

Soil Hydraulic Conductivity

Soil hydraulic conductivity ranges from 1.80 to 20.74 inches per hour (in/hr) across the study area. Test modeling indicated that areas underlain by 20.74 to 12.72 in/hr were more associated with the training points, and therefore associated with higher aquifer vulnerability. Conversely, areas underlain by 12.71 to 1.80 in/hr soil hydraulic conductivity 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 14.

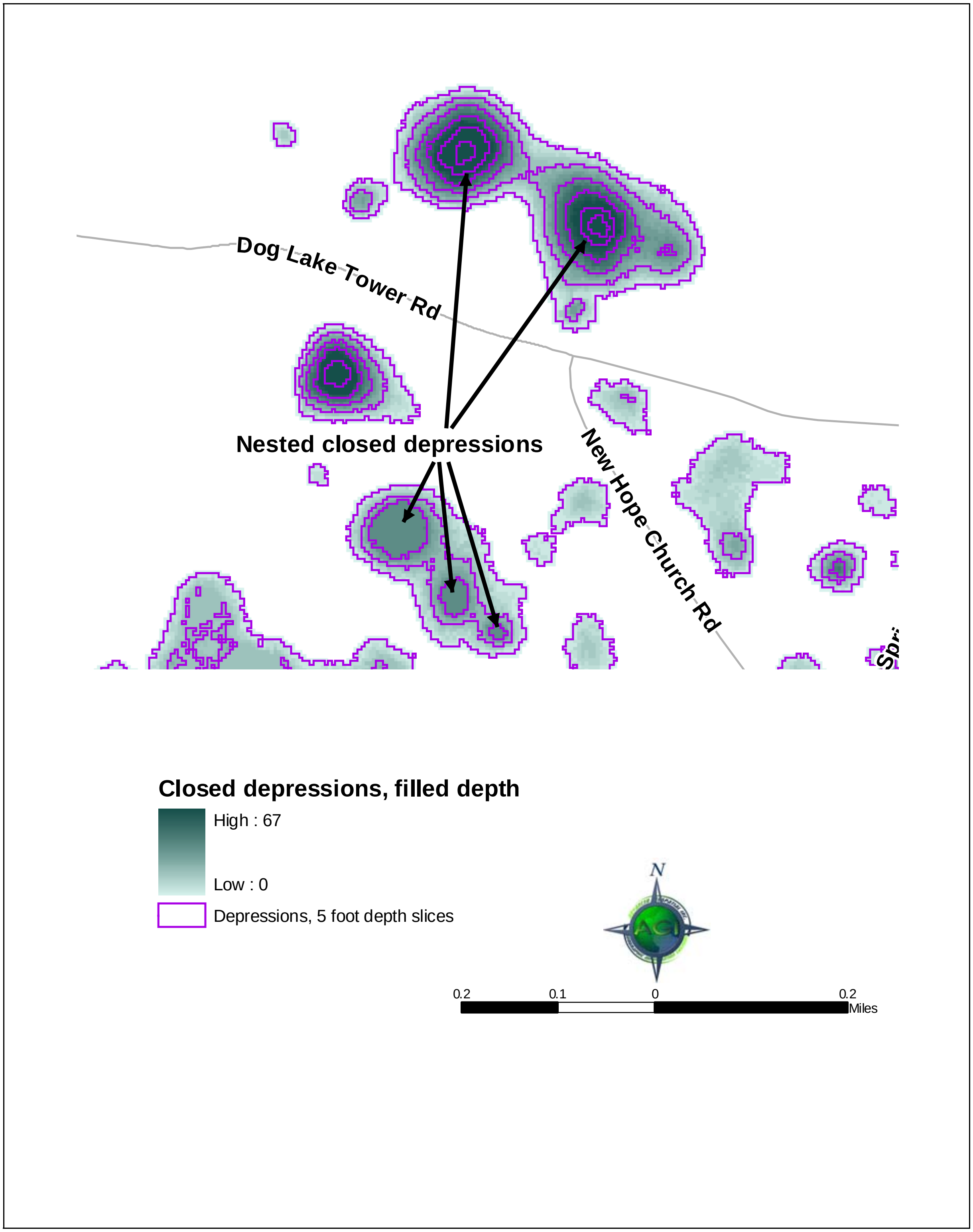

Figure 12. To avoid removal of nested karst features within larger, possibly karstic, but non-circular depressions, raster data was reclassified on a five-foot interval, and depressions produced by these "slices" were converted to vector features. The resulting polygons were merged into a seamless polygon layer that preserves the footprint of both nested and non-nested closed depressions.

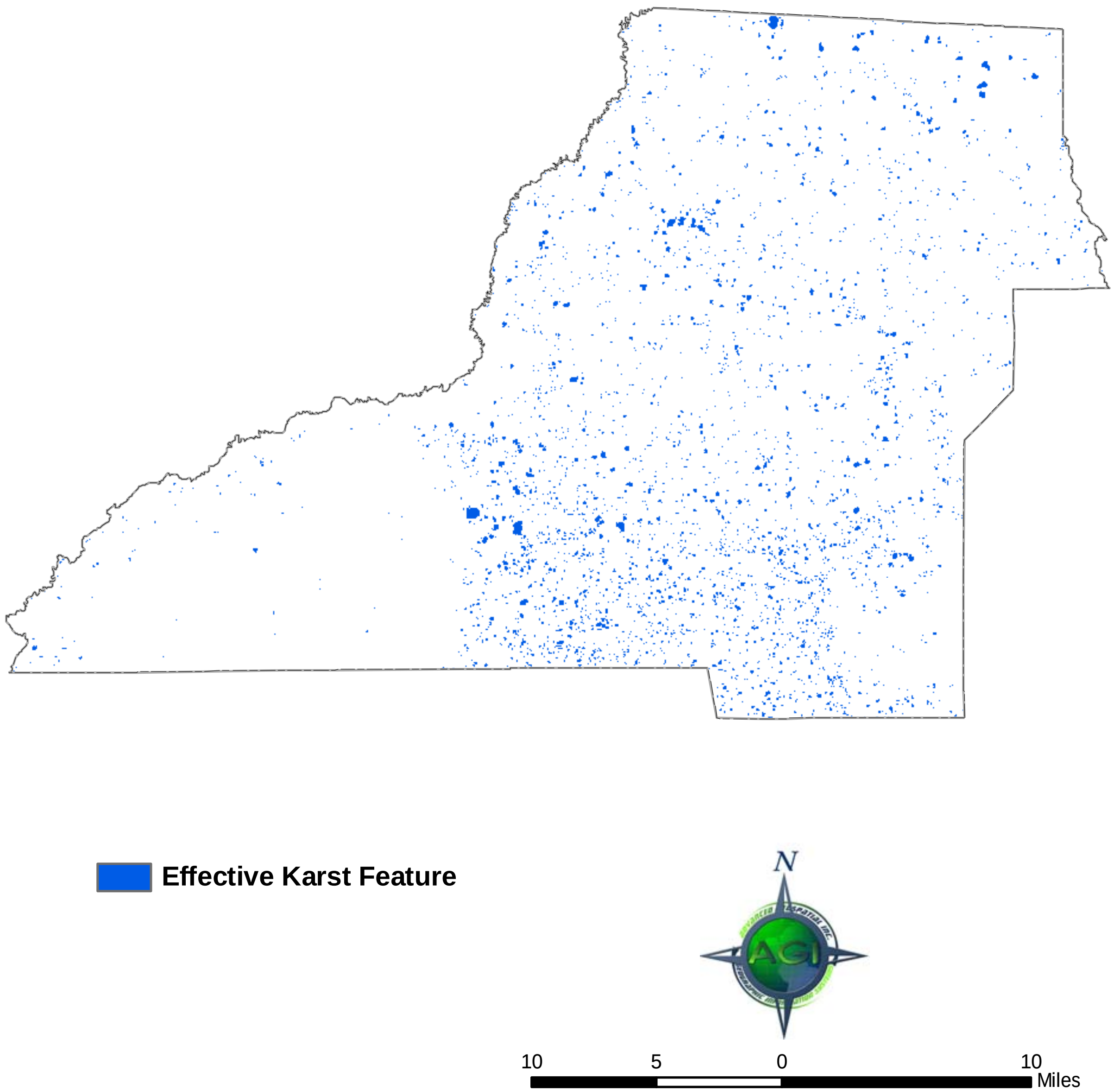

Figure 13. Effective karst features dataset derived from LIDAR-based closed topographic depressions. Filters applied include Focal Majority statistic on a 60-ft by 60-ft window, depth restriction, and circular index method.

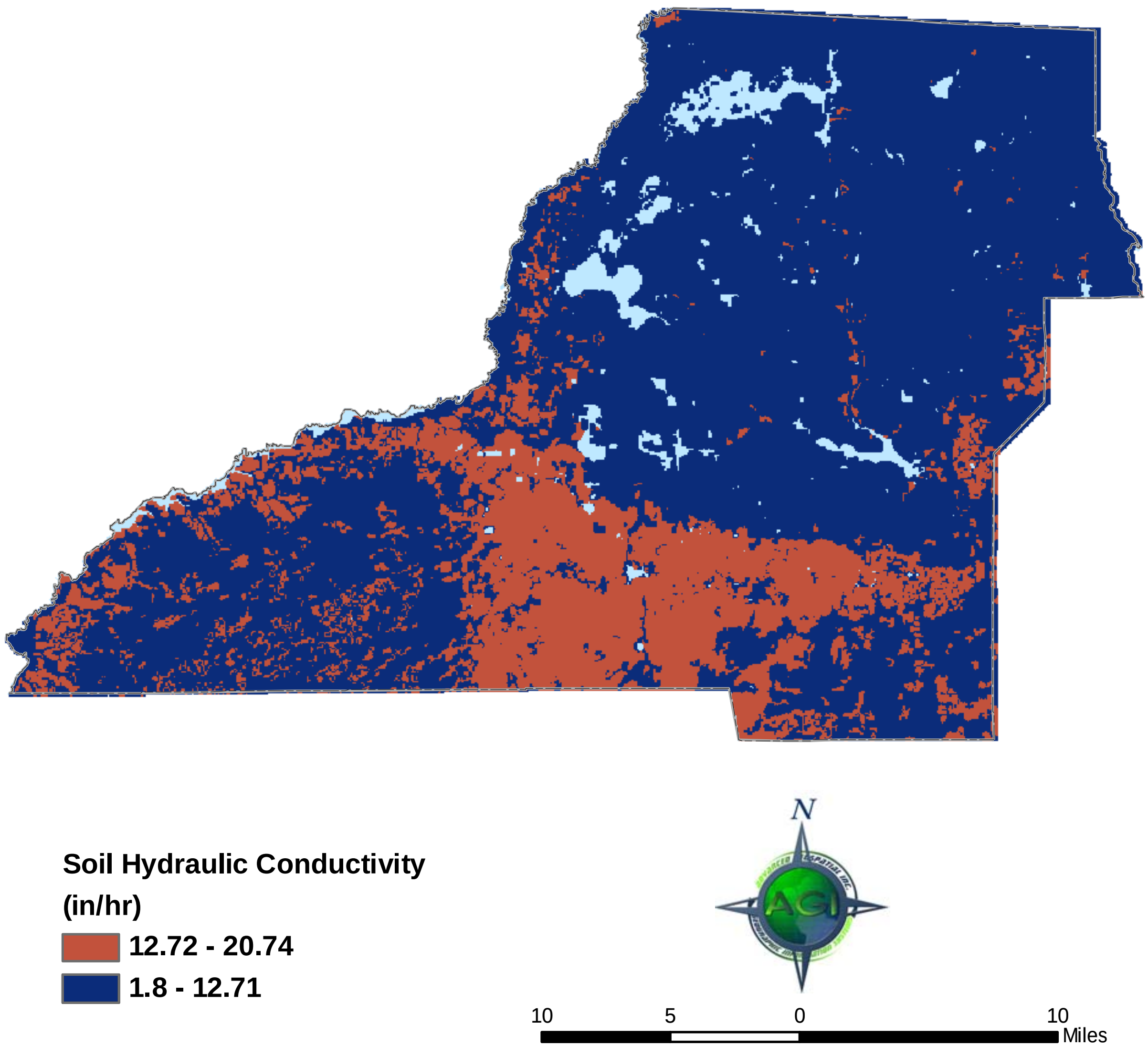

Figure 14. Generalized soil permeability evidential theme; based on calculated weights analysis blue areas share a weaker association with training points, whereas red areas share a stronger association with training points, or simply, higher aquifer vulnerability.

Intermediate Confining Unit / Overburden on the FAS Thickness Themes

Sensitivity analysis completed on both the ICU and the overburden on the FAS revealed both inputs share a very similar association with the training points (contrast value). However, the confidence value associated with the weights calculated for the thickness of overburden layer indicates that this layer is a stronger predictor of vulnerability than ICU theme (more on confidence in *Discussion*). As a result, the thickness of overburden on the FAS was chosen as the better controller of aquifer vulnerability because the confidence value is higher. The similarity in weights calculated is expected because the overburden sediments primarily comprise ICU stratigraphic units in much of the study area.

Overburden on the FAS ranges from absent to 215 feet thick across the study area. The analysis revealed that areas underlain by less than 49 feet of overburden thickness were more associated with the training points, and therefore associated with higher aquifer vulnerability. Areas underlain by 48 feet or greater of overburden thickness 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 15.

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 20-ft zones to allow for a proximity analysis (Figure 16). The analysis indicated that areas within 1,120 feet of a karst feature were more associated with the training points, and therefore with higher aquifer vulnerability. Conversely, areas greater than 1,120 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 17.

Response Theme

Using evidential themes representing effective karst, overburden on FAS, and soil hydraulic conductivity, weights of evidence was applied to generate a response theme (Figure 18), which is a GIS raster consisting of *posterior probability* values ranging from 0.00219 to 0.05295 across the study area. These probability values describe the relative probability 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 0.01030. 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 14 of the 18 training points are above the prior probability, indicating that this model is a strong predictor of training point locations.

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 19). 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.

As described in *Introduction*, the LAVA 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 LAVA results, along with addition of an extra vulnerability class, to define the relative vulnerability classes as displayed in Figure 18.

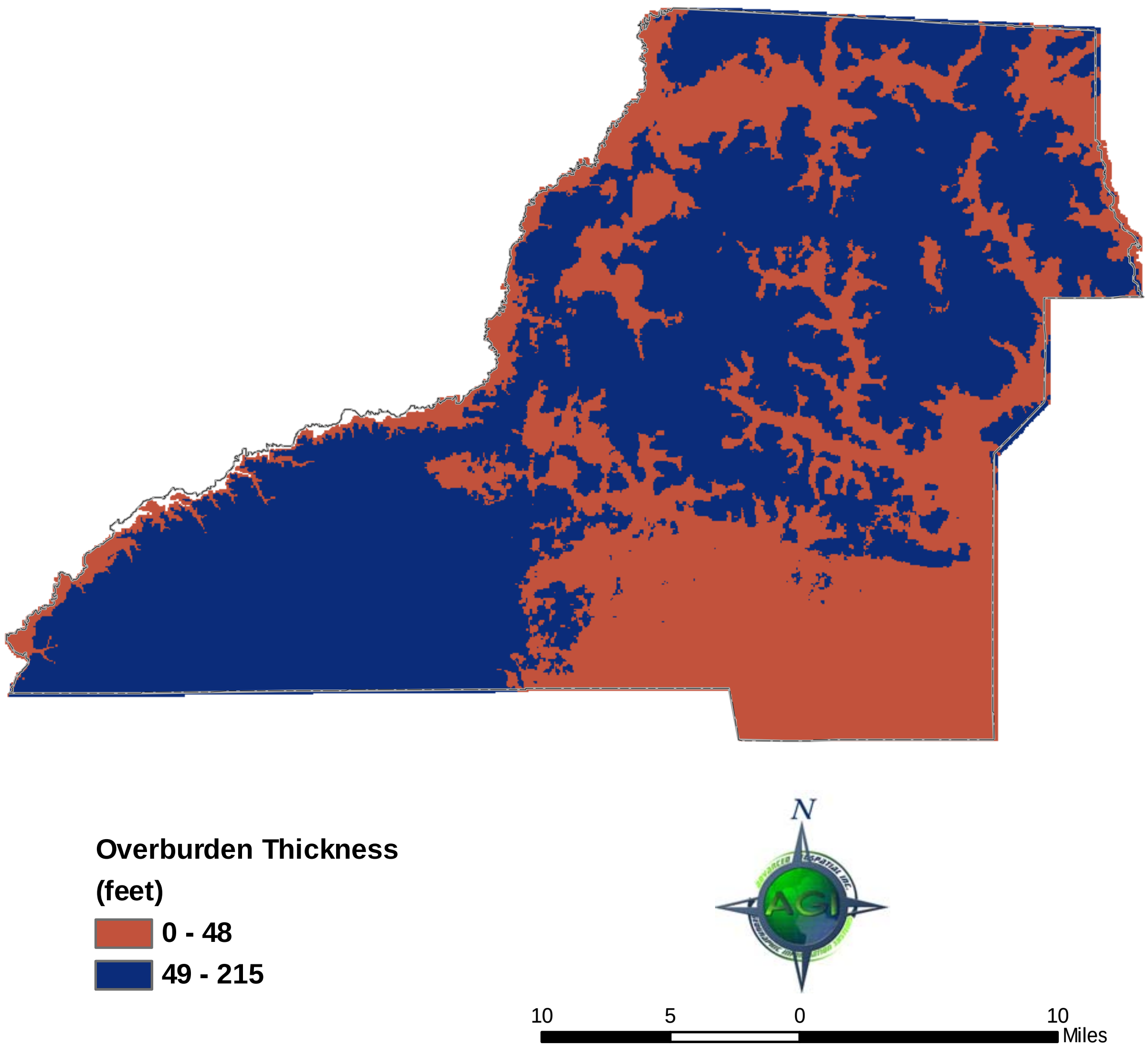

Figure 15. Generalized ICU evidential theme; based on calculated weights analysis blue areas share a weaker association with training points whereas red areas share a stronger association with training points, or simply, higher aquifer vulnerability.

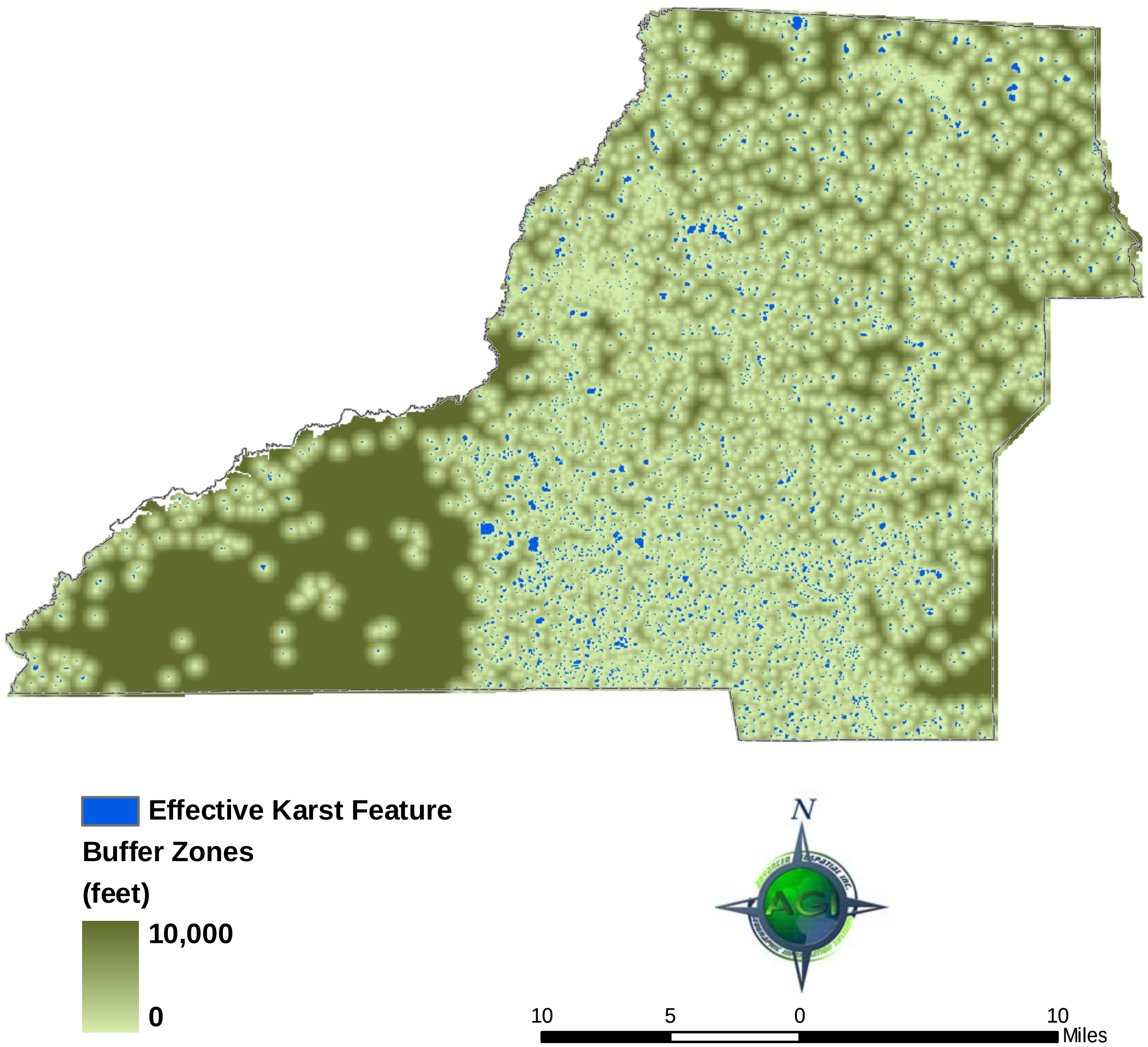

Figure 16. Buffered effective karst features. This method of representing karst in the model allows for a proximity analysis – areas closer to a feature are expected to be more vulnerable.

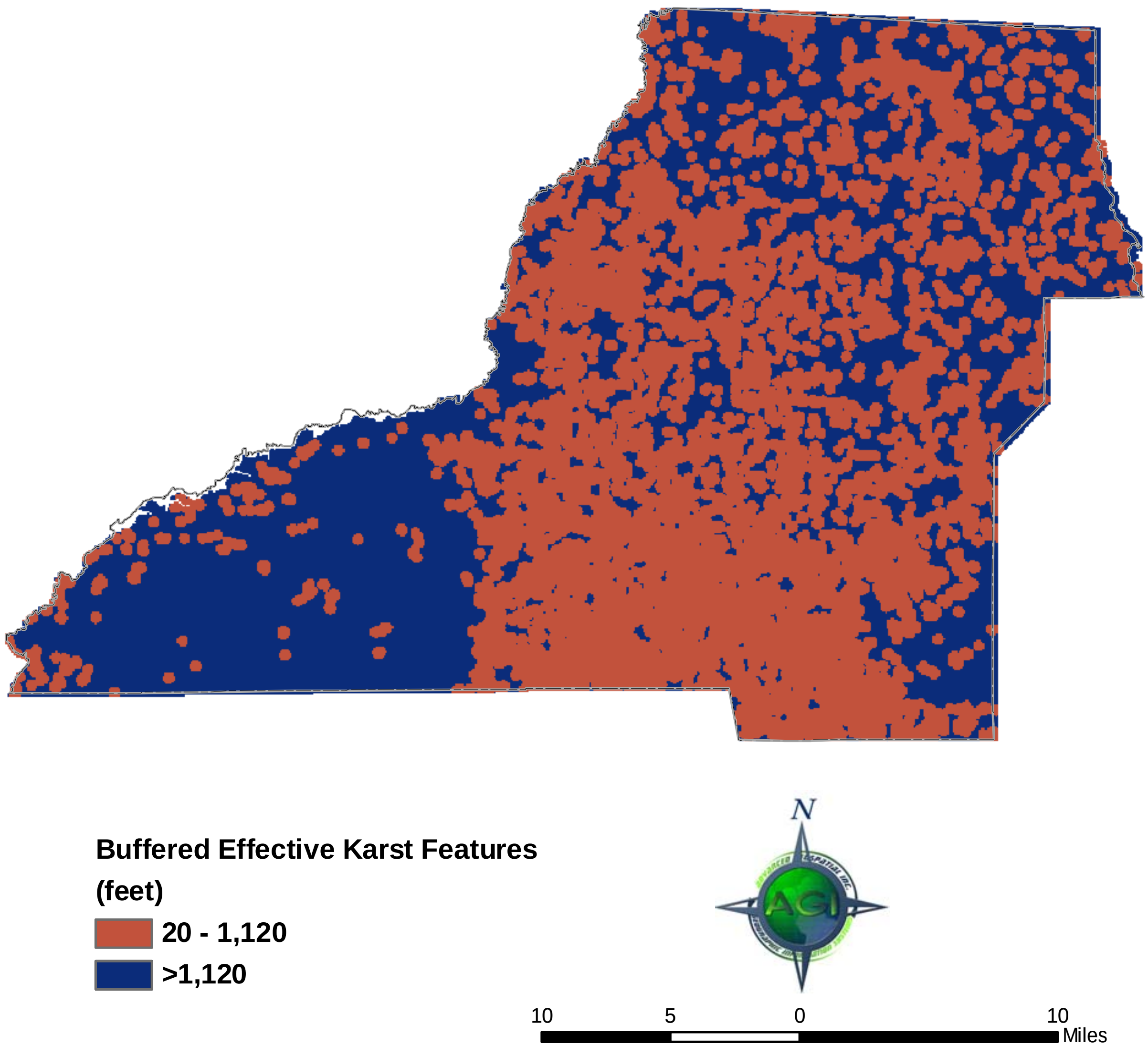

Figure 17. Generalized effective karst feature evidential theme; based on calculated weights analysis blue areas share a weaker association with training points whereas red areas share a stronger association with training points, or simply, higher aquifer vulnerability.

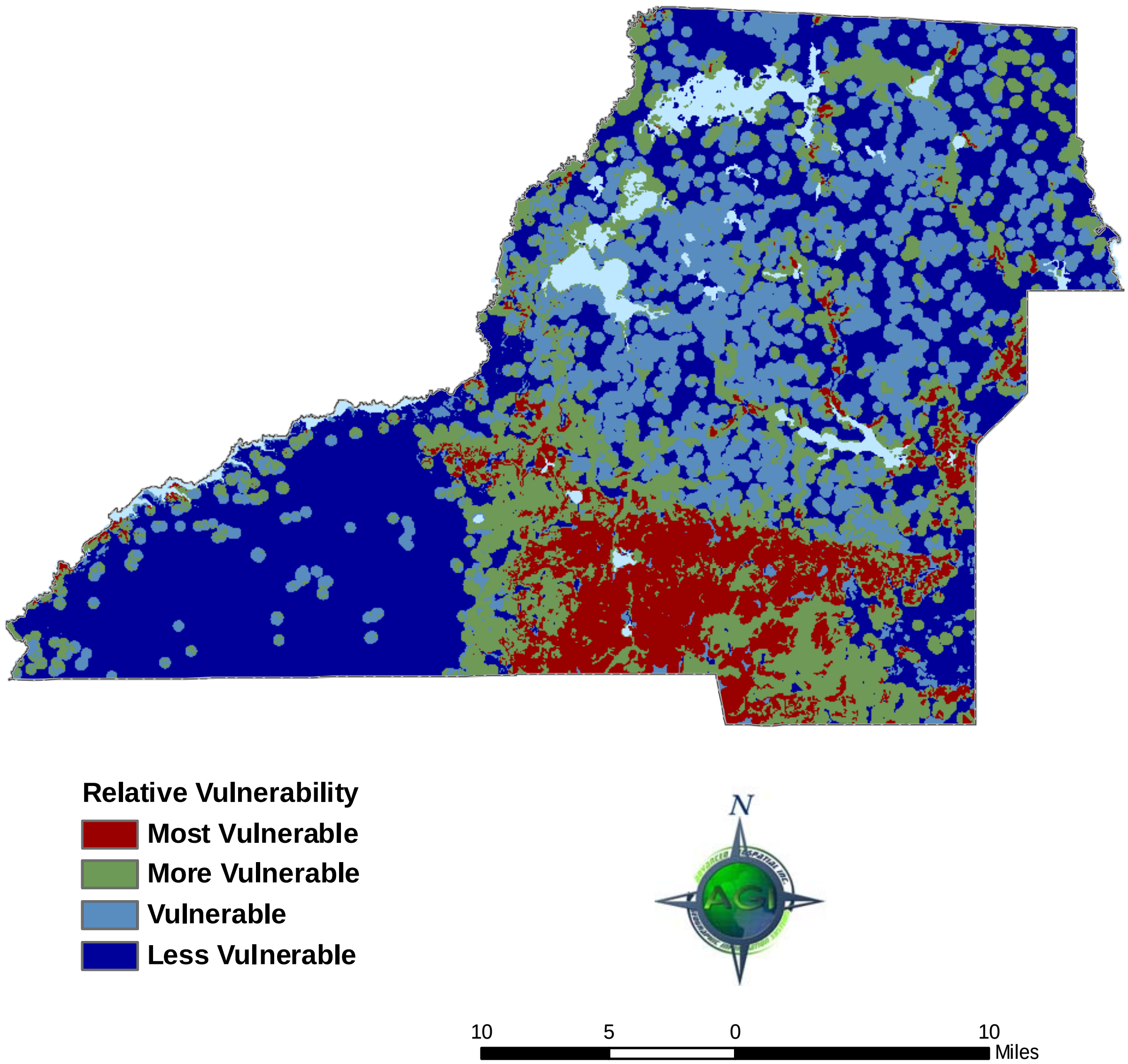

Figure 18. Relative vulnerability map for the Leon County Aquifer Vulnerability Assessment project. Classes of vulnerability are based on calculated probabilities of a unit area containing a training point (i.e., a monitor well with water quality sample results indicative of vulnerability).

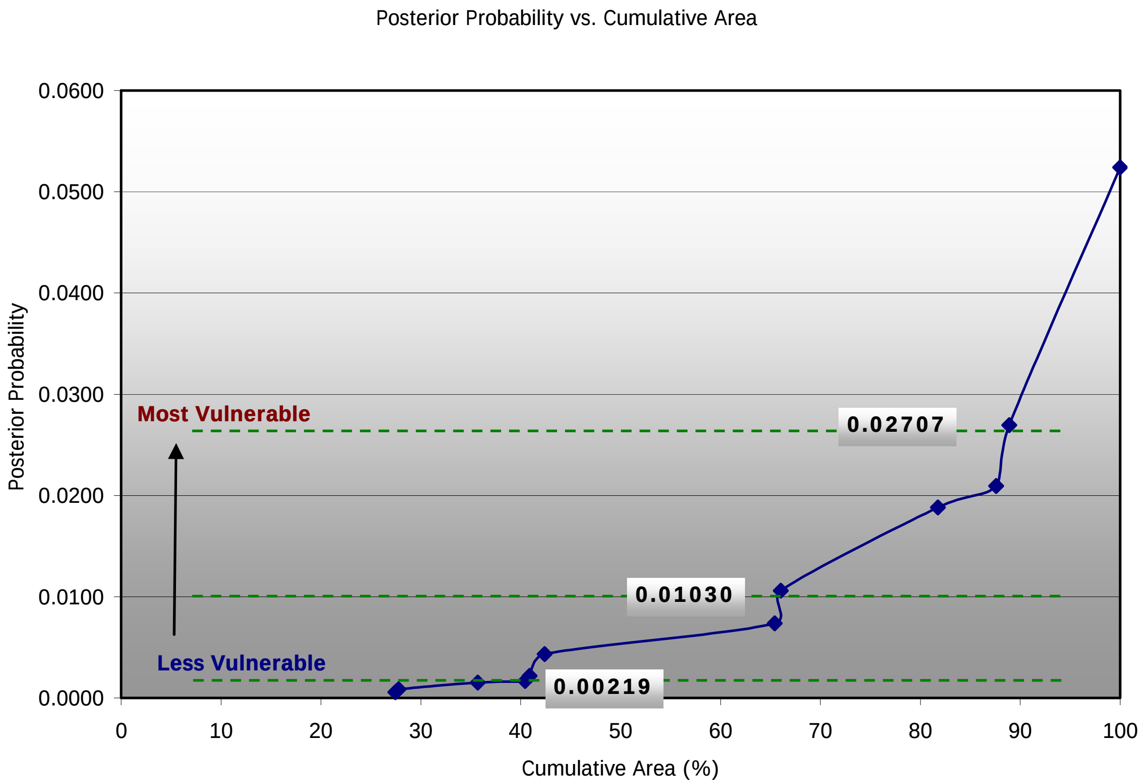

Figure 19. Vulnerability class breaks are defined by selecting where a significant increase in probability and area are observed.

As expected, the LAVA model response theme indicates that the areas of highest vulnerability are associated with areas where the overburden on the FAS is thin to absent, of dense effective karst-feature distribution, and of higher soil hydraulic conductivity. Conversely, areas of lowest vulnerability are determined by thicker overburden sediments, sparse karst-feature distribution, and lower soil hydraulic conductivity values.

Interpretation of Results in Context of FAVA

Results of the LAVA project have allowed delineation of new and unique zones of relative vulnerability for the FAS in Leon County, based on the county-specific model boundary used, incorporation of LIDAR-derived DEM, use of numerous well points for aquifer confinement characterization, incorporation of most recent soils data, 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 (Arthur et al., 2005) for the FAS indicate that the Leon County study area occurs in primarily a "more vulnerable" zone relative to other areas in Florida (Figure 20); as a result the new LAVA model output should be interpreted in the context of this major regional project. The new zones delineated in the LAVA project are unique to the LAVA study area, and reveal more detailed information regarding aquifer vulnerability within the regional "more vulnerable", and "vulnerable" zones identified in the FAVA project.

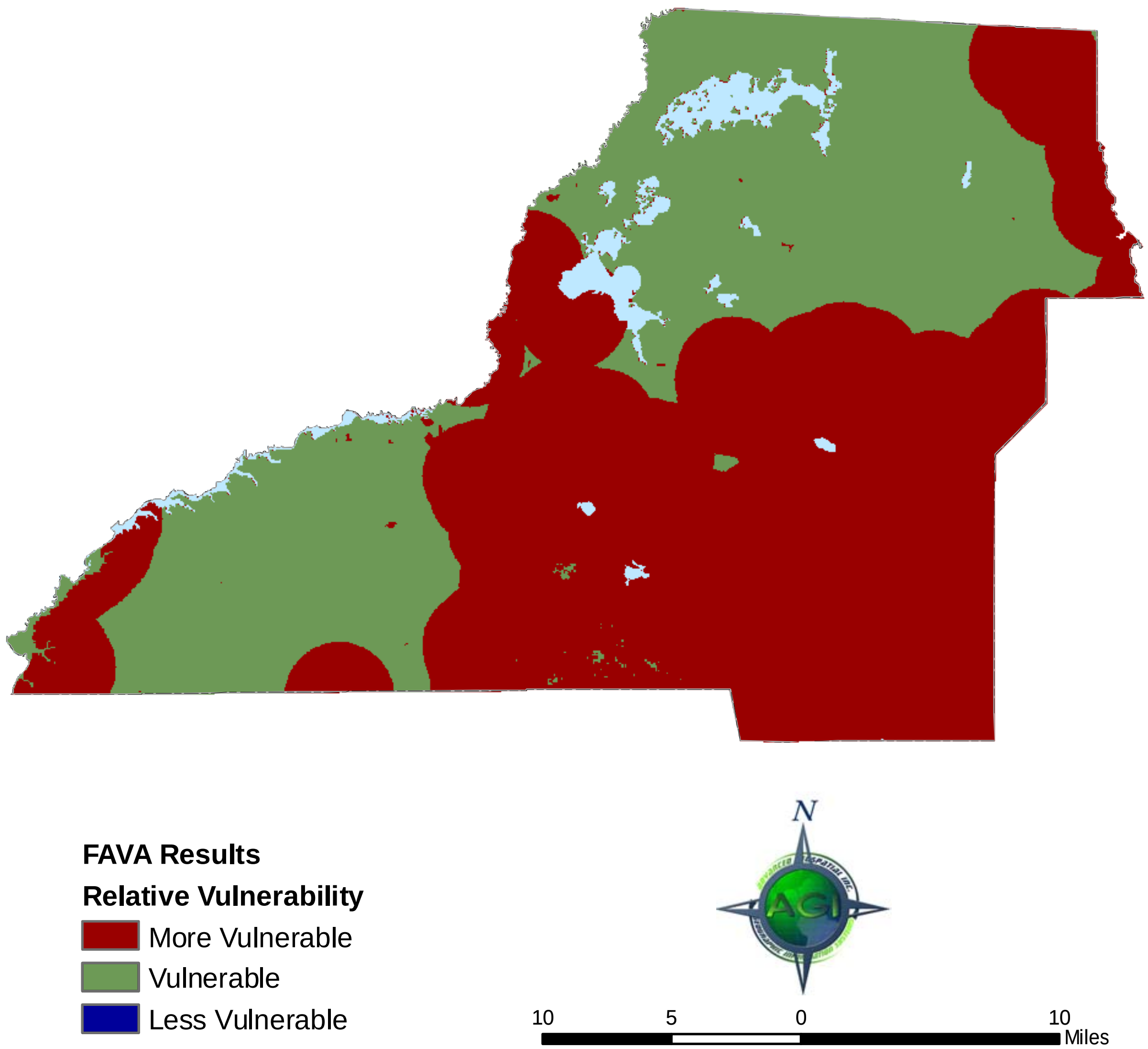

Figure 20. Results of the Florida Aquifer Vulnerability Assessment project (Arthur et al., 2005) for the FAS in Leon County. The LAVA model relative vulnerability zones, while based on more refined data than the FAVA project, still occur within the context of this regional model.

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 LAVA 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 values below 1.00 may indicate conditional dependence in one or more of the evidential themes. Conditional independence values within the range of 1.00 ± 0.15 (Bonham-Carter, 1994) generally indicate limited to no dependence among evidential themes. Values significantly outside this range can inflate posterior probabilities resulting in unreliable response themes. 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. Conditional independence was calculated at 0.82 for the LAVA project which is not significantly outside the range discussed above and indicates minimal dependence between evidential themes.

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 1.9649 corresponds to greater than 97.5% test value – or level of significance – and was the minimum calculated confidence level for LAVA 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 LAVA response theme is displayed in Figure 21. 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. The importance of this map is discussed further in *Model Limitations and Implementation* below.

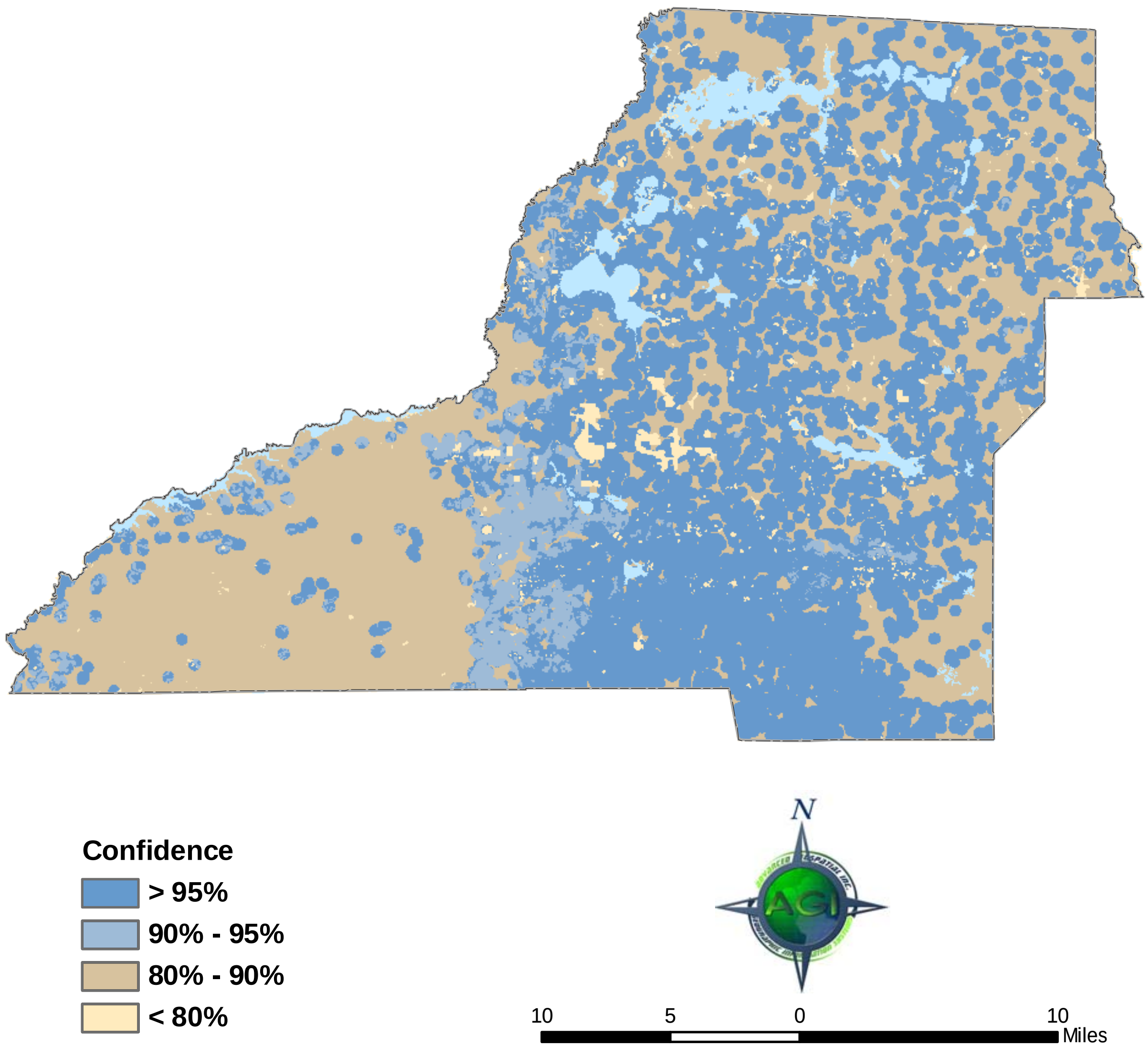

Figure 21. Confidence map for the LAVA model calculated by dividing the posterior probability values by the total uncertainty for each class to give an estimate of how well specific areas of the model are predicted.

Weights Calculations

Table 3 displays evidential themes used in the LAVA model, weights calculated for each theme, along with contrast and confidence values. Positive weights indicate areas where training points are likely to occur, while negative weights indicate areas where training points are 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.

Evidential Theme	W1	W2	Contrast	Confidence
Effective Karst Features	0.4994	-2.0390	2.5385	2.4642
Soil Hydraulic Conductivity	0.6979	-0.3692	1.0670	2.1808
Overburden on FAS Thickness	0.4835	-0.4715	0.9550	1.9649

Based on contrast values, the effective karst features theme had the strongest association with the training points and is the primary determinant in predicting areas of vulnerability in the LAVA model. Because the negative weight (W2) value for the effective karst theme is stronger (has greater absolute value) than the positive weight (W1), this evidential theme is a better predictor of where training points are *less* likely to occur. In contrast, soil hydraulic conductivity and overburden on FAS are better predictors of where training points are *more* likely to occur, as W1 values are stronger than W2.

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. All but four training points (14 of 18) were predicted in zones of posterior probability greater than the prior probability. Further strengthening the results were the evaluation of a minimum confidence threshold for evidential themes, evaluation of conditional independence within an acceptable range, and generation of a confidence map of the response theme, which is discussed further in *Model Limitations and Implementation*. In addition to these exercises, generation of a test response theme based on a subset of training points was completed to further strengthen the validity of the results.

Subset Response Theme

Perhaps the most rigorous validation exercise used to evaluate quality of model-generated output is to compare predicted model values with an independent dataset not used in the model. Because no suitable independent, secondary training set was available of the Leon County area (see *Training Point Theme*), a subset validation exercise was completed, which can be equally rigorous. This method involves use of the primary training dataset to develop two subsets: one to generate a test response theme, and one to validate output from this test response theme.

From the LAVA training point theme, a subset of 75% (14 wells) were randomly selected and used to develop a test response theme using the same three evidential themes in the LAVA model output. The remaining 25% (four wells) of the training points were used as the validation dataset for this test response theme. Comparison of the validation training point subset to the test response theme revealed that three of the four validation points occurred in areas of the test response theme with probability values higher than the prior probability (Figure 22; i.e., areas predicted to have a greater than chance probability of containing a training point). This adds strength to the conclusion that the LAVA model response theme is a reasonable estimator of vulnerability.

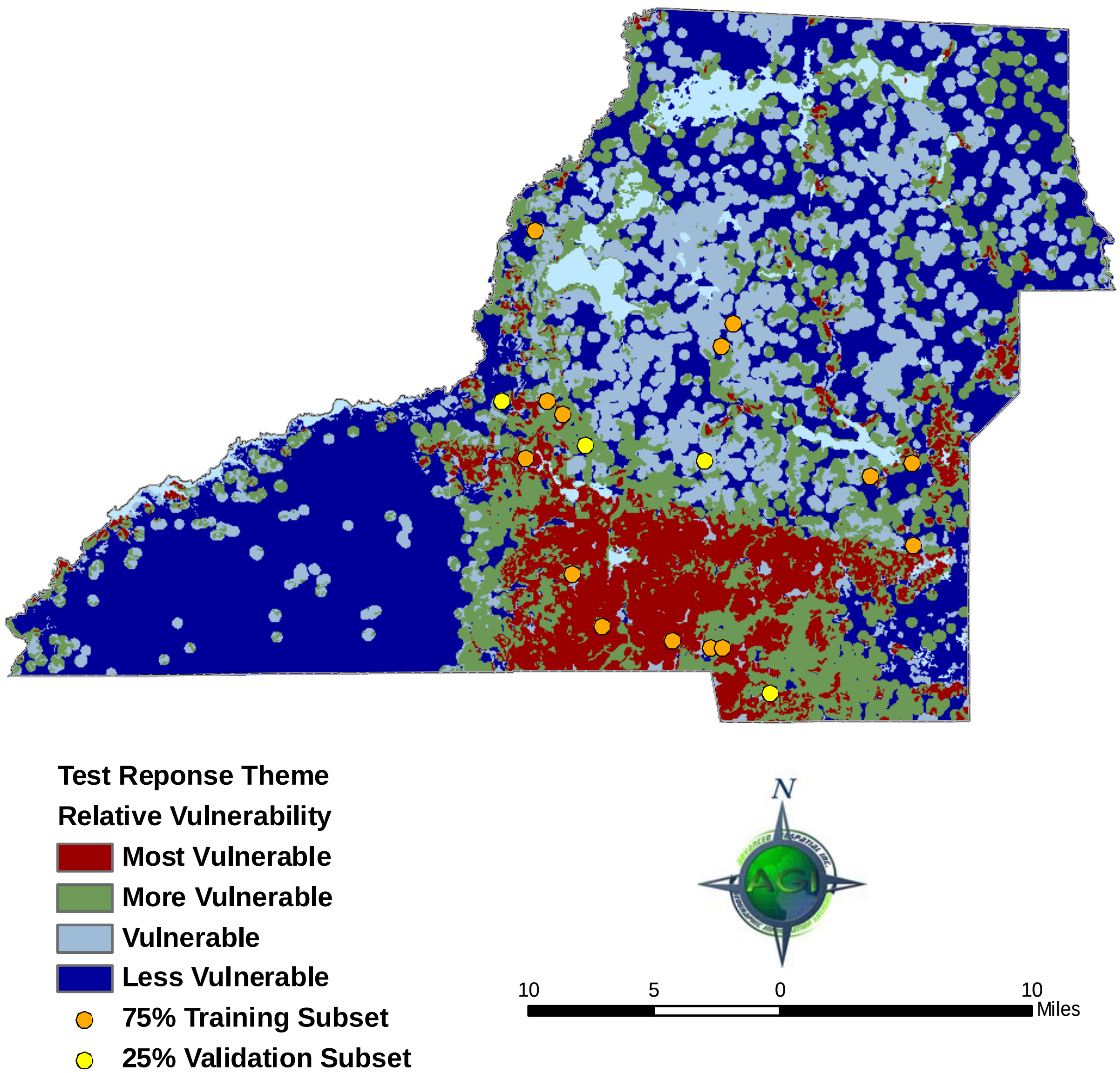

Figure 22. Test response theme with training subset and validation subset.

Model Implementation and Limitations

When implementing the LAVA project results, it is essential to remember that all aquifer systems in Florida, to some degree, are vulnerable to contamination; an invulnerable aquifer does not exist. Further, model results are based solely on features of the natural system that have significant association with the location of training points and thereby aquifer vulnerability. The LAVA project results provide a probability map that identifies zones of relative vulnerability in the study area based on these input data; as a result the LAVA model output is an estimation of intrinsic or natural aquifer 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 LAVA 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 themes and the LIDAR-derived DEM 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.

LAVA 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 confinement thickness represent an area approximately seven square miles (mi^2), for example; on the other hand, soils polygons or karst features derived from DEM data represent an area as small as 1,600 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 LAVA 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 LAVA 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 Floridan Aquifer System underlying Leon County increase, 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 LAVA project provide a science-based, water resource management tool that empowers local government to take a pro-active approach to protection of the FAS; as a result, the effectiveness of protection efforts can be increased. Model results will enable improved decisions to be made about aquifer vulnerability issues, including prioritization of focused protection efforts in sensitive areas such as springsheds and ground-water recharge areas.

The results of the LAVA 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 Floridan Aquifer System. 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 updated data becomes available. In other words, as the scientific body of knowledge grows regarding hydrogeologic systems, this methodology allows the ongoing incorporation and updating 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

Maps generated as part of this project were developed by Advanced GeoSpatial Inc. (AGI) to provide Leon County 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 Leon County 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 Leon County 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 Leon County 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 Leon County, 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 Leon County 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.

Ownership of Documents and Other Materials

This project represents significant effort and resources on both the part of Leon County 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 Leon County 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 Leon County and Advanced GeoSpatial Inc.

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 either ESRI®’s ArcReader or ArcMap™, version 9.x.

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".

Kappa Coefficient – Allows statistical comparison of map patterns. It is a multivariate accuracy assessment technique developed by Cohen (1960) to determine if one error matrix is significantly different than another.

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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