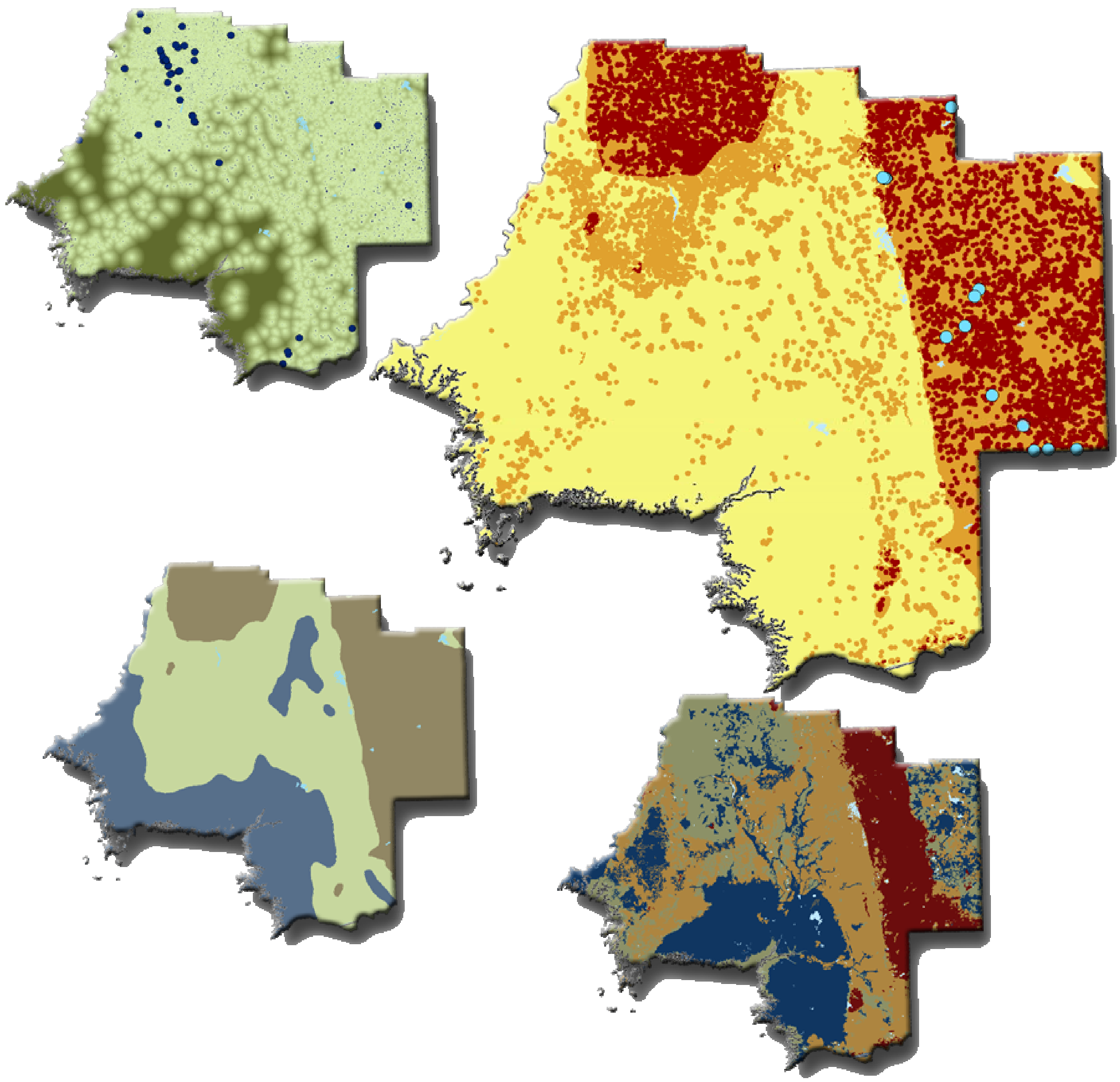
THE LEVY COUNTY AQUIFER VULNERABILITY ASSESSMENT

Part of Phase II of the Florida Aquifer Vulnerability Assessment (FAVA) Project, Florida Department of Environmental Protection Contract No. RM059



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

Version 1.4: September 14, 2009

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., 1949 Raymond Diehl Rd., Ste. D, Tallahassee, FL 32308

September 2009

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

September 14, 2009
Date

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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^{TM}, version 9.x.

THE LEVY COUNTY AQUIFER VULNERABILITY ASSESSMENT

Alan E. Baker, P.G. 2324, Alex R. Wood, and James R. Cichon
Advanced GeoSpatial Inc., 1949 Raymond Diehl Rd., Ste. D, Tallahassee, FL 32308

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 groundwater 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 13,150 self-supply wells in the county tapping the Floridan aquifer system providing fresh water to homeowners (SRWMD Water Use Specialist, 2007; SWFWMD, Well Construction Regulation Section, 2007). 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 study area (Figure 1) 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 groundwater 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. Aquifer vulnerability assessments benefit:

- 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/FDEP) contracted with Advanced GeoSpatial Inc. (AGI) in November of 2006 to co-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 groundwater quality. The project intent is to allow end users of the model to make improved decisions about aquifer

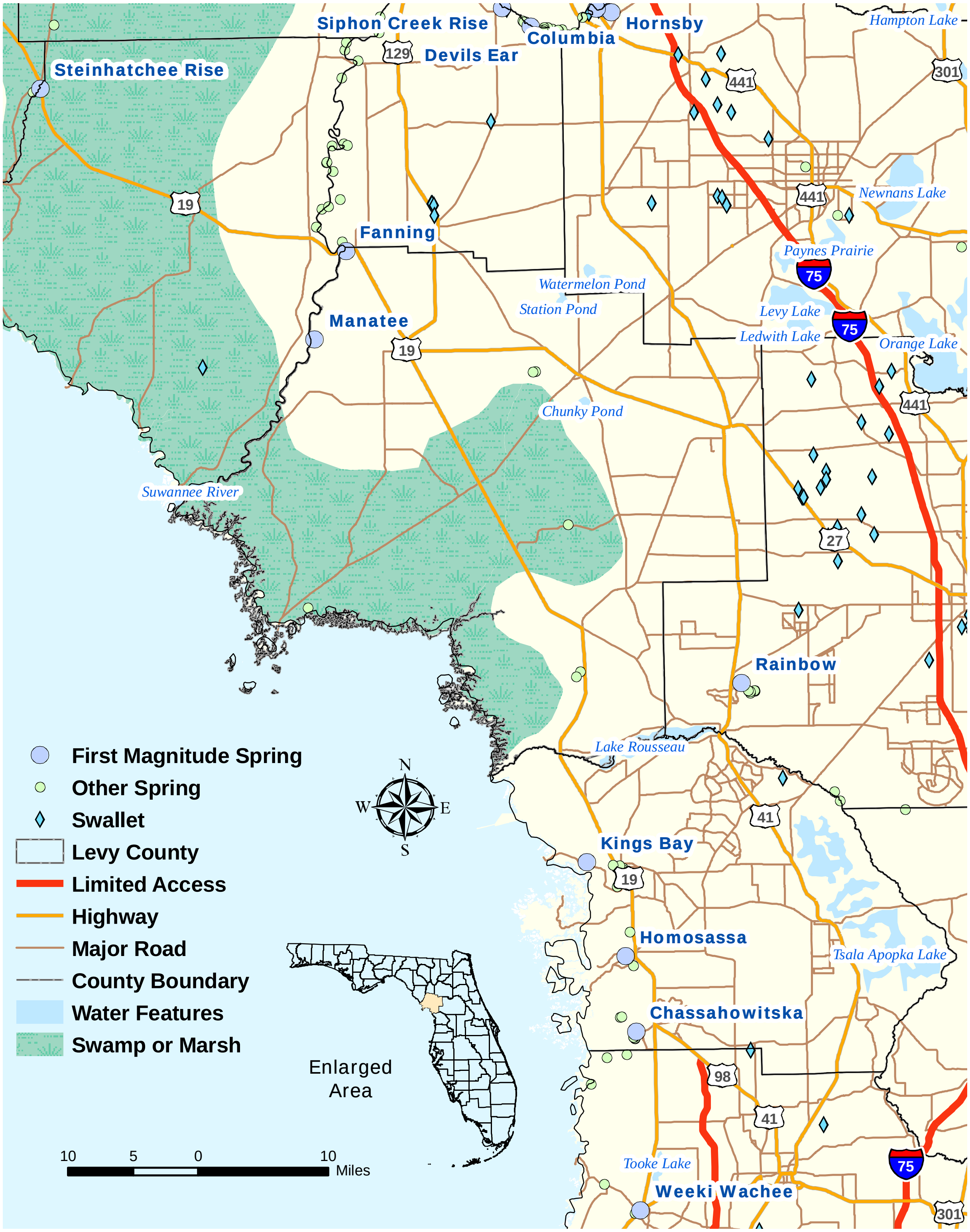


Figure 1. Levy County Aquifer Vulnerability Assessment project study area corresponds to the County's political boundary.

vulnerability with regard to model input selected, including focused protection of sensitive areas such as springsheds and groundwater recharge areas.

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 representing the natural hydrogeologic system (Arthur et al., 2005). As a result, LCAVA model output, like FAVA models, is considered an estimate of intrinsic vulnerability because it relies only on physical hydrogeologic factors and does not include natural and human sources of contamination or behavior of specific contaminants.

APPROACH

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
Jonathan Arthur, Ph.D., P.G.	Florida Geological Survey of FDEP
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

The weights of evidence methodology, and the weighted logistic regression methodology, were employed in FDEP's FAVA project (for detailed information refer to Arthur et al., 2005). Use of these methods involves combination of diverse spatial data that are used to describe and analyze interactions and generate predictive models (Raines et al., 2000). This section provides an overview of the methodology.

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. 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 (available for ArcView 3.x, and ArcGIS 8.x and 9.x). For more information on these methods please refer to Arthur et al. (2007), Kemp et al. (2001), Raines et al. (2000), and Bonham-Carter (1994). Primary benefits of applying these techniques to the WCAVA 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.

Weights of evidence involves the combination of diverse spatial data used to describe and analyze interactions and generate predictive models. Weights of evidence utilizes known occurrences (*training points)* to create maps from weighted continuous input data layers (*evidential themes*), which are in turn combined to yield an output data layer, or *response theme* (Raines, 1999). Resulting from conditional independence issues, weighted logistic regression was used to combine generalized evidential themes and generate final model output. Logistic regression is used to account for inflated probabilities associated with conditional independence problems by breaking down multi-class evidential layers into binary layers (see *Discussion* for more information).

Data Acquisition and Development

The initial phase of an aquifer vulnerability assessment project comprises acquisition, development and attribution of various GIS data 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 Confinement or Overburden Thickness
- Karst Features/Topographic Depressions
- Water-Quality Data
- Soil Hydraulic Conductivity/Soil Pedality
- Aquifer 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 probability maps.

Study Area and Training Points

The initial step in 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 of an event. In an aquifer vulnerability assessment, groundwater wells with water quality indicative of high recharge are selected as known occurrences. Dissolved oxygen or dissolved nitrogen analytical concentrations from ambient monitor well networks 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)

Evidential themes are defined as sets of continuous spatial data that are associated with the location of training points and are analogous to 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 location 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 (for more on generalization of evidential themes, see Arthur et al., 2005). 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.

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 groundwater 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 groundwater, yet are not attributable to human activity, 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 no samples were considered statistical outliers. The upper 25th 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 any evidential theme data. The prior probability value, a unitless parameter, for the LCAVA model is 0.0038 ([0.386 mi^2 model unit area * 11 training points] / 1,117 mi^2 = 0.0038). Posterior probability values generated during response theme development are interpreted relative to

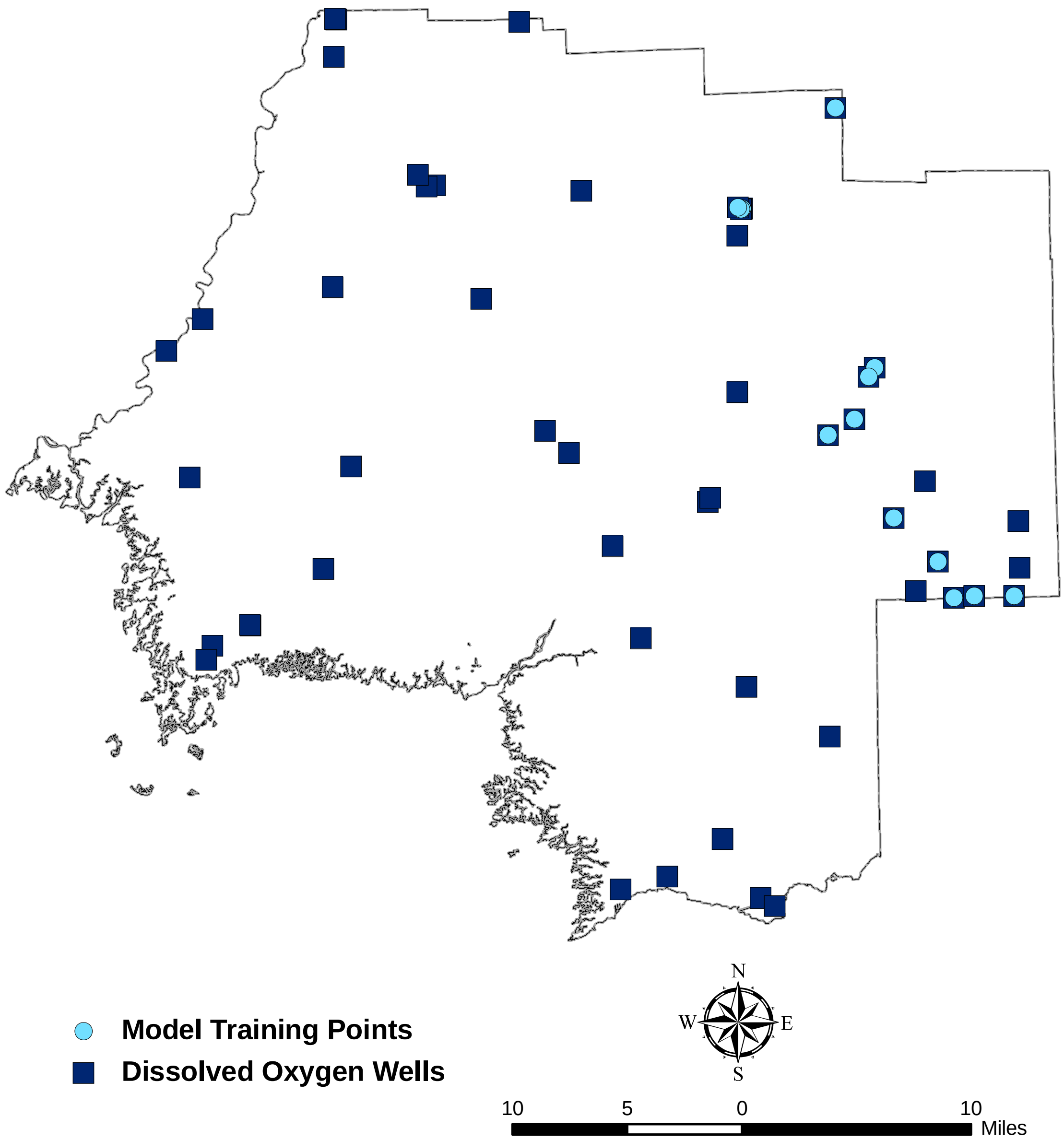


Figure 2. Location of all wells measured for dissolved oxygen, and locations of training point wells with median dissolved oxygen values higher than 4.45 mg/L.

the value of prior probability with higher values generally indicating areas with higher probability of containing a training point.

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 for LCAVA. Posterior probability values generated during response theme development are interpreted relative to the value of prior probability with higher values generally indicating areas with 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/FDEP 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 expanded for the study area and made available by the Natural Resources Conservation Service. This expansion included adaptation into ESRI geodatabase compatible format, and specific soils values were updated (U.S. Department of Agriculture, 2006). 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 test evidential themes were generated and were 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.

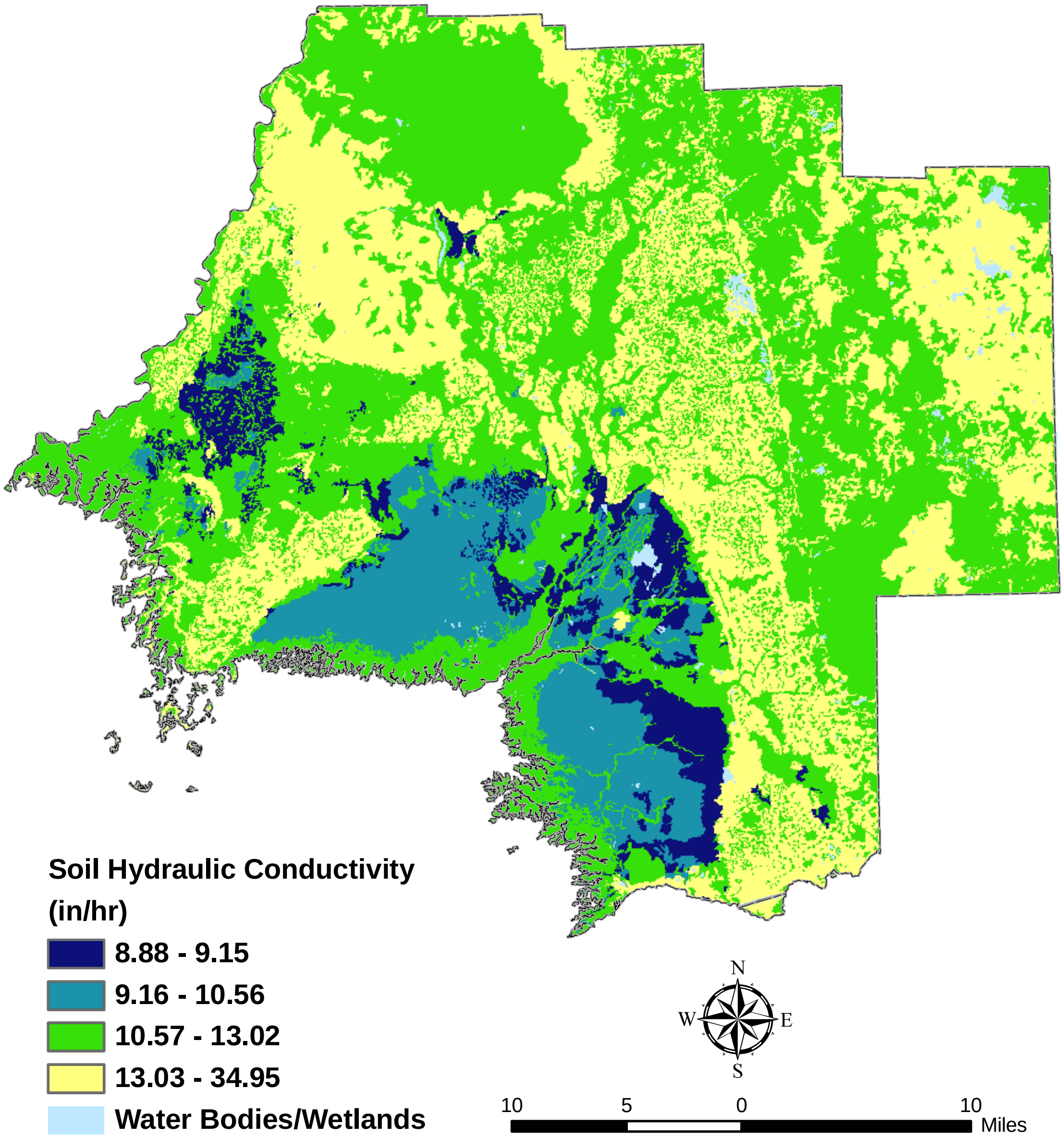


Figure 3. Distribution of soil hydraulic conductivity values across the LCAVA study area.

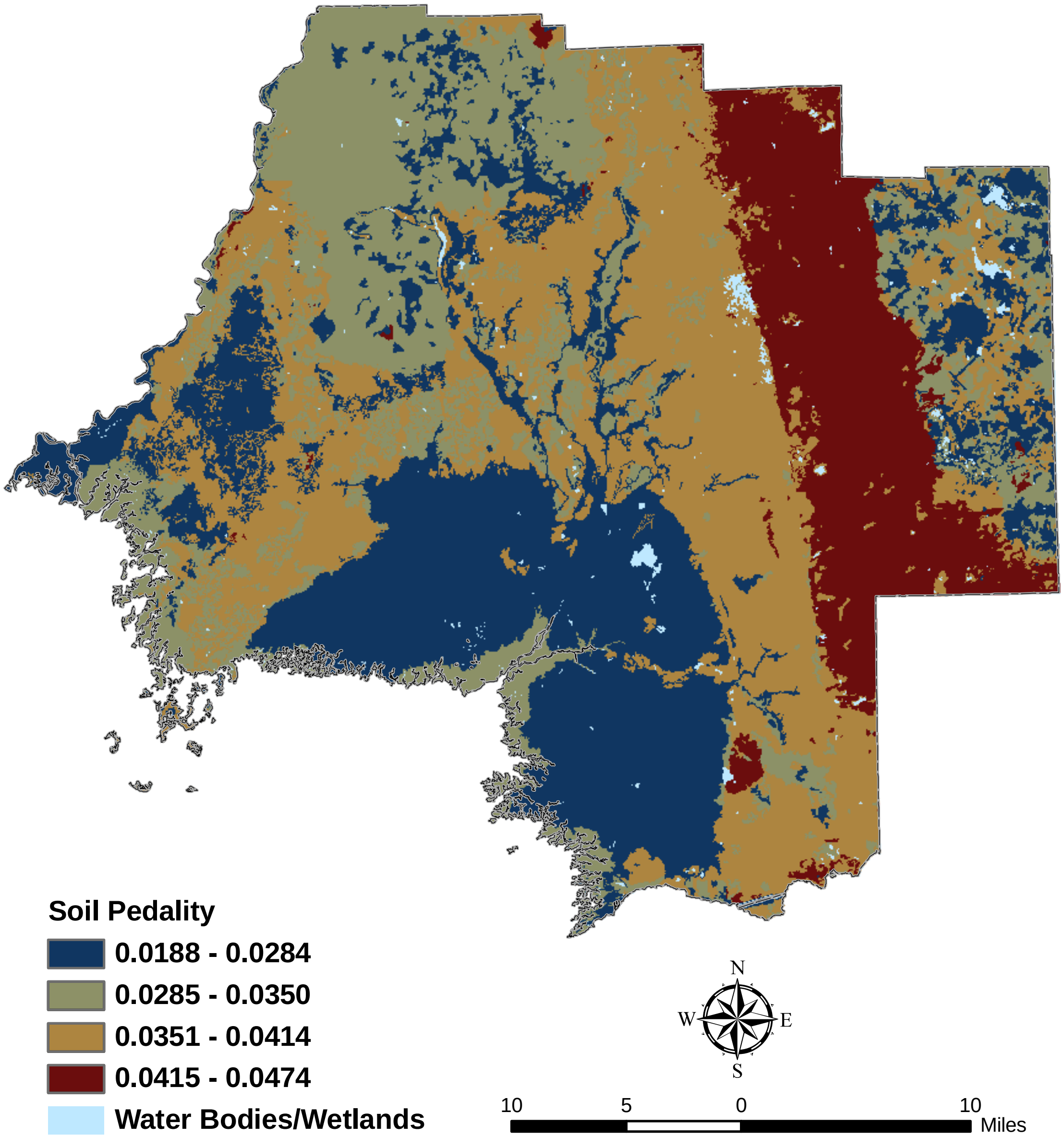


Figure 4. Distribution of soil pedality values (unitless) across the LCAVA study area.

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 (ICU) 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 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 U.S. Geological Survey 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/FDEP 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*.

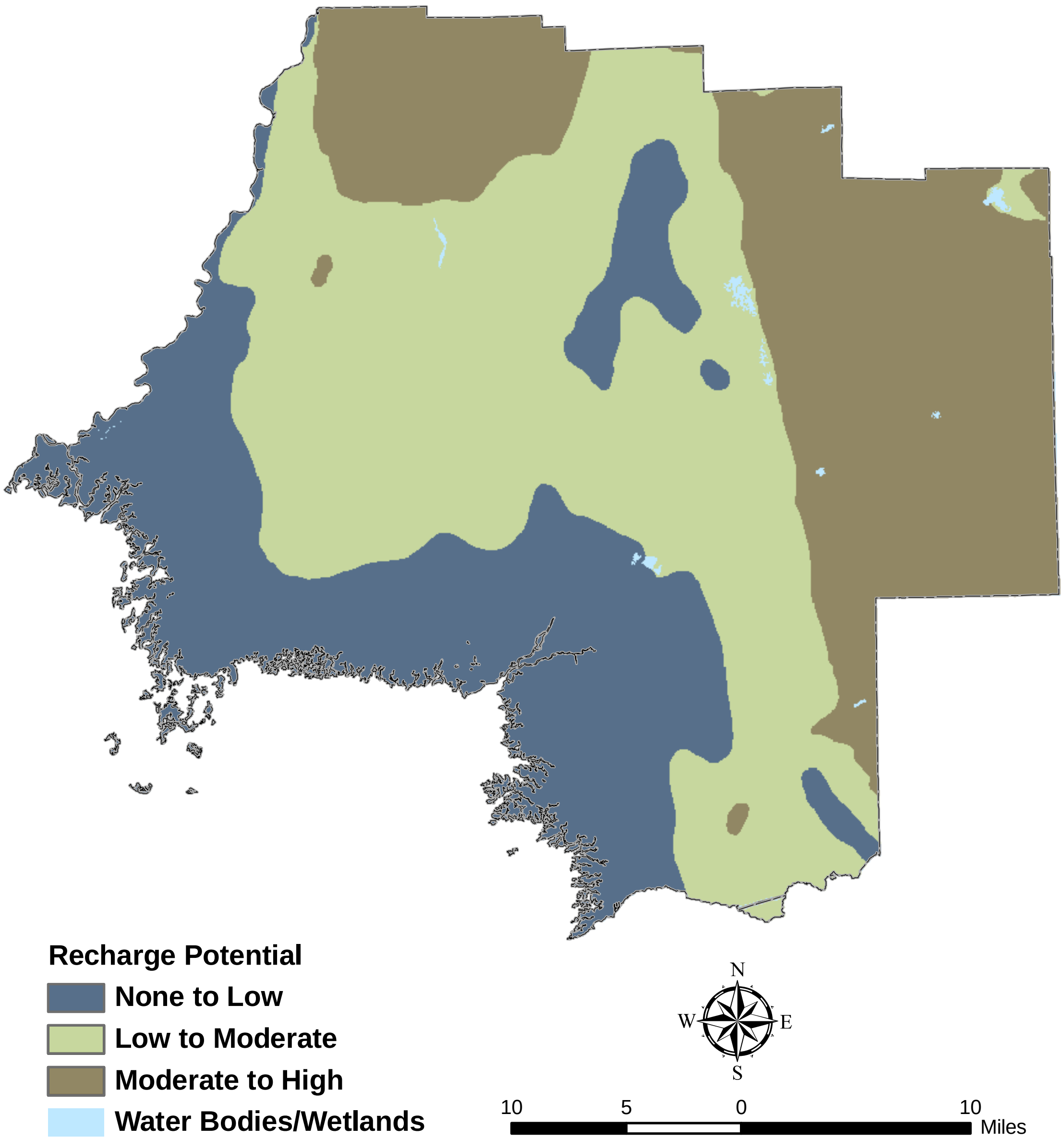


Figure 5. Recharge potential estimated from FAS potentiometric surface data, land surface elevation and estimates developed for Copeland et al., (1991).

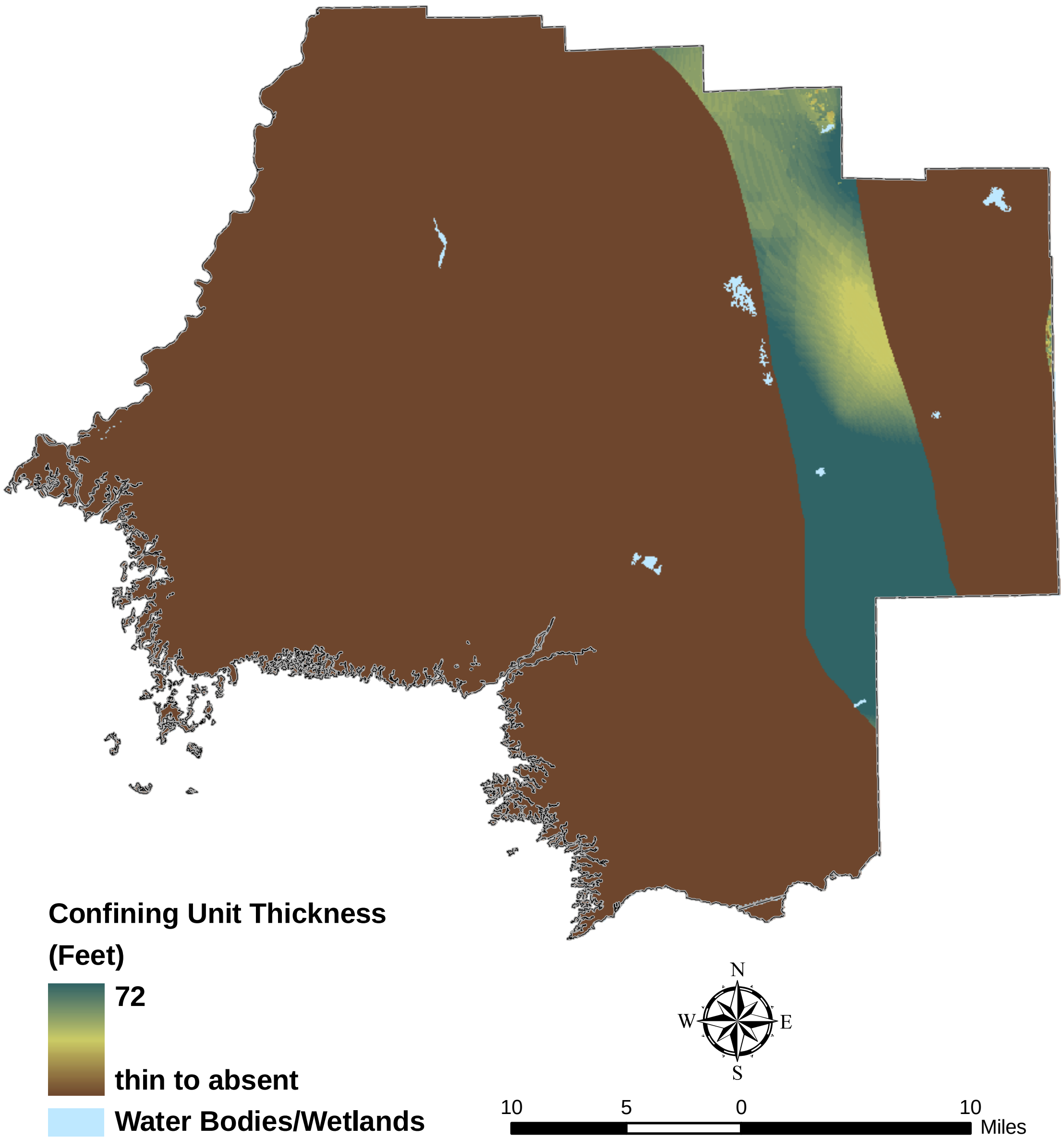


Figure 6. Thickness of the ICU calculated by subtracting predicted surface of ICU from predicted surface of FAS as generated by FGS / FDEP.

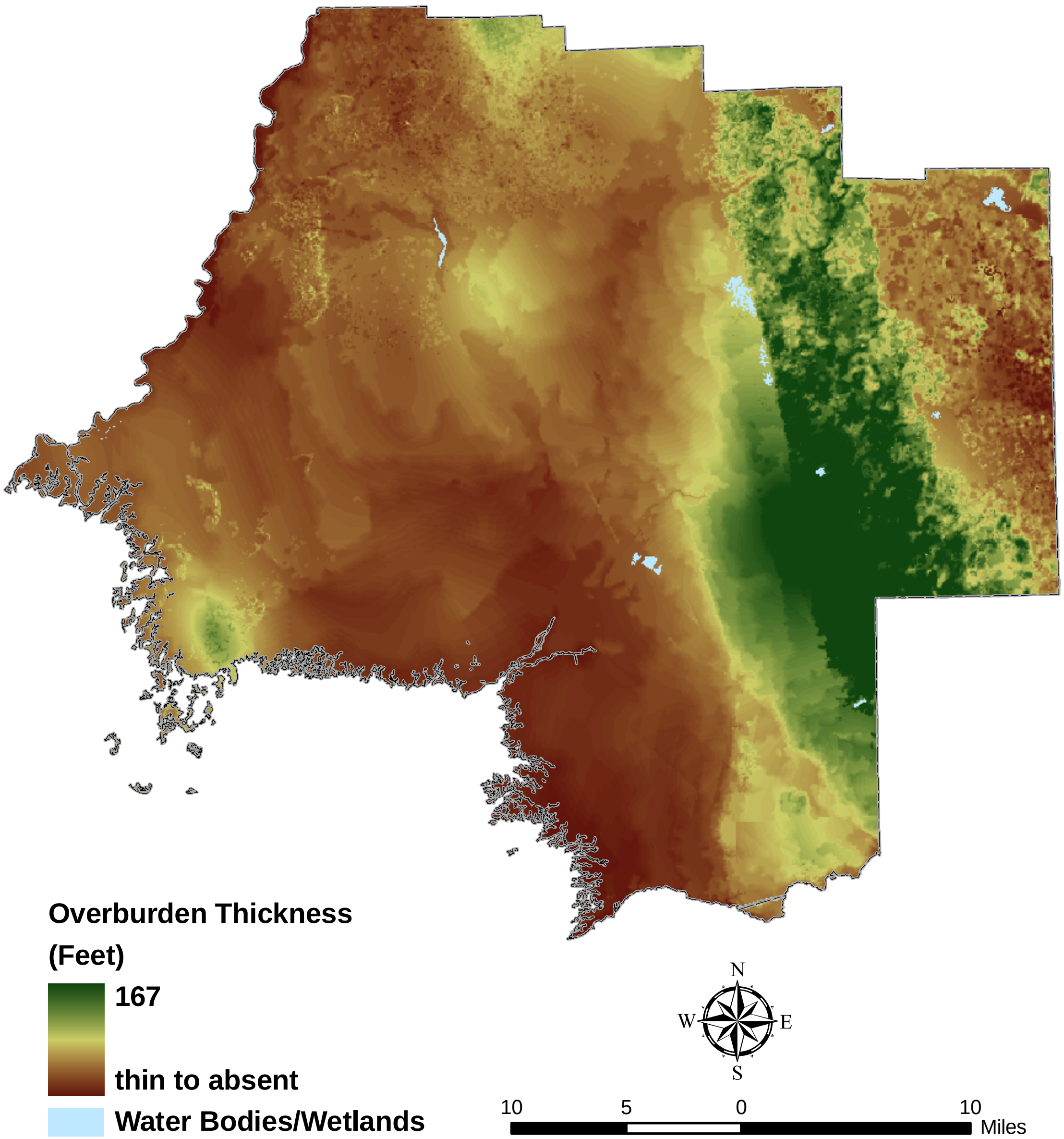


Figure 7. Thickness of sediments overlying the FAS calculated by subtracting digital elevation data from predicted surface of FAS as generated by FGS / FDEP.

Potential 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 potential karst features in the study area (Figure 8). To supplement these data, the FGS/FDEP 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 a potential karst features evidential theme.

It is recognized that using closed topographic depressions to develop a potential karst features theme may or may not represent all true karst features, however, application of analytical processes to digital elevation maps and models to estimate karst has been 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/FDEP sinkhole features to create a potential 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 potential 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

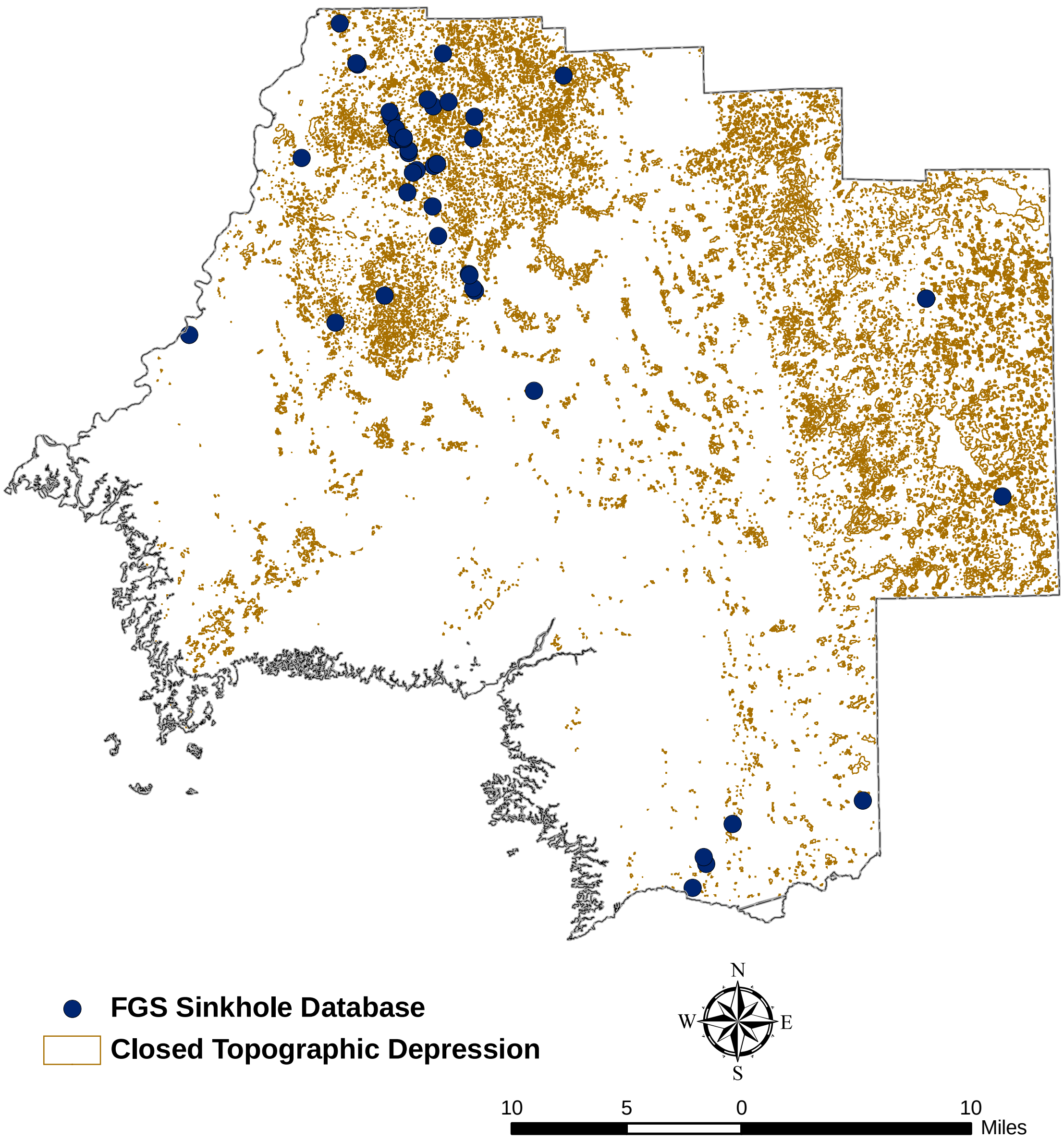


Figure 8. All closed topographic depressions extracted from U.S. Geological Survey 7.5-minute topographic contour lines and sinkholes from the FGS/FDEP sinkhole database.

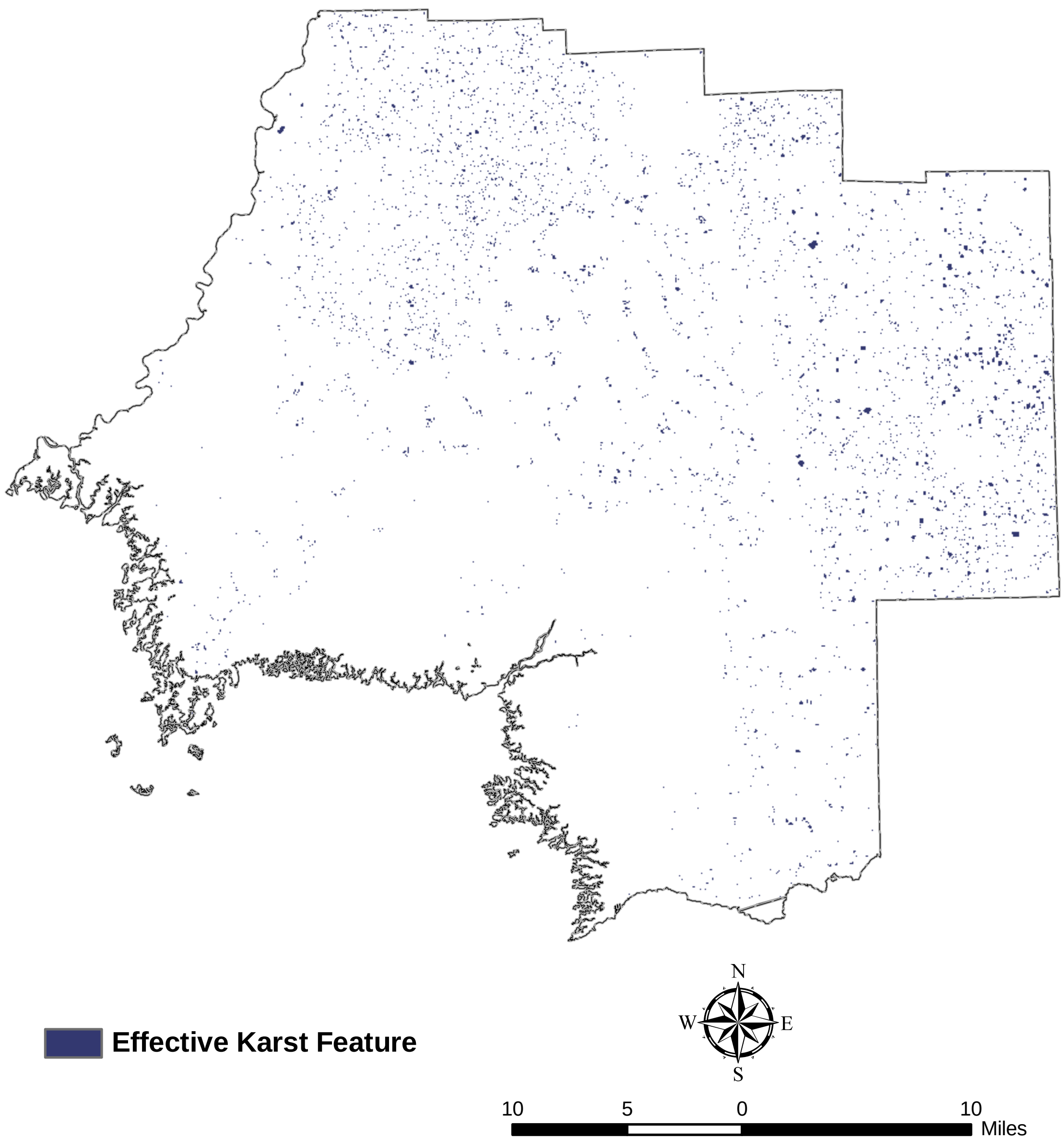


Figure 9. Potential karst features resulting from circular index method applied to U.S. Geological Survey 7.5-minute topographical contour lines combined with sinkholes from the Florida Geological Survey sinkhole database.

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 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.

Potential Karst Features

As mentioned above, areas closer to a potential 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.

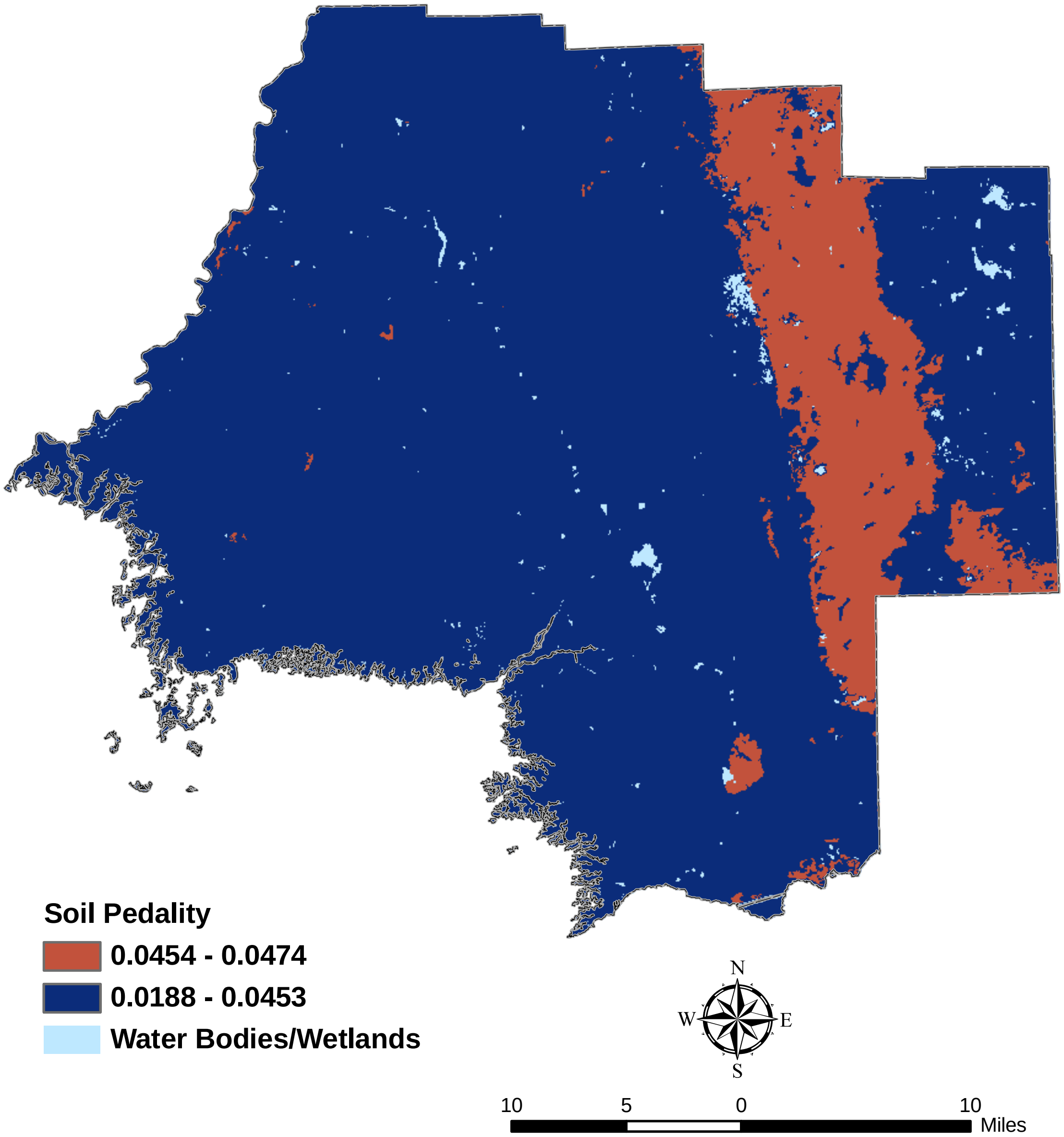


Figure 10. Generalized soil pedality evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby relatively lower aquifer vulnerability, whereas red areas share a stronger association with training points.

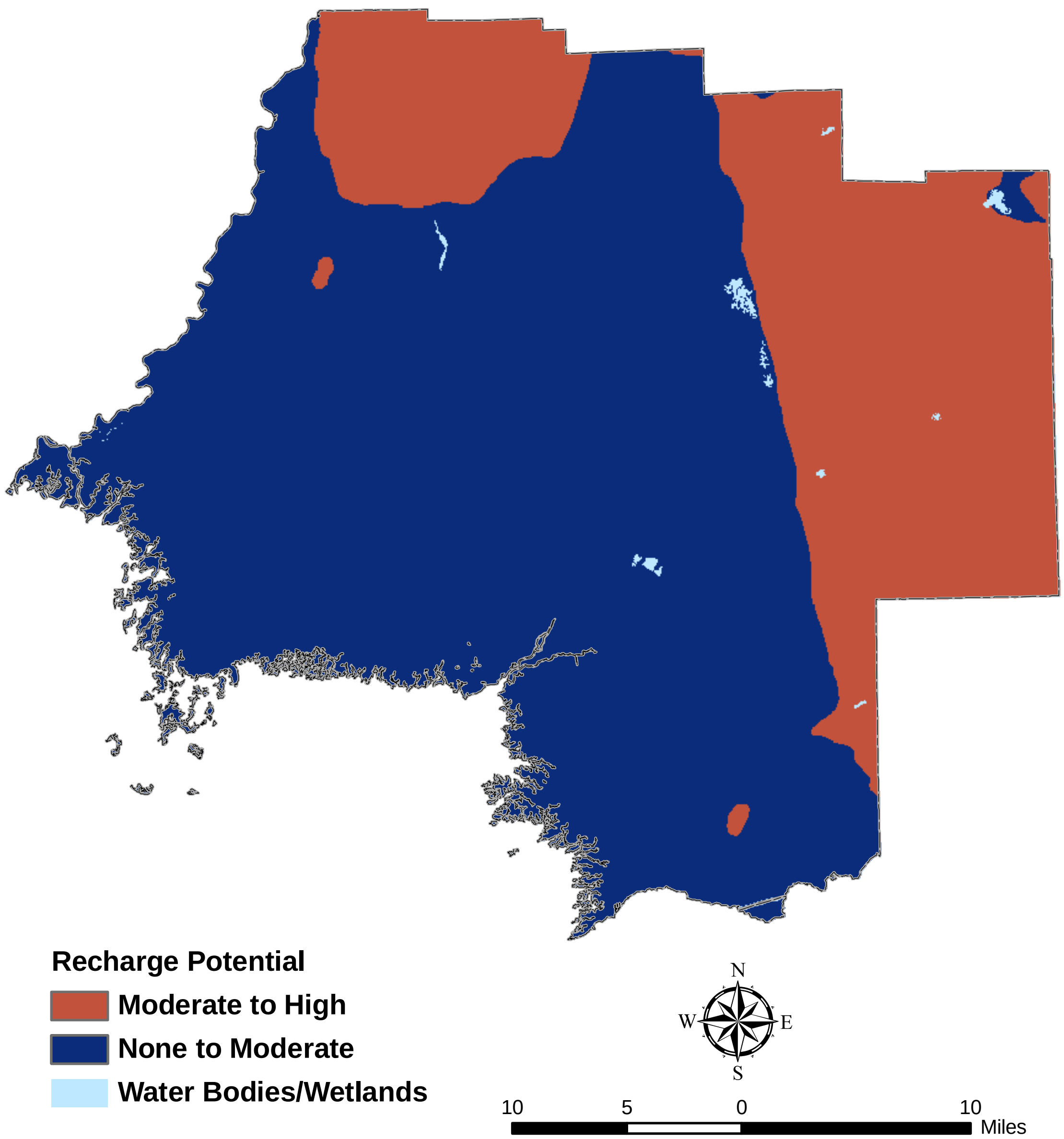


Figure 11. Generalized recharge potential evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby relatively lower aquifer vulnerability, whereas red areas share a stronger association with training points.

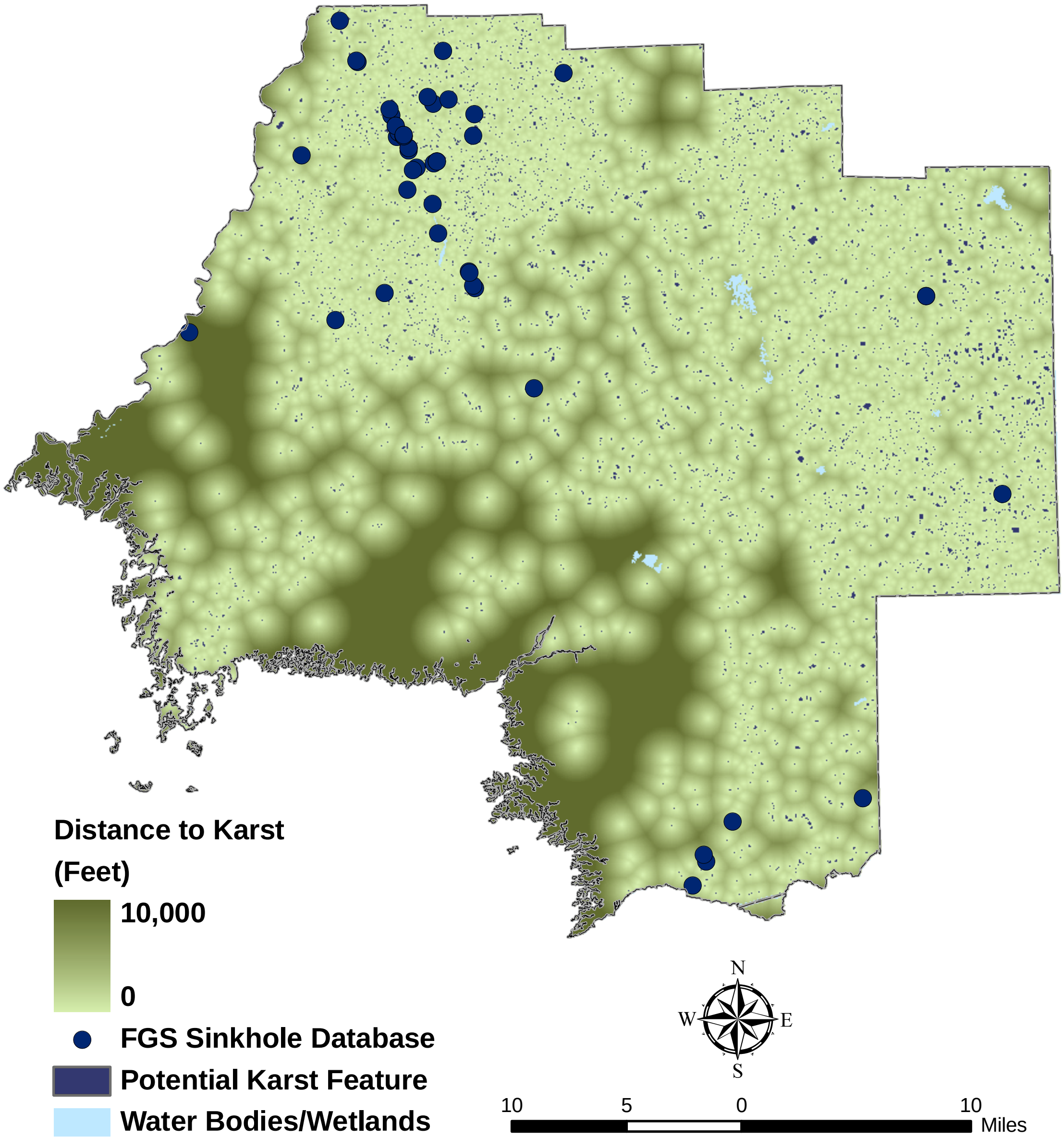


Figure 12. Potential karst features evidential theme buffered into 100-ft zones for proximity analysis in the weights of evidence analysis.

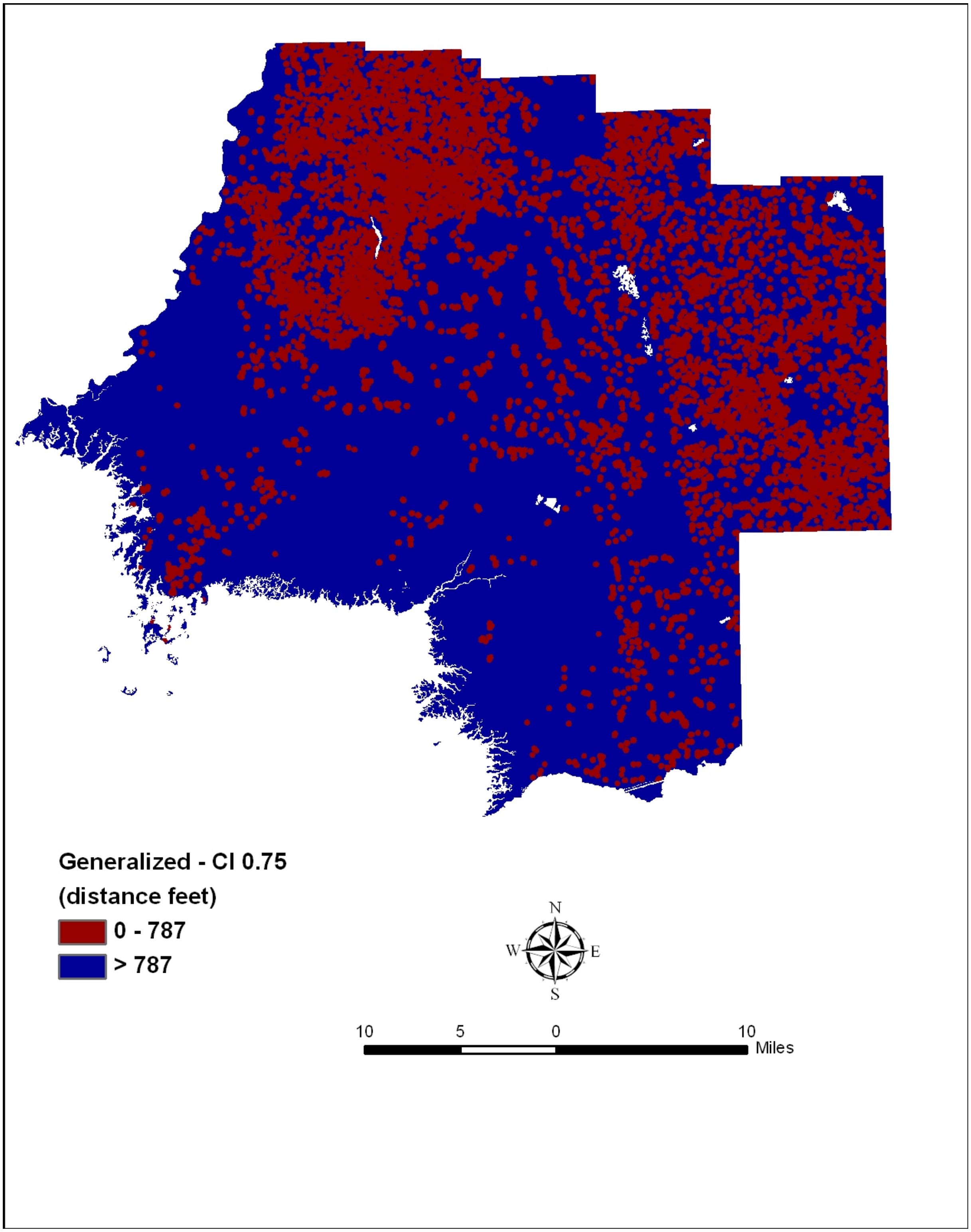


Figure 13. Generalized potential karst feature evidential theme; based on calculated weights analysis blue areas share a weaker association with training points and thereby relatively lower aquifer vulnerability, whereas red areas share a stronger association with training points.

Response Theme

Using evidential themes representing soil pedality, recharge potential, and potential karst, 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 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 0.0038. 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.

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.

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 potential 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 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*.

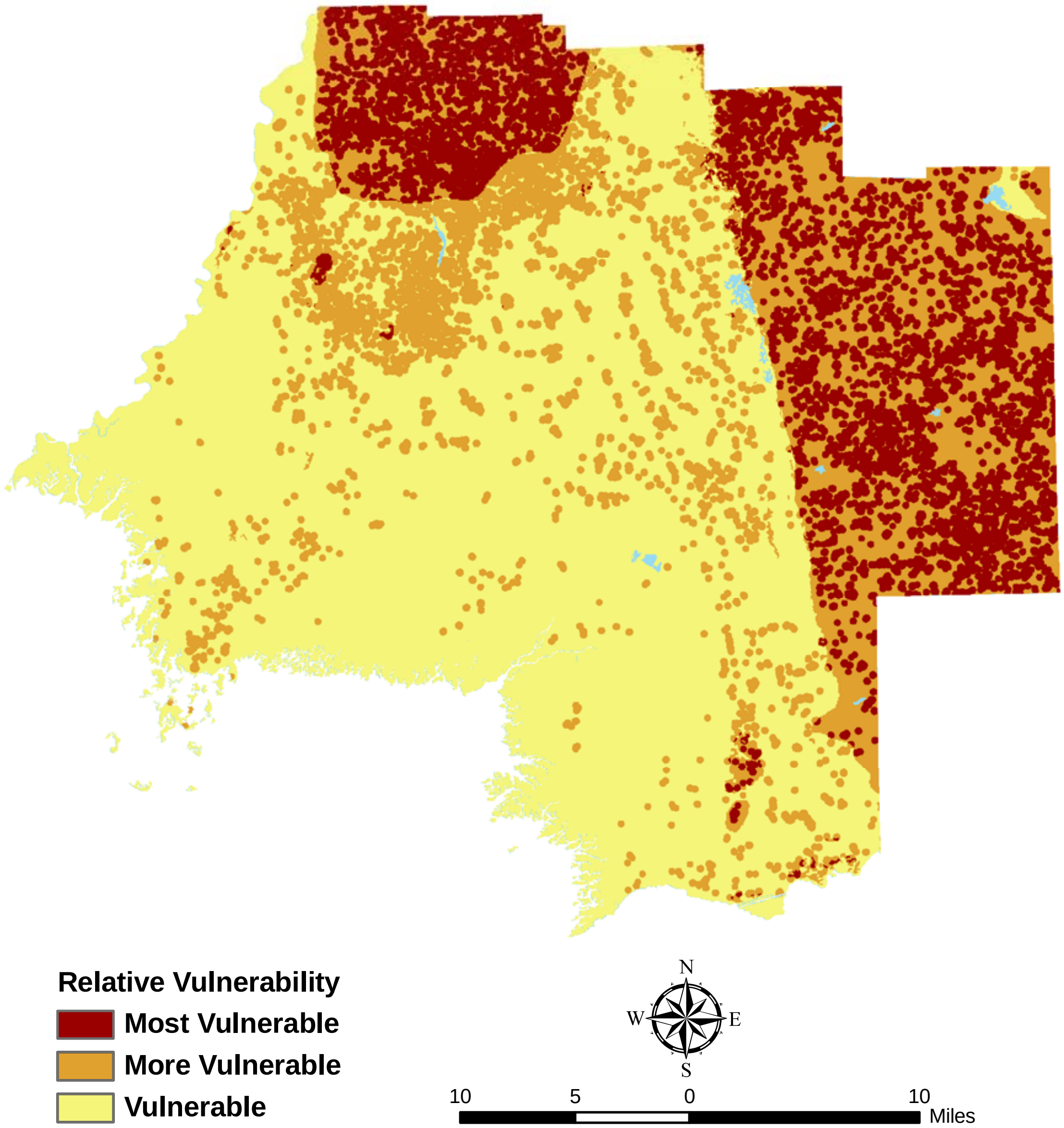


Figure 14. Relative vulnerability map for the Levy County Aquifer Vulnerability Assessment project. Classes of vulnerability are based on calculated probability of a unit area containing a training point, or a monitor well with water quality sample results indicative of vulnerability.

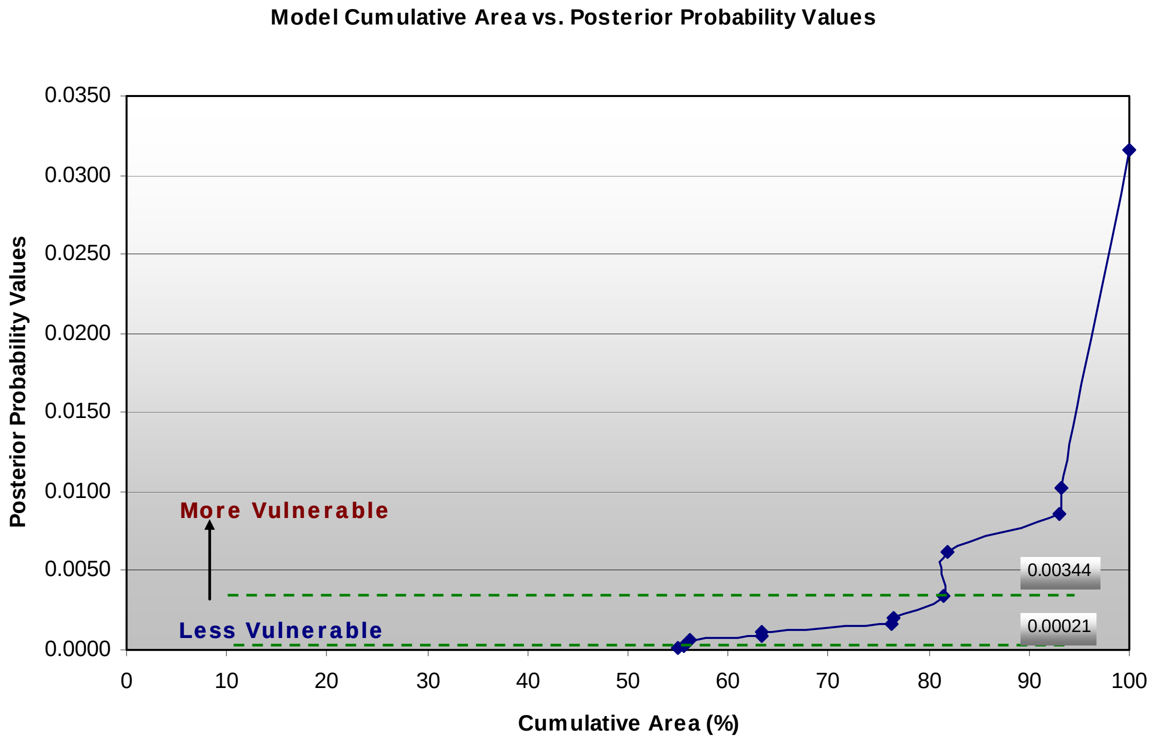


Figure 15. Vulnerability class breaks are defined by selecting where a significant increase in probability and area are observed.

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).

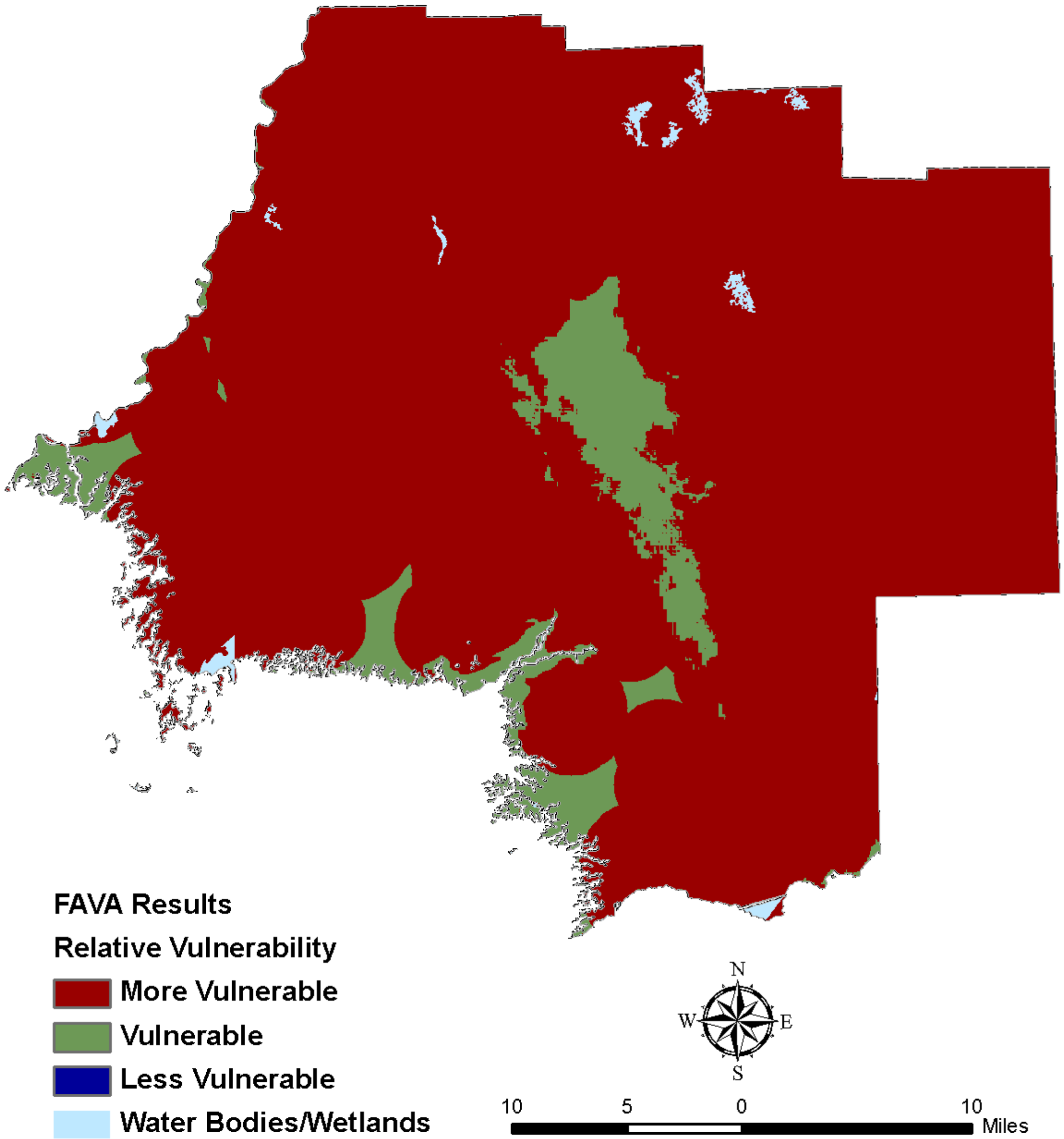


Figure 16. Results of the Florida Aquifer Vulnerability Assessment project (Arthur et al., 2005) for the FAS in Levy County. The LCAVA model relative vulnerability zones, while based on more refined data than the FAVA project, occur within the context of this regional model.

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. Confidence of the evidential theme is also calculated and is equal to the contrast divided by its standard deviation (a student T test). Confidence is a measure of significance due to uncertainties of the weights and missing data (Raines, 1999). A positive contrast that is significant, based on its confidence, suggests that a generalized evidential theme is a useful predictor.

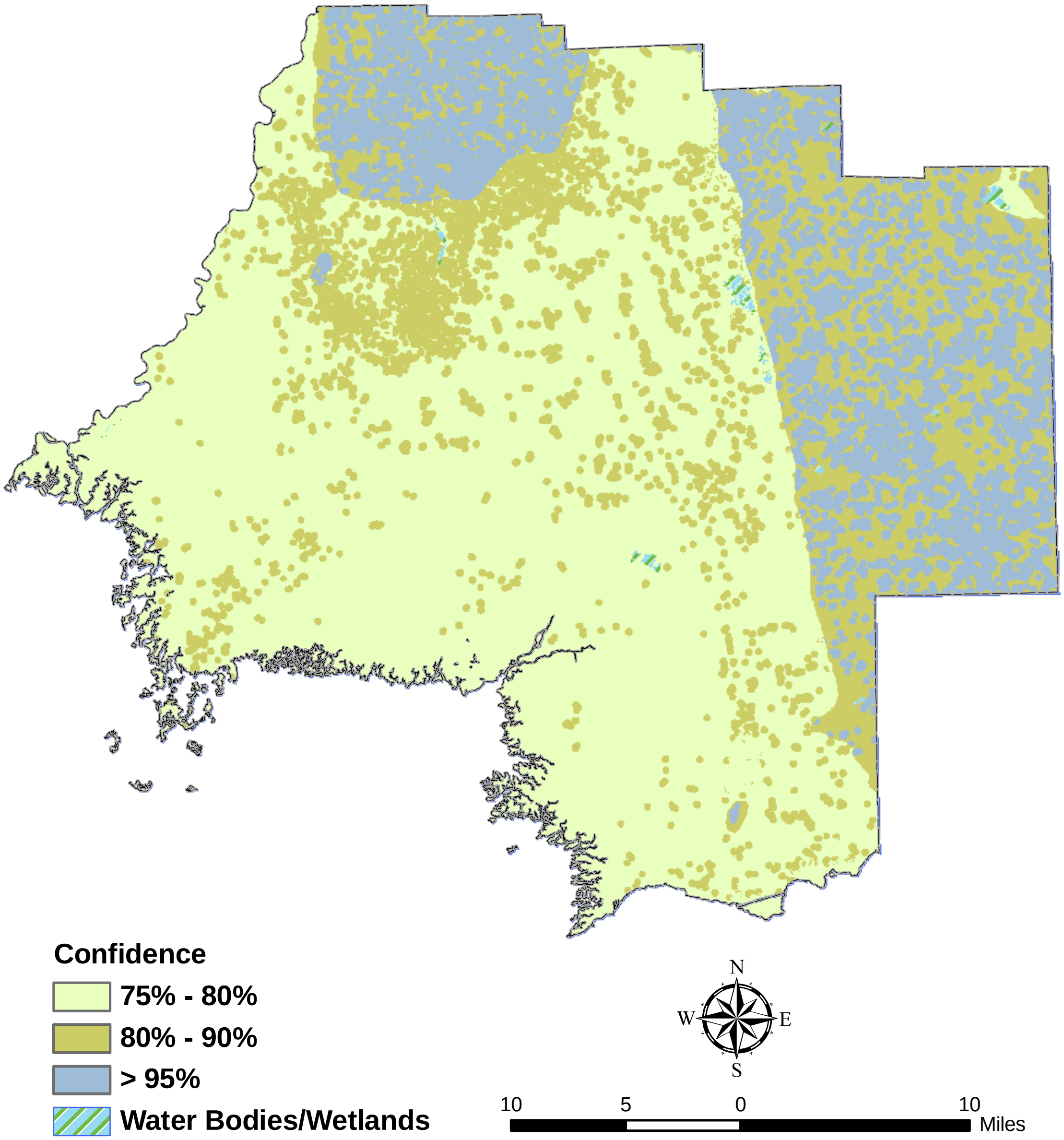


Figure 17. Confidence map for the LCAVA model calculated by dividing the posterior probability values by the total uncertainty for each class to give an estimate of how well specific areas of the model are predicted.

Table 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
Potential 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 potential 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.

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

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

Based on coefficient values, the potential 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.

From the LCAVA training point theme, a subset of 75% (eight wells) were randomly selected and used to develop a test response theme; the remaining 25% (three wells) of the training points were used as the validation dataset for the test response theme. This comparison revealed that all three test wells in the validation subset, or 100%, occur in areas of the test response theme with predicted probability values higher than the prior probability value. This further supports the conclusion that the LCAVA model response theme is a reasonable estimator of vulnerability.

Dissolved Oxygen Data vs. Posterior Probability

It was expected that comparison of posterior probability values to the dissolved oxygen dataset from which the training point theme was extracted would reveal a proportional trend, in other words, as dissolved oxygen values increase, so should posterior probability values. Dissolved oxygen median concentrations were binned and averaged for each posterior probability value calculated in model output. The average values were plotted in a chart against posterior probability values (Figure 19) and a positive trend was observed.

An additional test involved applying a Pearson's correlation coefficient (r) test to all dissolved oxygen values versus posterior probability values. This test revealed a value of 0.64 indicating more than a 99% degree of statistical significance between the response theme values and the dissolved oxygen data.

Model Implementation and Limitations

When implementing the CAVA model results, it is vital to remember that aquifer systems in Florida are vulnerable to contamination; an invulnerable aquifer does not exist. Model results are based on features of the natural system that have significant association with the location of training points and thereby aquifer vulnerability. The CAVA project results provide a probability map that identifies zones of relative vulnerability in the study area based on input data; as a result the CAVA model output is an estimation of natural aquifer vulnerability and the results do not account for activities at land surface, contaminant type, groundwater flow paths or fate/transport of chemical constituents.

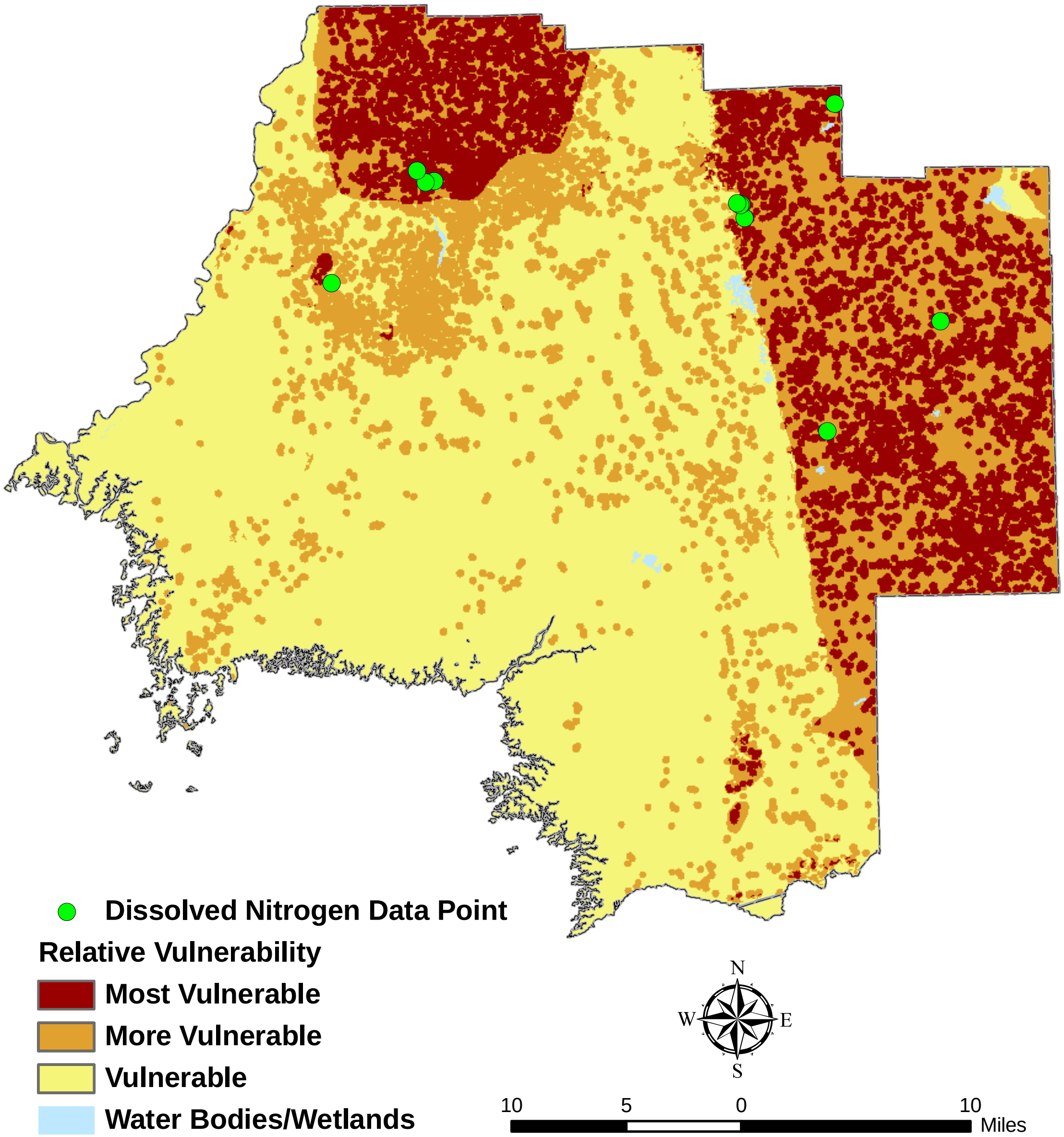


Figure 18. Dissolved nitrogen validation training points plotted in the dissolved oxygen response theme. Comparison reveals 11 of 13 wells (85%) of the independent water quality dataset are located in "most vulnerable" areas.

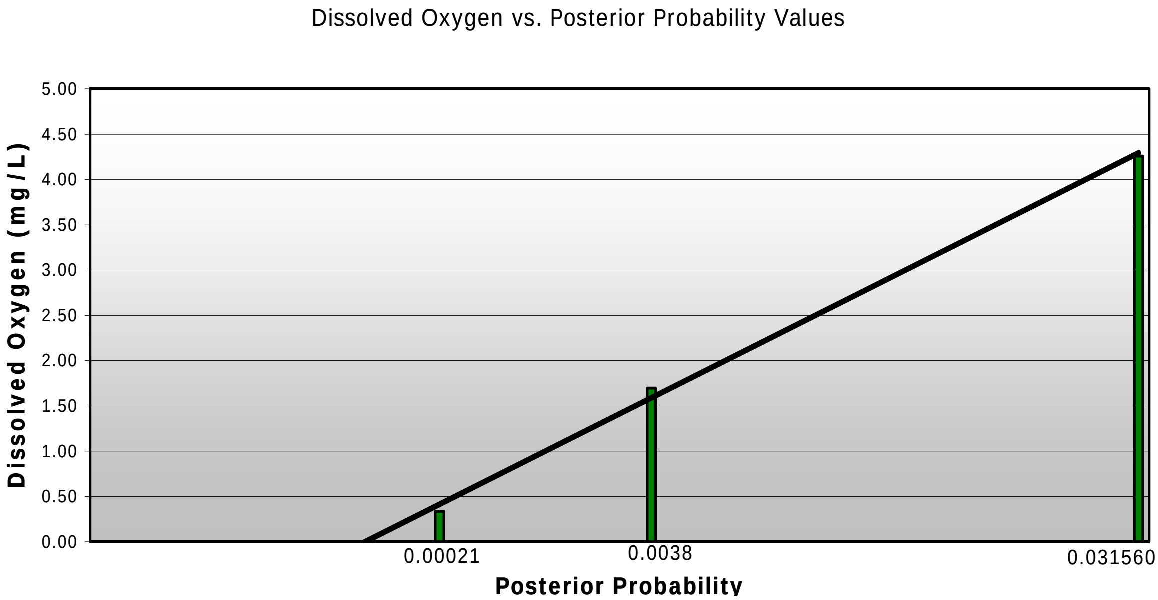


Figure 19. Dissolved oxygen values (averaged per posterior probability class) versus probability values to reveal trend between increasing dissolved oxygen concentrations and posterior probability.

Derivative Products: Protection Zones

Relative vulnerability zones defined in this project may be applied to develop derivative maps, such as a protection-zone map (Cichon et al., 2005). 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 groundwater 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.

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 total uncertainty. 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 (Mihalasky 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 groundwater 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.

LCAVA model output is, in a sense, as accurate as the most detailed input layer, and as inaccurate as the least detailed layer. The potentiometric surface map used in the development of the recharge potential evidential theme was mapped at 1:500,000, for example; on the other hand, soils polygonal data represent an area as small as 19,375 ft^2.

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. As mentioned above, the confidence map, because it is an indicator of the meaningfulness of the vulnerability classes, should be used to help guide implementation of the vulnerability map. For example, in the LCAVA confidence map (Figure 17), local-scale land-use decisions might be more defensible in with the higher vulnerability classes (more vulnerable and most vulnerable) as these areas are associated with highest confidence values.

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 groundwater 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 groundwater 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 groundwater recharge areas.

The results of the LCAVA vulnerability model are useful for development and implementation of groundwater 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 groundwater resources.

QUALIFICATIONS

Disclaimer and Funding Source

Maps generated as part of this project were developed by AGI to provide the FDEP with a groundwater 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.

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); a map data layer used as a predictor 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 probability 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.

REFERENCES

Agterberg, F.P., Bonham-Carter, G.F., Wright, D.F., 1990, Statistical pattern integration for mineral exploration, in Gaal, G., and Merriam, D.F., eds., Computer Applications in Resource Estimation Prediction and Assessment of Metals and Petroleum: New York, Pergamon Press, p. 1-12.

Arthur, J.D., Wood, H.A.R., Baker, A.E., Cichon, J.R., and Raines, G.L., 2007, Development and Implementation of a Bayesian-based Aquifer Vulnerability Assessment in Florida: Natural Resources Research Journal, v.16, no. 2, p. 93-107.

Arthur, J.D., Baker, A.E., Cichon, J.R., Wood, H.A.R., and Rudin, A., 2005, Florida Aquifer Vulnerability Assessment (FAVA): Contamination potential of Florida's principal aquifer systems: Report submitted to Division of Water Resource Management, Florida Department of Environmental Protection, 148 p.

Baker, A.E., Wood, H.A.R., and Cichon, J.R., 2007, The Marion County Aquifer Vulnerability Assessment; final report submitted to Marion County Board of County Commissioners in fulfillment of Marion County Project No. SS06-01, March 2007, 42 p.

Baker, A.E., Wood, H.A.R., Cichon, J.R., and Arthur, J.D., 2005, Alachua County Aquifer Vulnerability Assessment; final report submitted to Alachua County, January 2005, 36 p. (unpublished).

Bonham-Carter, G. F., 1994, Geographic Information Systems for Geoscientists, Modeling with GIS: Oxford, Pergamon, 398 p.

Cichon, J.R., Baker, A.E., Wood, A.R., Arthur, J.D., 2005, Wekiva Aquifer Vulnerability Assessment: Florida Geological Survey Report of Investigation No. 104, 36 p.

Copeland, R., Scott, T.M., Lloyd, J.M., 1991, Florida's Ground Water Quality Monitoring Program: Hydrogeological Framework: Florida Geological Survey Special Publication No. 32, 97 p.

Cohen, J., 1960, A coefficient of agreement for nominal scales: Educational and Psychological Measurement, v. 20, no. 1, p. 37-46.

Denizman, C., 2003, Morphometric and spatial distribution parameters of karstic depressions, Lower Suwannee River Basin, Florida: Journal of Cave and Karst Studies, v. 65, no. 1, p. 29-35.

Kemp, L.D., Bonham-Carter, G.F., Raines, G.L. and Looney, C.G., 2001, Arc-SDM: Arcview extension for spatial data modeling using weights of evidence, logistic regression, fuzzy logic and neural network analysis: http://ntserv.gis.nrcan.gc.ca/sdm/, 2002.

Lin, H.S., McInnes, K.J., Wilding, L.P., and Hallmark, C.T., 1999, Effect of Soil Morphology on Hydraulic Properties: I. Quantification of Soil Morphology, Soil Science Society of America Journal, v. 63, p. 948-954.

Mihalasky, M.J., and Moyer, L.A, 2004, Spatial databases of the Humboldt Basin mineral resource assessment, northern Nevada: U.S. Geological Survey Open-File Report 2004-1245, 17 p.

National Research Council, 1993, Ground Water Vulnerability Assessment: Predicting Relative Contamination Potential under Conditions of Uncertainty: Washington, National Academy Press, 204 p.

Raines, G. L., Bonham-Carter, G. F., and Kemp, L., 2000, Predictive Probabilistic Modeling Using ArcView GIS: ArcUser, v. 3, no.2, p. 45-48.

Raines, Gary L., 1999, Evaluation of Weights of Evidence to Predict Epithermal-Gold Deposits in the Great Basin of the Western United States: Natural Resources Research, vol. 8, no. 4, p. 257-276.

Scott, T.M., Means, G.H., Meegan, R.P., Means, R.C., Upchurch, S.B., Copeland, R.E., Jones, J., Roberts, T., and Willet, A., 2004, Springs of Florida: Florida Geological Survey Bulletin No. 66, 377 p.

Scott, T.M., Campbell, K.M., Rupert, F.R., Arthur, J.D., Missimer, T.M., Lloyd, J.M., Yon, J.W., Duncan, J.G., 2001, Geologic Map of the State of Florida: Florida Geological Survey Map Series 146, Scale 1:750,000, 1 sheet.

Southwest Florida Water Management District, 2006, 2003 (Revised) and 2004 Estimated Water Use Reports: Southwest Florida Water Management District, 471 p.

United States Census Bureau: American Factfinder State and County Quick Facts, 14-Feb-2007, 13:08 EST: http://factfinder.census.gov/. Source: U.S. Census Bureau, Census 2000, Census 1990.

United States Department of Agriculture, Natural Resources Conservation Service, 2005, National Soil Survey Handbook, title 430-VI. [Online] Available: http://soils.usda.gov/technical/handbook/.

United States Geological Survey, 2001, Potentiometric Surface of the Upper Floridan Aquifer, West-Central Florida, U.S. Geological Survey Open File Report 01-310, Arc/Info Geospatial Data Layer; 1:500,000.