FLORIDA GEOLOGICAL SURVEY
FLORIDA DEPARTMENT OF ENVIRONMENTAL PROTECTION

PLATE 2

Relative Vulnerability Map of the Intermediate Aquifer System

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Study Area and Extent

The Intermediate Aquifer System (IAS) includes all rocks and sediments that lie between and collectively restrict the exchange of water between the overlying SAS and underlying FAS (Southeastern Geological Society, 1986). This unit generally acts as a confining unit for the FAS where it is present, but also contains localized moderate-yielding aquifers throughout the State. It is also a major source of ground water only in the southwestern part of Florida, and as discussed in *Results – Data Coverages – Intermediate Aquifer System Thickness* is the only region that includes the IAS FAVA study area.

The IAS in southwestern Florida comprises a major regional aquifer system providing ground water to municipalities, industries and agriculture. Various researchers have identified several production zones within this aquifer system (e.g., Metz, 1993, Torres et al., 2001). Due to the complex and discontinuous nature of these zones, it is not feasible to map them or model their individual vulnerability within the scope of this project.

The extent of the IAS was based on the combination of the distribution of FDEP public water supply wells and an extent proposed by Miller (1986). FDEP wells were plotted in a GIS with a 20-km buffer. This method accounted for major production zones of the IAS in the southern part of the region, but did not adequately represent areas where the IAS is a principal aquifer system for domestic supply in Polk, Sarasota, Manatee, and Hardee Counties. For this region, Miller's (1986) extent was applied. By combining the polygons for these two areas, a comprehensive extent of the IAS where it is predominantly used for public supply was developed for input into the FAVA model.

Large water bodies (those covering greater than approximately 50 acres) were omitted from IAS FAVA model because a well would never be drilled in these areas – therefore, they would never contain a training point. If the lakes were left in the model, the surface area was increased with no chance of increasing the number of training points. This would unnecessarily bias the model. Further, large water bodies typically have no soils or other input data associated with them, thus the model output omits these areas due to lack of data or potential bias in the calculated probabilities.

Weights of Evidence Model

Use of the Weights of Evidence (WofE) modeling technique involves the combination of diverse spatial data that are used to describe and analyze interactions and generate predictive models (for a detailed discussion of this statistical modeling technique see Bonham-Carter, 1994; Raines et al., 2000). WofE is a data- driven process that utilizes known occurrences as model training sites to create maps from weighted continuous input data layers. These input data layers, known as evidential themes, are then combined to yield an output data layer (or result of the model), known as a response theme (Raines, 1999). WofE was adapted to mineral potential mapping in a GIS and is based on the application of Bayes' Rule of Probability, with an assumption of conditional independence (Raines et al., 2000). Although Bayesian theory has been applied to ground-water related issues in recent years (e.g., Soulsby et al., 2003; Meyer et al., 2003; and Feyen et al., 2004), the specific application of WofE to ground-water issues is very limited to date (Cheng, 2004).

Training Points Theme and Prior Probability

Training points are locations of known occurrences. In mining applications for example, ore deposits are known occurrences. In an aquifer vulnerability assessment, wells with water quality indicative of high recharge are potential known occurrences. Training points are used in WofE to calculate the following parameters: *prior probability* (or, density of training points), weights for each *evidential theme*, and posterior probability of the *response theme*.

Evidential Themes

An evidential theme is defined as a set of continuous spatial data that is associated with the location and distribution of known occurrences, i.e., training points. In GIS terms, an evidential theme is analogous to a data layer or coverage. Evidential themes in the mining example might include an area's proximity to faults. In the FAVA project, soil permeability and thickness of confinement are examples of evidential themes. Weights calculated in WofE establish spatial associations between training points and evidential themes. The two evidential themes used for the IAS FAVA model are displayed to the right and include soil permeability, and a theme created by combining information from both Intermediate Aquifer System overburden thickness and karst features.

Generalization of evidential themes follows calculation of weights in the WofE modeling process. Themes are generalized in an effort to establish which areas of the evidence share a greater association with locations of training points. During calculation of weights for each evidential theme, a contrast value is calculated, which is a combination of the positive and negative weights (positive weight – negative weight) as described in *Introduction – Approach – Models Considered – Weights of Evidence*. 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).

Response Theme

Following the generalization of evidential themes, WofE output results are generated and are known as response themes. A response theme is an output data layer showing the probability (posterior probability) that a unit area contains a training point based on the evidence (evidential theme) provided. Areas of higher posterior probability indicate that an area is more likely to contain a training point, whereas areas of lower posterior probability indicate that an area is less likely to contain a training point. For the FAVA project, a response theme can be a probability map that is displayed in classes of relative vulnerability based on selected water- quality analytes in training point wells.

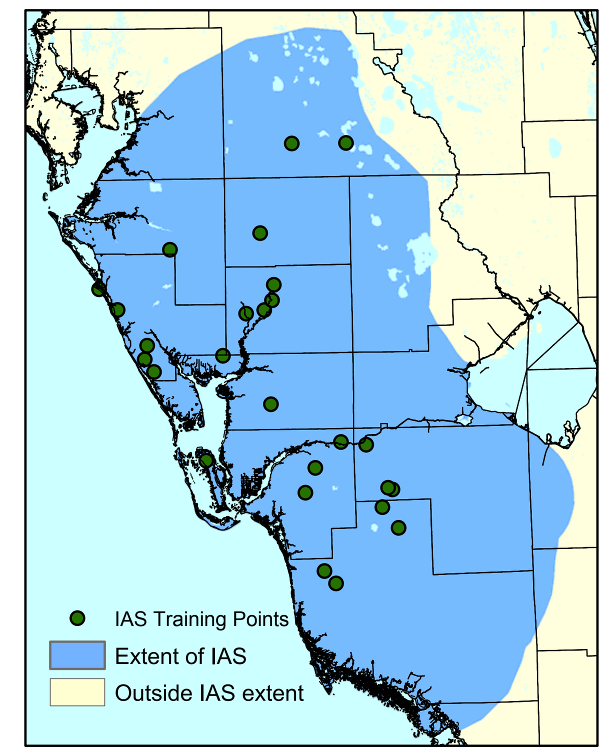
Training Points

There were a total of 295 wells in the FDEP Background Water Quality Monitoring Network that were completed in the IAS study area. These wells were located throughout the State, but for this project, only those falling within the IAS study area displayed in the figure to the right were used. Criteria for selecting IAS training point wells also included that the wells be sampled for both ammonia and dissolved nitrogen during the same sampling event. There were 130 wells that met these criteria. The measured values were then combined to provide a single analyte value per well, total dissolved nitrogen, on which statistical analyses could be completed.

Ammonia concentrations were incorporated into the IAS training point dataset because nitrogen in the form of ammonia can be more prevalent than dissolved nitrogen in deeper parts of the IAS where lack of dissolved oxygen creates a reducing environment. If ammonia was not used in conjunction with dissolved nitrogen, weights calculated for evidential themes using WofE did not produce significant contrast values for use in generalizing the themes.

Using statistical methods described in *Results – Data Coverages –Training Points*, 32 wells were identified as outliers and removed from the dataset leaving 98 wells for further analysis. Further statistical analysis returned a 75th percentile combined median value for a total dissolved nitrogen concentration of 0.457 mg/L. There were 26 wells occurring in the dataset with a total dissolved nitrogen value greater than 0.457 mg/L. These 26 wells were used to create the training point theme for input into the IAS FAVA model. The resulting prior probability was calculated at 0.0009, which represents the chance that a training point will occupy any given unit area within the study area, independent of any evidential theme data.

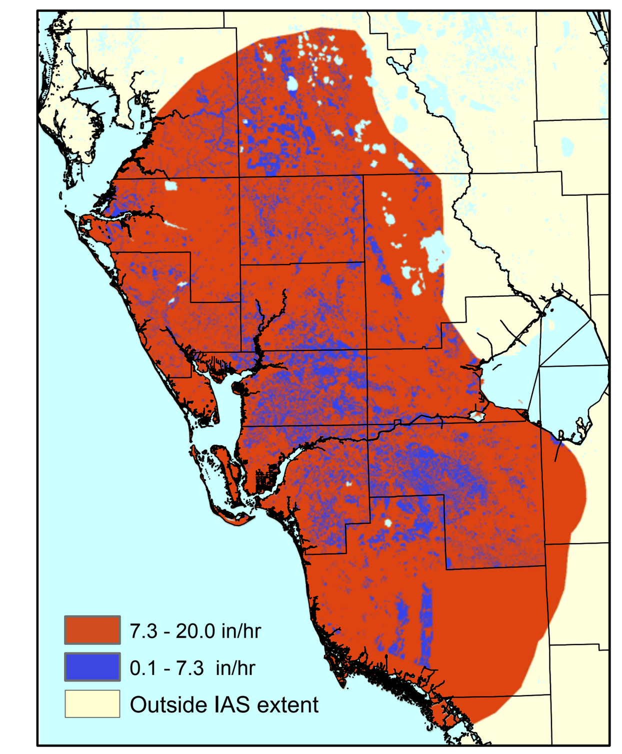
Training Points:
Total Dissolved Nitrogen > 0.457 mg/L



Soil Permeability

Soil permeability is a measure of the rate at which water travels through the upper vadose zone. Areas with high soil permeability values are normally associated with higher aquifer vulnerability. Weights were calculated for soil permeability using the cumulative descending method of the WofE model technique. The highest contrast of any class was calculated at 7.3 in/hr. As defined by the analysis of this evidential theme, the most appropriate break in the soil permeability evidential theme was at 7.3 in/hr creating a binary generalized theme for input into the IAS FAVA model. In other words, this analysis indicates that areas underlain by soils with permeability values ranging from 0.1 to 7.3 in/hr were, based on the location of training points, associated with areas of lower vulnerability. Conversely, the analysis indicates that areas underlain by soils with permeability values ranging from 7.3 to 20.0 in/hr, based on the location of training points, were associated with areas of higher vulnerability.

Evidential Theme:
Soil Permeability (Weighted Average)

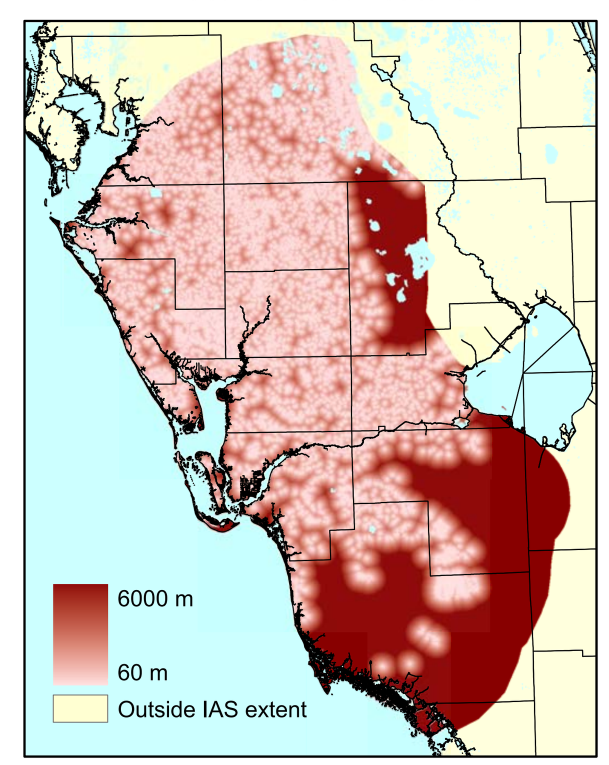


Effective Karst Features

Effective karst is defined herein as those closed topographic depressions that are believed to increase hydrologic communication between land surface and the underlying aquifer system. To develop an appropriate representation of karst features in the IAS model, an effective karst GIS grid was created based on closed topographic depressions and thickness of IAS overburden. This was accomplished by filtering out those depressions underlain by more than 100 feet of IAS overburden. The 100-ft threshold of overburden thickness has been used to identify karst-prone areas by Cichon et al. (2004) and Wright (1974). Though the location of training points was not used to select this filter threshold, the lack of their occurrence in areas underlain by more than 100 feet of overburden thickness lends support to the use of this filter. This calculation provided an effective karst evidential theme for use in the IAS FAVA model. Moreover, this filtering procedure removed several karst "sags" formed by the dissolution of shell material in shallow sediments. Removal of sags from this evidential theme was appropriate because the features do not provide deep vertical preferential pathways to allow surface water to more rapidly reach the IAS.

Because areas nearer to a karst feature are considered more vulnerable to contamination than areas further away, a proximity analysis was completed for the effective karst evidential theme by creating a 6,000-m buffer zone around each karst feature within which equally-spaced 60-m intervals were delineated. The outermost interval contained all areas of the IAS extent which lie 6,000 m or further from a karst feature. Based on spatial analysis, all training points occurred within 6,000 m from an effective karst feature, thereby lending support to that radial distance as a lateral threshold for the delineation of intervals within the buffer zone. This data coverage was combined with proximity to karst features using Fuzzy Logic as described below.

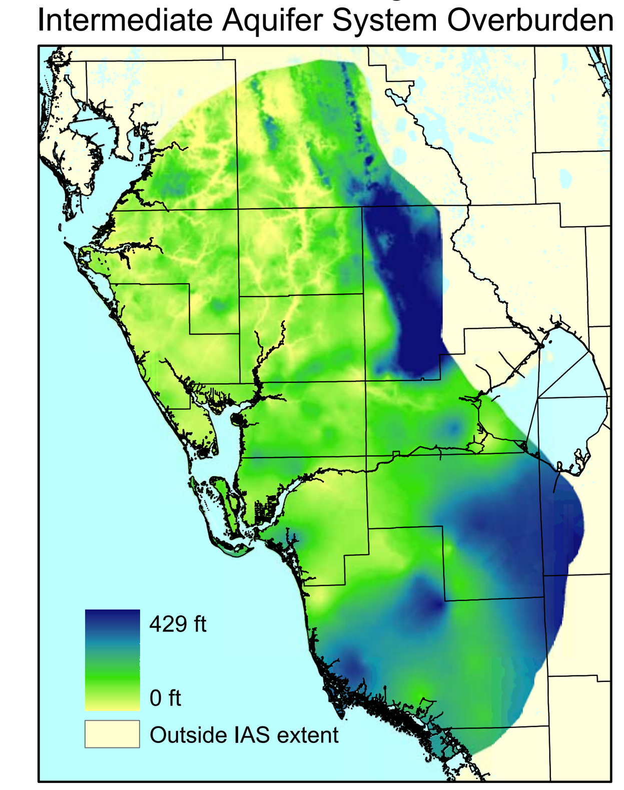
Data Coverage:
Effective Karst Features



Intermediate Aquifer System overburden

Where the IAS is a major regional and productive aquifer system in southwest Florida, overlying sediments form an important protective layer. The materials include undifferentiated sands and clays, shelly sediments of Plio-Pleistocene age, including the uppermost permeable sediments of the Tamiami Formation. To calculate the thickness of sediments overlying the IAS, the surface of the IAS was subtracted from the FDEP DEM. This grid was clipped to the extent of the IAS and used as input into the IAS FAVA model. The thickness of the overburden ranged from a few feet in the northwestern area of the IAS extent to 429 feet along the eastern edge in Highlands County. This data coverage was combined with effective karst features using fuzzy logic as described below.

Data Coverage:
Intermediate Aquifer System Overburden



IAS Overburden and Effective Karst Feature Interdependence – Fuzzy Logic

In the IAS model, IAS overburden and effective karst features were statistically related because the IAS overburden data coverage was used to develop the effective karst layer (see the two figures below for more information on these two data coverages). Specifically, karst features were removed based on the presence of more than 100 feet of IAS overburden thickness. When both coverages were used as themes in the IAS model separately, conditional independence problems arose for the model output. As a result, fuzzy logic was utilized to combine the effective karst and IAS overburden into a single evidential theme displayed in the figure to the right. As discussed in *Introduction – Approach – Models Considered*, fuzzy logic handles the concept of partial truths and can be described as the process of assigning values to events using a gradational or continuous scale between 0 and 1, where 1 represents full membership and 0 is full non-membership.

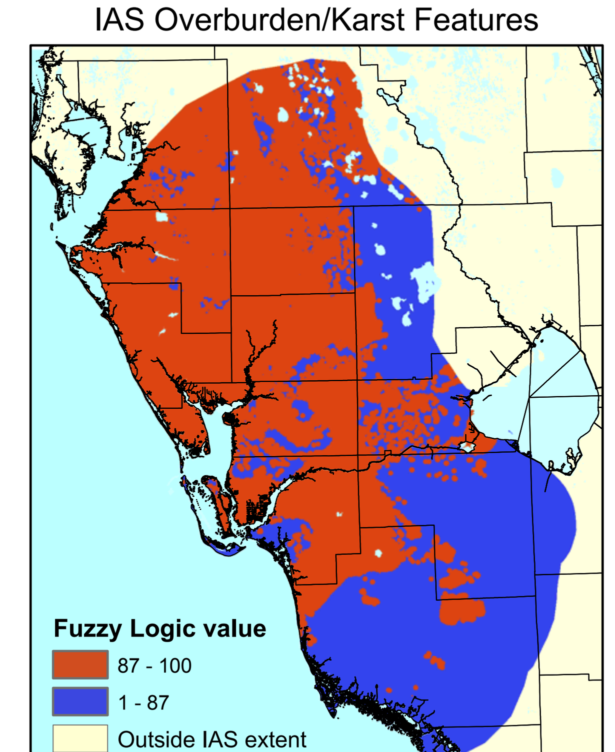
In the effective karst feature evidential theme, a fuzzy membership value of 1 was assigned to all areas that were within 60 meters of an effective karst feature. These areas represent full membership. A fuzzy membership value of 0 was assigned to the class representing areas 6,000 m from karst features, representing full non-membership. Intermediate values were then interpolated in a linear manner.

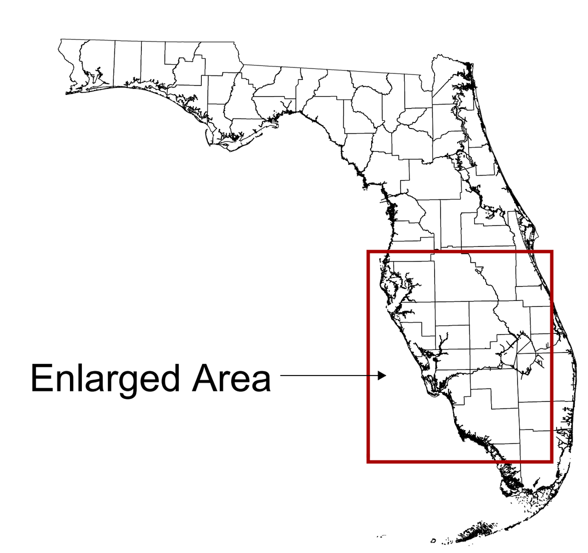
For the IAS overburden evidential theme, areas where the overburden was calculated at zero were assigned a fuzzy membership value of 1 representing full membership and areas where the overburden was thickest (429 feet) were assigned a value of 0, or full non-membership. Intermediate values were then interpolated in a linear manner as well.

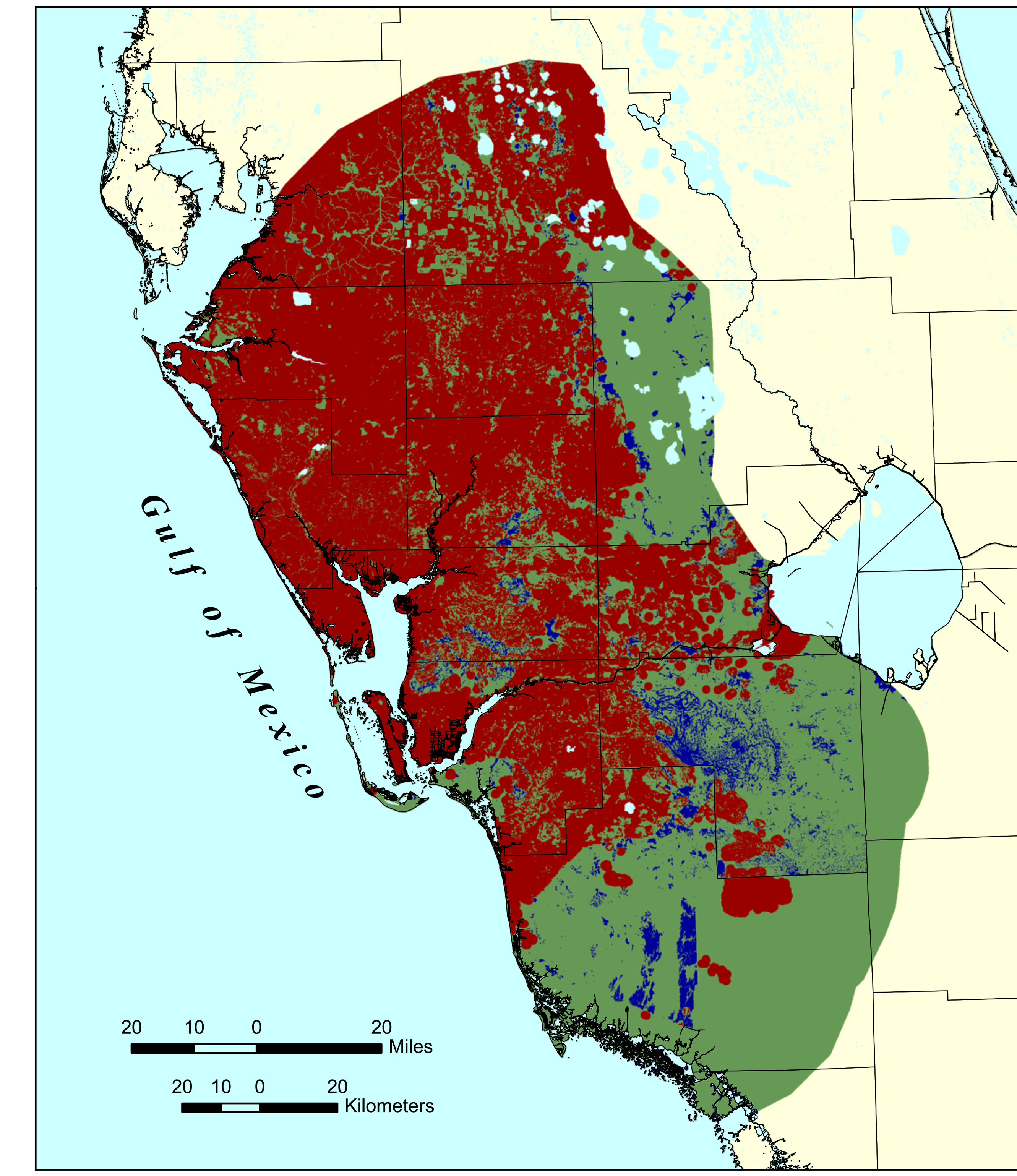
Using these fuzzy membership values the two evidential themes were combined using the fuzzy logic Boolean operator OR. This operator was chosen because it involves the union of a set of values where the maximum input controls the output. The result is an output map, used as evidence, where the values are the "best" of both pieces of evidence. The fuzzy logic output was converted to a GIS integer grid to be consistent with other evidential themes; and, to preserve data resolution, all values were multiplied by 100. The final fuzzy logic output values therefore range from 0-100.

Areas of the IAS overburden/effective karst features evidential theme with higher values correspond to dense karst feature distribution and thin IAS overburden sediments and were therefore associated with higher aquifer vulnerability. For these reasons, weights were calculated for this evidential theme using the cumulative descending method of the WofE analytical technique. The highest contrast of any class was calculated at a fuzzy logic value of 87. As defined by the analysis of this evidential theme, the most appropriate break in the IAS overburden/effective karst features evidential theme was at 87 creating a binary generalized theme for input into the IAS FAVA model. In other words, this analysis indicates that areas where the fuzzy logic value exceeds 87 (i.e., thin overburden and dense effective karst) were, based on the location of training points, associated with areas of higher vulnerability. Conversely, the analysis indicates that areas where the fuzzy logic value is less than 87 (i.e., thicker overburden and sparse effective karst) were, based on the location of training points, associated with areas of lower vulnerability.

Evidential Theme:
IAS Overburden/Karst Features







Relative Vulnerability

- More Vulnerable
- Vulnerable
- Less Vulnerable
- Surface Water Features
- Outside Study Area

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Vulnerability Zones

Zones of relative vulnerability of the Intermediate Aquifer System (IAS) calculated using Weights of Evidence are displayed in the large map above. As noted in the report, all ground water is vulnerable to contamination. As a result, this generalized IAS FAVA map reflects three levels of vulnerability. Each zone represents a range of probability values that an area is vulnerable to contamination from land surface. Evidential themes (data coverages) used for input into this model include: soil permeability and a theme created by combining information from both Intermediate Aquifer System overburden thickness, and effective karst features.

More Vulnerable
Areas of the vulnerability map designated in red represent the *more vulnerable* zone based on output probabilities calculated using WofE. The *more vulnerable* zone encompasses approximately 952 km^2, which is approximately 53% of the total study area.

Vulnerable
Areas of the vulnerability map designated in green represent the *vulnerable* zone based on output probabilities calculated using WofE. The *vulnerable* zone encompasses approximately 12,012 km^2, which is approximately 44% of the total study area.

Less Vulnerable
Areas of the vulnerability map designated in blue represent the *less vulnerable* zone based on output probabilities calculated using WofE. The *less vulnerable* zone encompasses approximately 14,494 km^2, which is approximately 3% of the total study area.