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SCIENTIFIC INVESTIGATIONS MAP 3204
Transmissivity of the Upper Floridan aquifer in Florida and parts of Georgia, South Carolina, and Alabama, 2012
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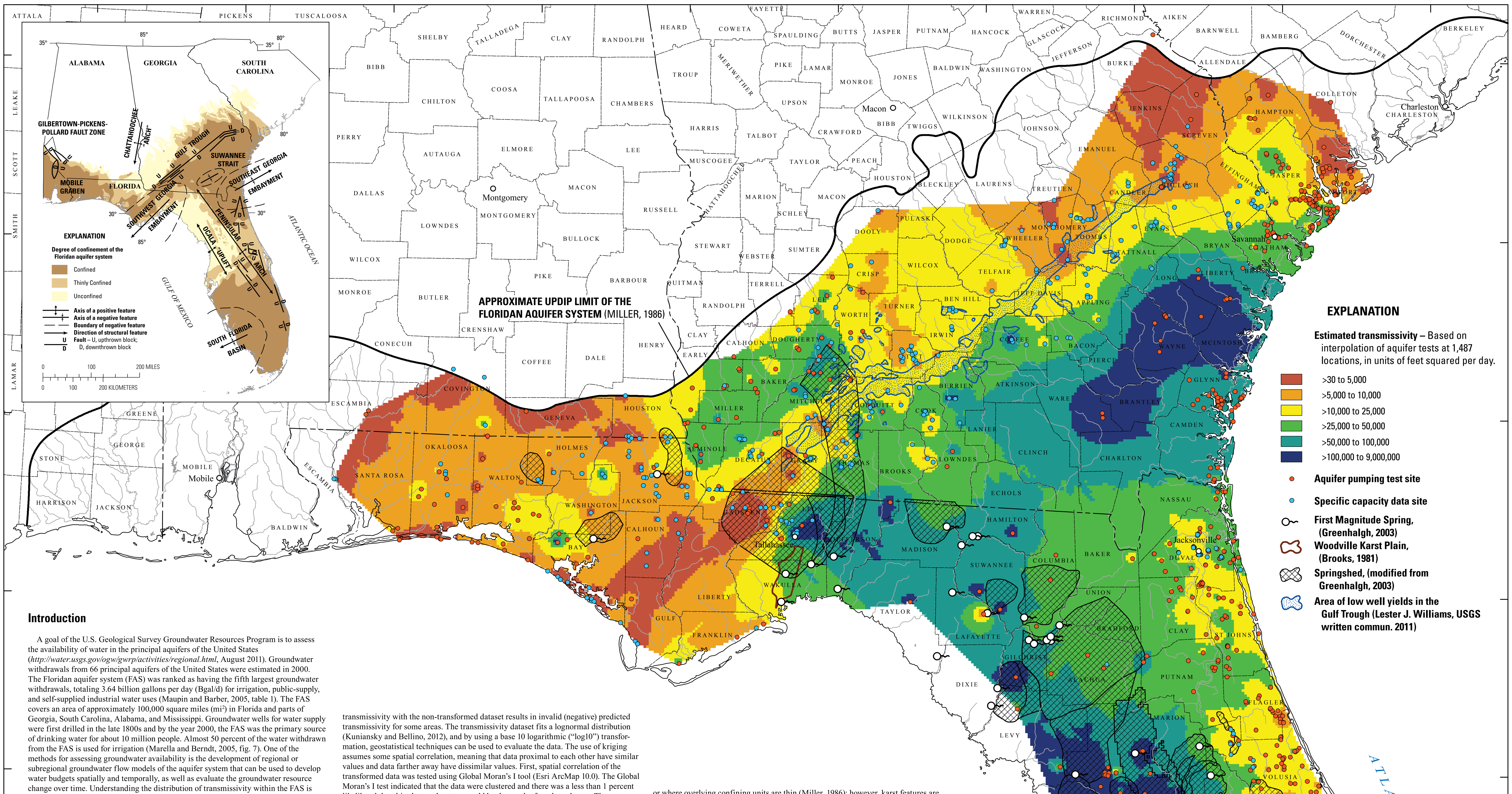

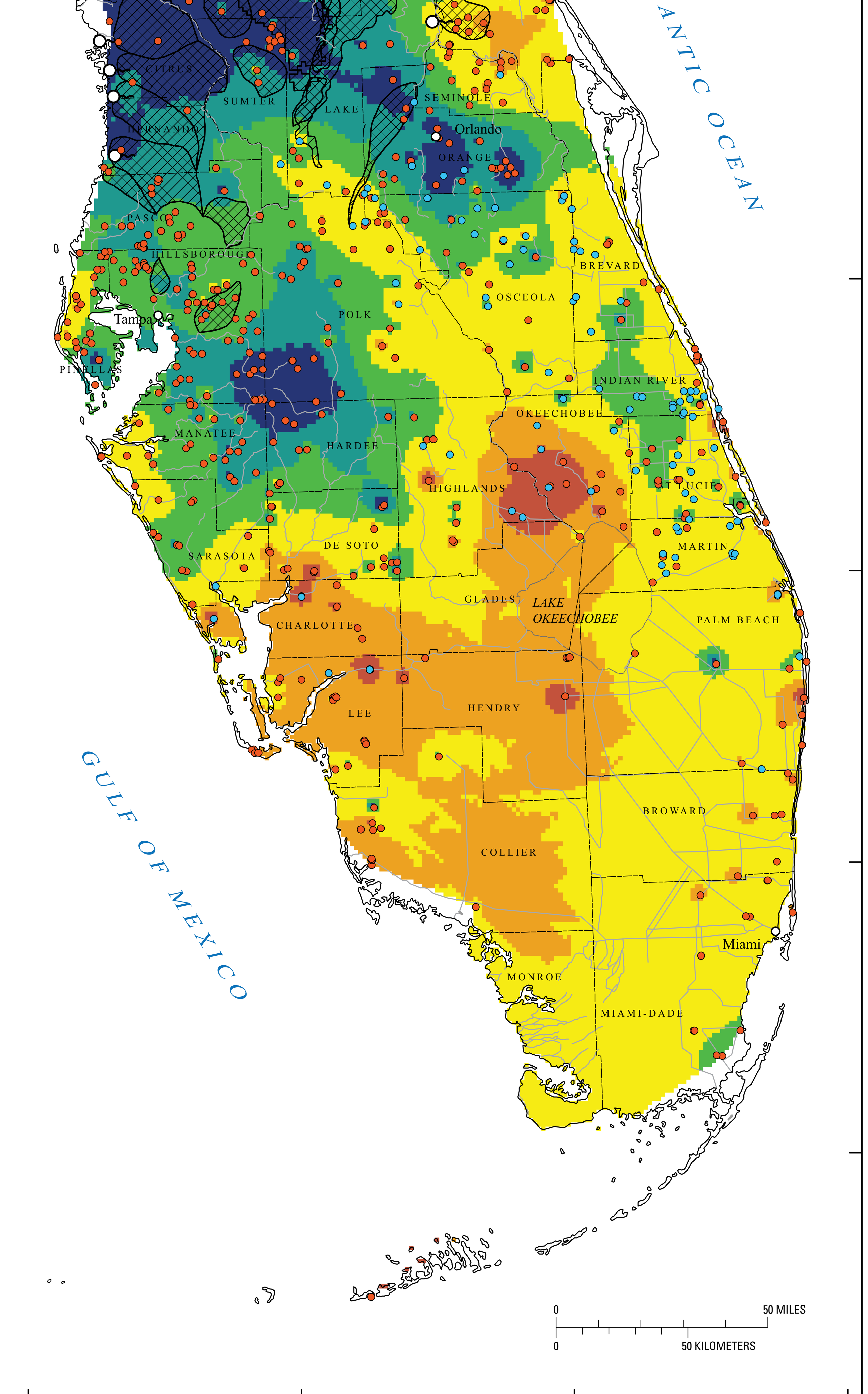

Introduction

A goal of the U.S. Geological Survey Groundwater Resources Program is to assess the availability of water in the principal aquifers of the United States (*http://water.usgs.gov/ogw/gwrp/activities/regional.html*, August 2011). Groundwater withdrawals from 66 principal aquifers of the United States were estimated in 2000. The Floridan aquifer system (FAS) was ranked as having the fifth largest groundwater withdrawals, totaling 3.64 billion gallons per day (Bgal/d) for irrigation, public-supply, and self-supplied industrial water uses (Maupin and Barber, 2005, table 1). The FAS covers an area of approximately 100,000 square miles (mi^2) in Florida and parts of Georgia, South Carolina, Alabama, and Mississippi. Groundwater wells for water supply were first drilled in the late 1800s and by the year 2000, the FAS was the primary source of drinking water for about 10 million people. Almost 50 percent of the water withdrawn from the FAS is used for irrigation (Marella and Berndt, 2005, fig. 7). One of the methods for assessing groundwater availability is the development of regional or subregional groundwater flow models of the aquifer system that can be used to develop water budgets spatially and temporally, as well as evaluate the groundwater resource change over time. Understanding the distribution of transmissivity within the FAS is critical to the development of groundwater flow models.

The FAS is a sequence of carbonate rocks, predominantly of Tertiary age, that generally thickens seaward from the northern boundary of the system. The top of the FAS is confined by late and middle Miocene series rocks and the bottom is confined by early Paleocene series rocks (Miller, 1990). From top to bottom, the major hydrogeologic units of the FAS defined by Miller (1986) are the Upper Floridan aquifer (UFA); middle Floridan confining units (MCU), which are discontinuous units of relatively lower permeability that can be semi-confining or confining; and the Lower Floridan aquifer (LFA). The UFA is the most productive part of the system, containing freshwater throughout the majority of the FAS. Ninety percent of withdrawals from the FAS in 2000 were from the UFA (Marella and Berndt, 2005, p. 5). The LFA contains freshwater over some of the study area, but contains saltwater south of Lake Okeechobee, Florida; in addition, the coastal extent of freshwater in the LFA is generally less than that of the UFA (Bush and Johnston, 1988).

Miller (1986) published a generalized transmissivity map of the UFA based on 114 aquifer tests as well as his understanding of the geologic processes that created the rocks that form the aquifer. Bush and Johnston (1988) modified this transmissivity map after their model calibration and included the aquifer test dataset. Both maps cover the most productive part of the FAS, which is the UFA over most of the system, but also include parts of the MCU and/or LFA in areas where the MCU is semi-confining or absent. Kuniansky and Bellino (2012) tabulated 1,487 estimates of transmissivity from aquifer tests (1,045 values) and specific capacity data (442 values) from wells open to the UFA only and the UFA with parts of the MCU and/or LFA. The map presented herein differs from the previous maps in that it is based on interpolation of the 1,487 values of transmissivity. The transmissivity values in the dataset range from 8 to 9,000,000 feet squared per day (ft^2/d) with the majority of the values ranging from 10,000 to 100,000 ft^2/d. The wide range in transmissivity (6 orders of magnitude) is typical of carbonate rock aquifers, which are characterized by a wide range in karstification. Commonly, the range in transmissivity is greatest in areas where groundwater flow creates conduits in facies that dissolve more readily or areas of high porosity units that have interconnected vugs, with diameters greater than 0.1 foot (ft). These are also areas where transmissivity is largest.

The purpose of this report is to provide an updated map of the estimated transmissivity for the most productive part of the FAS based on aquifer test data; show the delineated springsheds of first magnitude springs indicative of areas that may have large dissolution conduits; and show areas within the Gulf Trough in Georgia where it is unlikely that a high yielding well can be developed in the UFA. Additionally, the geospatial datasets are available for downloading along with the map at (*http://pubs.usgs.gov/sim/3204*). The full database documented in Kuniansky and Bellino (2012) is also available at (*http://pubs.usgs.gov/ds/669*).

Acknowledgments

The transmissivity data used for this map are from aquifer-test data collected and analyzed by the U.S. Geological Survey (USGS); the South Carolina Department of Natural Resources (SCDNR); St. Johns River Water Management District (SJRWMD) and Suwannee River Water Management District (SRWMD), Florida; Northwest Florida Water Management District (NWFWMD); Southwest Florida Water Management District (SWFWMD); and South Florida Water Management District (SFWMD). The authors wish to thank Drennan Park (SCDNR); Rob Devlin and Camille Ransom, South Carolina Department of Health and Environmental Control (SCDHEC); Emily Richardson (SFWMD); Robert Peterson (SWFWMD); Chris Richards (NWFWMD); David Toth and Dale Jenkins (SJRWMD); Carlos Herd (SRWMD); Trey Grubbs, Christy Crandall , and Hal Davis (USGS-Tallahassee, Florida); Lester Williams, John Clarke, Jaime Painter, and Lynn Torak (USGS-Atlanta, Georgia) for providing electronic versions of their databases and tables of aquifer tests. Lester Williams also materially contributed to the map by delineating the area within the Gulf Trough (Ga.) where high yield wells in the UFA are unlikely to be developed. The delineation was made from well yields for approximately 9,000 active wells included in the agricultural well inventory data provided by the Georgia Environmental Protection Division Agricultural Permitting Unit, Tifton, Ga.

Transmissivity Map Development

The map shows ranges of transmissivity predicted by interpolation methods and shows areas of first magnitude springsheds and springs. Also shown on the map are areas within the Gulf Trough in Georgia where well yields from approximately 9,000 active wells and information from drillers indicate a poor likelihood of developing a high yielding UFA well (Lester J. Williams, U.S. Geological Survey, written commun., 2011). The inset location map shows geologic structural features, as well as the extent of the UFA aquifer and where the UFA is shown as unconfined, thinly confined, and confined (from Miller, 1986).

This section of the report describes the geostatistical methods used to explore the transmissivity data and the decision process for the final interpolation method used to create the map. The large number of values and the fairly good spatial distribution of values over most of the UFA allow the use of interpolation. Geospatial tools in ArcGIS (Esri ArcMap 10.0) were used to explore the dataset. The main reason for using geostatistics was to determine if there was spatial correlation in the data and over what distance the correlation occurs. If a dataset does not follow a Gaussian (normal) distribution, as in the case of this transmissivity dataset, many forms of statistical analysis fail. In fact, using geostatistical techniques such as kriging to predict transmissivity with the non-transformed dataset results in invalid (negative) predicted transmissivity for some areas. The transmissivity dataset fits a lognormal distribution (Kuniansky and Bellino, 2012), and by using a base 10 logarithmic ("log10") transformation, geostatistical techniques can be used to evaluate the data. The use of kriging assumes some spatial correlation, meaning that data proximal to each other have similar values and data farther away have dissimilar values. First, spatial correlation of the transformed data was tested using Global Moran's I tool (Esri ArcMap 10.0). The Global Moran's I test indicated that the data were clustered and there was a less than 1 percent likelihood that this clustered pattern could be the result of random chance. Thus, interpolation methods that assume the data are spatially correlated, such as kriging or inverse distance weighting are appropriate.

There is some subjectivity to the process of kriging, as a number of different covariance or semivariogram models can be applied, and several of these were in fact examined. Additionally, different software implementations of kriging have different advantages and disadvantages. The ArcGIS software has an algorithm that uses optimization to find the best fit to the data among the different semivariogram/covariogram models and kriging methods applied, but does not allow weighting of values. Oridnary kriging assumes no spatial trend in the data. Because the thickness of the aquifer increases downdip, which may increase transmissivity, universal kriging was also tested. Universal kriging with constant trend removal provided the best fit to the dataset for prediction of log10 transmissivity. The main parameters of interest from the kriging are the following:

- Range—the distance at which the semivariogram model begins to asymptote, which means that this is the distance where the variance in data becomes constant;
- Nugget—the value of the semivariogram model where it intercepts the y-axis;
- Sill—the value of the variogram at distances greater than the range; and
- Partial sill—the sill minus the nugget.

Additionally, the geostatistical exploration indicated that there was no spatial anisotropy (when values are correlated over different distances in different directions, like the two axes of an ellipse). The nugget was 0.10843 (log10(ft^2/d)), the sill was 0.19724 (log10(ft^2/d)), the partial sill was 0.08881 (log10(ft^2/d)), and the range was calculated as 16,571 ft (3 miles). Trend removal resulted in a fairly flat semivariogram model, with the sill being slightly greater than the nugget.

The implementation of any interpolation method on a computer requires that the estimates be made for the surface by creating a grid in which an interpolated value is computed at each grid cell (grid cell size is determined by the software by dividing the longest extent of the data in the horizontal or vertical direction by 250–2,070 ft per side). Thus, the location of the estimated value may not correspond exactly to the location of the well and the interpolated surface will result in a predicted transmissivity that differs from the "measured" value. The fit of the kriging model to the log10-transformed data resulted in a root-mean square error of 0.53754 and mean error of 0.00290. To put these residuals into context, the range of the log10-transformed data was 6.08, with a mode of 3.47, mean of 4.30, and standard deviation of 0.72. More information about geostatistics and kriging is provided by Isaaks and Srivastava (1989).

The results of the geostatistical exploratory analysis were used to develop the parameters for the deterministic interpolation. This deterministic interpolation approach honors the test data, allows aquifer test estimates to have greater weighting than specific capacity estimates, and makes no assumptions about the spatial variogram and statistical distribution of the data in order to create a transmissivity surface. The final map was developed using inverse-distance weighting with a four-sector search rotated 45 degrees and a search radius of 39,170 ft. The search radius from kriging is set by the software and is a little more than double the range; however, if values are found closer to the grid centroid, then those values are used–a minimum of 10 and maximum of 15 weighted values.

Inverse-distance weighting (IDW) is considered an exact interpolation method because, in theory, the method produces the exact values of the data at the locations of known values. However, the implementation on the computer uses the same griding method as the kriging, thus the grid size was determined in the same manner. A benefit of the use of IDW for the final map presented is the ability to apply additional weighting based on the method for estimating an individual value. Transmissivity estimates from single- and multi-well aquifer performance tests (APT) are better estimates than those calculated from specific capacity data (SPC). Therefore, weighting based on the test method was applied in addition to inverse-distance weighting (any details about the quality of individual estimates are in the reference or remark field of the database (Kuniansky and Bellino, 2012)). Transmissivity estimates from APT and SPC were given weights of 1.0 and 0.5, respectively, indicating that estimates from SPC are half as good as estimates from APT. If multiple values were approximately in the same location for the interpolation, the mean value was used. Although the search method and radius were set to the values determined from kriging, and the additional weighting of APT and SPC tests was applied in the IDW, the optimization function was used to determine the power of the inverse distance weighting. The optimal power is typically between 1 and 2, and was 1.276 in this case. The mean error (predicted minus measured) for the IDW interpolation of the log10-transformed transmissivity was 0.03168 and the root mean square error was 0.54181, similar to the errors previously shown for universal kriging interpolation. The transmissivity ranges shown with differing color shading were based on rounding natural breaks in the distribution of the values. Only 52 (3 percent) of transmissivity values were less than 1,000 and 21 (1 percent) were greater than 1,000,000 ft^2/d. Additionally, the final IDW transmissivity surface was converted to a raster dataset where all raster values outside a polygon created from the outer points of the transmissivity data and the extent of the FAS were deleted and the final grid cell side length for the raster shown is 1 mile per side.

Discussion of the Transmissivity Map

The FAS contains many different facies and has been exposed to a range of post-depositional processes, the details of which are discussed in Miller (1986). Bush and Johnston (1988) did not try to determine transmissivity in the highly karstified areas of the FAS. In general, the greatest areas of karstification are where the limestone crops out or where overlying confining units are thin (Miller, 1986); however, karst features are present over most of the extent of the FAS (Veni and others, 2001; Tobin and Weary, 2004). Although the presence of sinkholes also indicates karstification, less permeable cover materials may fill in the sinkholes and their associated conduits (Sinclair and Stewart, 1985; Wilson and Shock, 1996; and Tihansky, 1999). Thus, sinkholes are not used to identify areas that might have large submerged cave passages, nor are they shown on the map.

Large dissolution conduits generally are near many of the first magnitude springs and springsheds. Generalized springsheds for these springs are shown in Greenhalgh (2003). Over the past 20 years, submerged, large-diameter interconnected caves have been mapped in the Woodville Karst Plain (Brooks, 1981). The Woodville Karst Plain and springshed areas shown are generalized from the original maps (Tom Greenhalgh, Florida Geolological Survey, written commun., August 2011), and the estimates of transmissivity may underestimate the actual range in transmissivity in these areas. Wells that intercept conduits greater than 5 ft in diameter could have a transmissivity greater than 10 million ft^2/day (Shoemaker and others, 2008), whereas a nearby well that did not intercept a conduit could have a transmissivity orders of magnitudes lower. An example of this is on the map in Lafayette County, Florida, where there is a low transmissivity bulls eye associated with one well in an area surrounded by first magnitude springs and wells with orders of magnitude greater transmissivity estimates.

The interpolated transmissivity ranges shown on this map reflect the geologic structure and karstified areas. Transmissivity is large in the areas where the system is unconfined, such as west-central Florida and southwest Georgia just northwest of the Gulf Trough. Transmissivity is small along the Gulf Trough and Southwest Georgia Embayment (referred to as Apalachicola Embayment in some reports). Both features are known to have a thick accumulation of fine-grained sediment, and often are treated as a single low hydraulic conductivity feature within the FAS (Miller, 1986; Kellam and Gorday, 1990; Davis, 1996; Torak , Painter and Peck, 2010). Transmissivity is also small in the thin, updip part of the system near its northern boundary. Another area of large transmissivity coincides with the Southeast Georgia Embayment, where the FAS thickens and is composed of carbonate rocks (Miller, 1986).

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