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GEOSTATISTICAL ANALYSIS: WATER QUALITY MONITORING NETWORK FOR THE UPPER FLORIDAN AQUIFER IN EAST-CENTRAL FLORIDA

by

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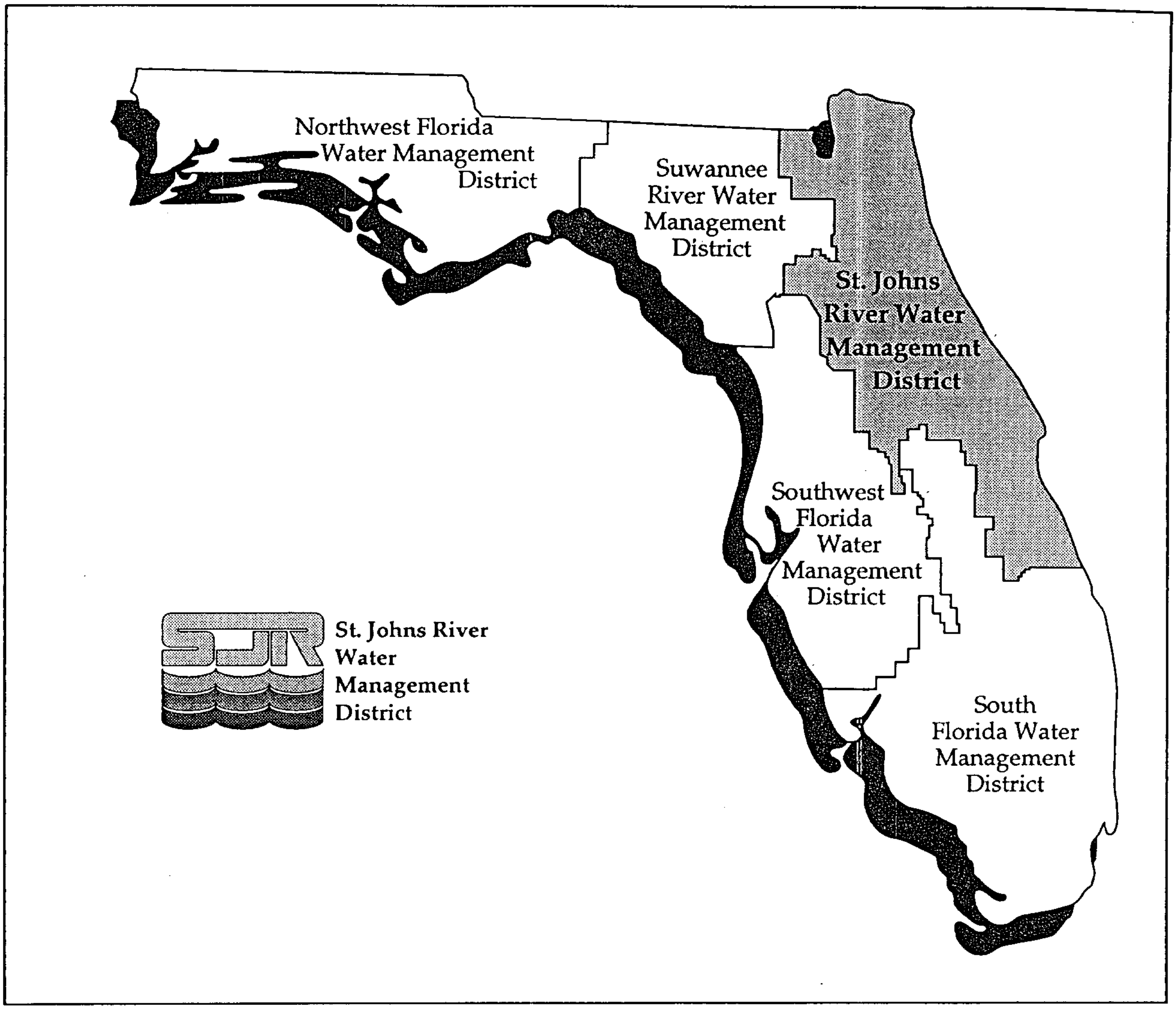

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EXECUTIVE SUMMARY

Geostatistics provides a framework for the analysis, characterization, and estimation of spatial data. A geostatistical analysis was undertaken to assess regional chloride conditions in the Upper Floridan aquifer. This analysis was based on data from the current water quality monitoring network in the De Land groundwater basin. The analysis was undertaken as a means of devising a more efficient monitoring network for this area within the St. Johns River Water Management District.

Chloride concentration data from 84 wells in the De Land groundwater basin were analyzed. Because of anomalous data (very high chloride concentrations) and the distribution of the data, the data were transformed to yield a normally distributed data set that is suitable for geostatistical analysis.

An anisotropic variogram model was fitted to the transformed chloride data. A variogram is a graph that depicts the spatial variability between samples and the distance between samples. Sensitivity analysis of model parameters was performed to validate the suitability of the selected model. Cross-validation was performed to assess the overall quality of the selected model and estimation procedures.

A chloride concentration map was created for the De Land groundwater basin. This map displayed the zone of high chloride concentration along the coast of the Atlantic Ocean (the eastern edge of the basin) where there is a mixing of freshwater in the Floridan aquifer with intruded seawater. Areas of high chloride concentration were also displayed along the western edge of the groundwater basin in discharge areas near the St. Johns River, where there is a mixing of upwelling residual seawater with freshwater in the Floridan aquifer. An area of high chloride concentration also was displayed in Flagler County where freshwater mixes with residual formation water that has not been replaced by fresh recharge water. The areas of low chloride concentrations were located in the upland ridge recharge areas of the Floridan aquifer. The geostatistical analysis resulted in a valid

characterization of chloride concentrations in the De Land groundwater basin.

The modeled network minimizes the number of wells required to evaluate regional water quality conditions in the Upper Floridan aquifer. A 30,000-foot hexagonal grid consisting of 81 grid cells was selected as the optimal grid to determine regional water quality conditions. Of the 81 grid cells, 30 had no well data. New or existing wells should be added to the regional monitoring network in these locations, particularly in southeastern Volusia County, northern Brevard County, and southern Flagler County.

In designing this regional network, consideration was given to certain areas in the De Land groundwater basin—areas of critical concern. The data needs in these areas are subregional and require a well network that is denser than the proposed regional network. Primary critical concern areas were identified as those areas in the Upper Floridan aquifer with projected water level drawdowns of greater than 3 feet by the year 2010. Secondary critical concern areas include the areas of high chloride concentration along the eastern and western edges of the basin.

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INTRODUCTION

An effective groundwater monitoring program is required to ensure that water quality is acceptable for an intended use. The Upper Floridan aquifer is the primary source of water for public supply, agricultural, and industrial uses in the De Land groundwater basin and most other areas in the St. Johns River Water Management District (SJRWMD) (Figure 1). The De Land groundwater basin is located in east-central Florida. The basin encompasses most of Volusia County; southeastern Putnam, southern Flagler, and northern Brevard counties; and a small part of northeastern Seminole County (Figure 2).

Geostatistics (see glossary) provides a framework for the analysis, characterization, and estimation of spatial data, such as water quality data. This report evaluates the adequacy of the existing monitoring network to assess water quality conditions and recommends changes for future monitoring.

OBJECTIVES

The primary objective of this study was to evaluate the regional water quality monitoring network for the Upper Floridan aquifer in the De Land groundwater basin. The primary uses of the current network are to assess water quality conditions on a regional basis and to detect changes or trends in water quality that may occur over time. Changes may stem from human, climatic, or hydrogeologic factors. The objective was achieved through the analysis of available water quality data, using geostatistics.

The secondary objective was to define the subregional areas within the regional network that require increased spatial and temporal monitoring.

WATER QUALITY MONITORING NETWORK FOR THE UPPER FLORIDAN AQUIFER

The water quality monitoring network for the Upper Floridan aquifer in the De Land groundwater basin is a regional network. The regional nature of the network requires uniform spatial coverage with an

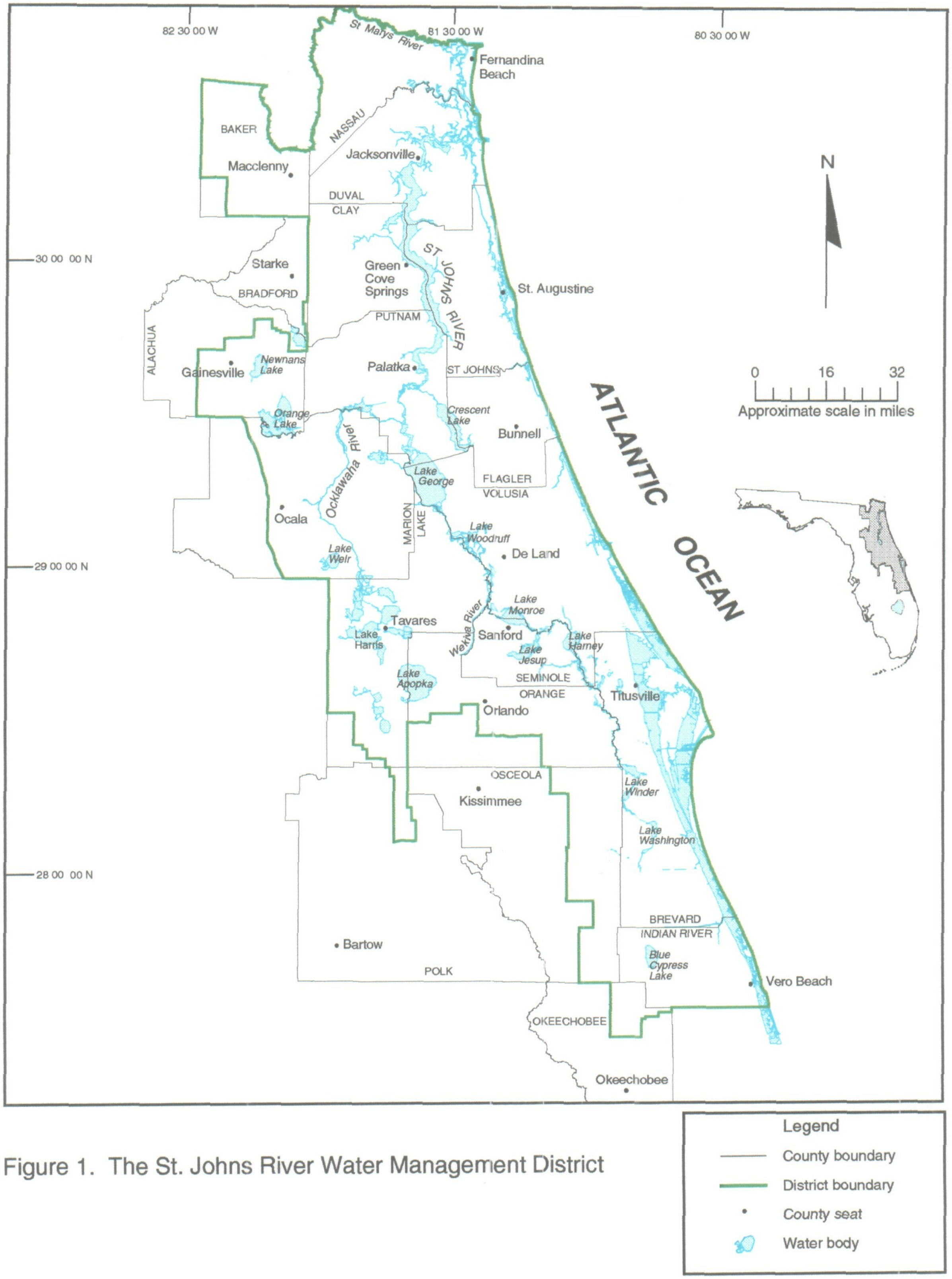


Figure 1. The St. Johns River Water Management District

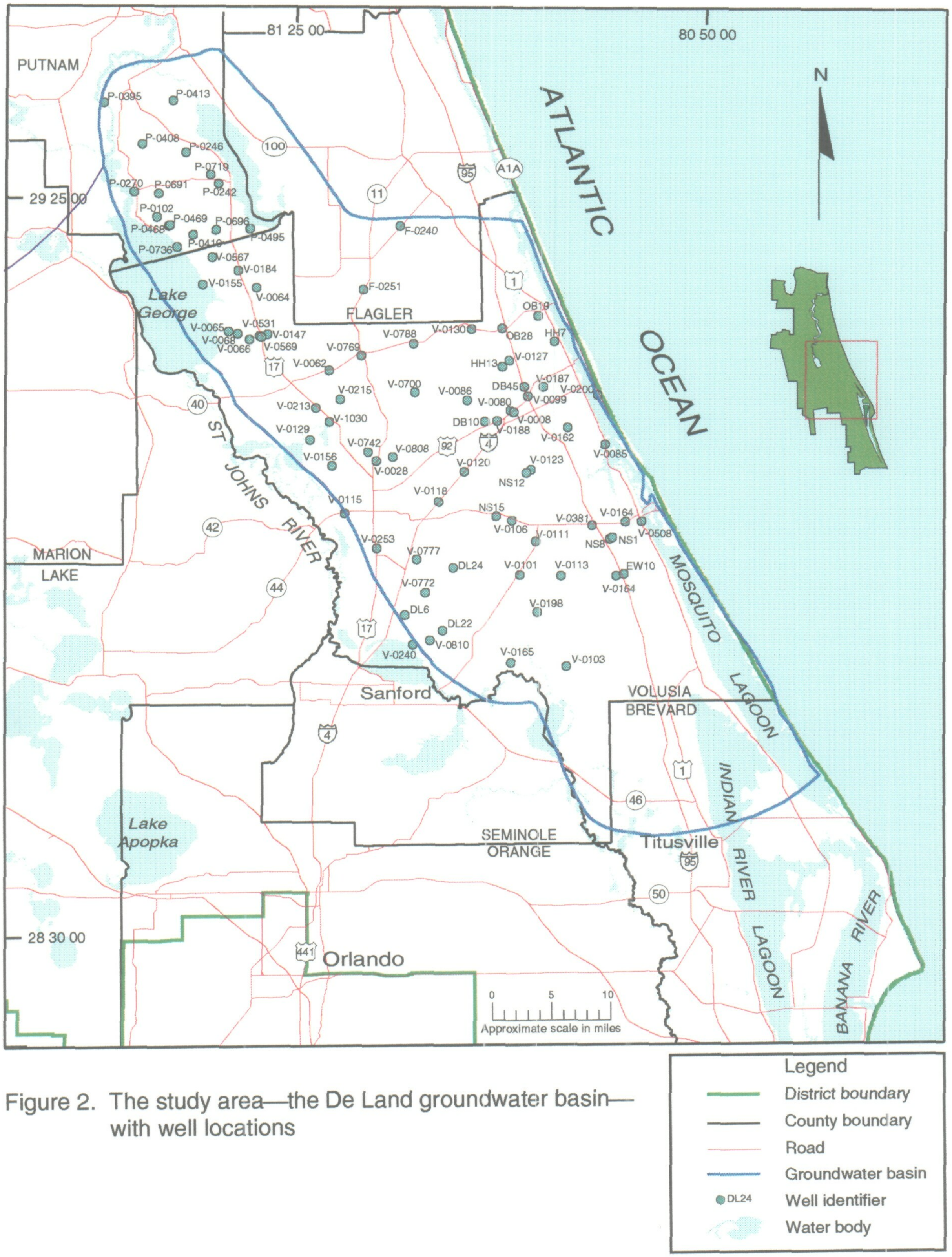


Figure 2. The study area—the De Land groundwater basin—with well locations

adequate density to assess current water quality conditions. This regional design may not provide adequate information to address subregional issues, such as seawater intrusion or the sustainability of major wellfields. Increased spatial well coverage and sampling will likely be required to address such subregional issues.

The water quality data used in this study came from 84 wells completed in the Upper Floridan aquifer within the De Land groundwater basin (Figure 2) (Appendix A). The majority of the data came from samples collected and analyzed as part of the SJRWMD Ground Water Quality Monitoring Program (GWQMP) in conjunction with the Florida Department of Environmental Protection and as part of the SJRWMD District Observation Well Network (DOWN) project. The data from these monitoring wells are representative of groundwater quality in the Upper Floridan aquifer near the sampled wells. Water quality data from public supply wells were also used; these data were provided by water supply utilities within the De Land groundwater basin. Due to frequent pumpage from these wells, the measured chloride concentrations are representative of large capture zones surrounding the sampled wells. These wells are mostly located in areas where the chloride concentrations are relatively low and uniform. Therefore, the public supply well data, like the monitoring well data, are assumed to be representative of water quality in the vicinity of the sampled wells.

WATER QUALITY DATA

The water quality of an aquifer is characterized by the chemical constituents and the physical properties of the water. The chemical and physical characteristics of a groundwater sample represent the net effect of all the previous chemical processes that have dissolved, altered, or precipitated the chemical constituents. The primary factors that influence these chemical processes and determine the chemical and physical characteristics of groundwater in an aquifer system are listed below.

- Climatic conditions and precipitation chemistry
- Land surface features and soil types in the recharge area
- Lithology and mineralogy of the aquifer materials
- Recharge, discharge, and leakage relationships among aquifers

- Precipitation and dissolution of minerals
- Flow paths and residence time
- Mixed water of different chemical compositions
- Aquifer biochemistry
- Cultural effects resulting from human activities

Hem (1985) contains more detailed discussions on these factors.

The GWQMP and the DOWN project provided data on the cations and anions that constitute a major part of the total dissolved solids content of water and on other chemically related variables, and also on field measurements (Appendix B). Cations included calcium, magnesium, sodium, and potassium; anions included chloride, sulfate, and alkalinity. Chemically related variables included total dissolved solids and hardness. Field measurements included temperature, pH, and specific conductance. The GWQMP and DOWN data were from samples collected and analyzed from 1990 through 1996. Chloride data were also available from 1997 analyses reported by the public supply utilities. If a well was sampled more than once, the mean of the data values was used in the analysis.

Chloride was the water quality variable selected for geostatistical analysis. Chloride is a very soluble ion that does not readily enter into any major precipitation or dissolution reaction under the conditions found in Florida's aquifer systems. Chloride has been measured in each of the 84 wells, providing an ample base for analysis. The sources of chloride in Florida's aquifer systems are recent seawater that has intruded into freshwater zones, residual seawater in the aquifer, and marine aerosols. Analysis of chloride data is useful for evaluating the extent of seawater intrusion and fresh groundwater/residual seawater mixing.

Chloride is regulated as a secondary drinking water standard. The state standard for chloride in groundwater is 250 milligrams per liter (mg/L). Chloride concentrations over 250 mg/L are associated with bad taste and corrosion.

GEOSTATISTICAL ANALYSIS

Geostatistics is a collection of statistical methods for the analysis and estimation of spatial data. These methods incorporate the spatial characteristics of actual data into statistical estimation processes. Water quality data, such as chloride concentrations, typically vary widely within a groundwater basin. Classical (i.e., nonspatial) statistical estimation methods have traditionally been used on such data. These methods usually assume that the collected data are unbiased, unclustered, and independent, or devoid of any correlational structures. In practice, however, groundwater quality data are expected to display a degree of spatial structure and may be clustered around critical locations.

Geostatistics recognizes these factors and uses well-defined criteria to provide the statistical tools for (1) calculating the most accurate estimations, based on sample results, (2) quantifying the accuracy of these estimations, and (3) selecting the optimal locations to be sampled. As a result of the successful application of geostatistical tools, the U.S. Environmental Protection Agency (1990) has recommended use of these tools in spatial environmental data analysis.

GEOSTATISTICAL SOFTWARE AND STANDARD GUIDES

ISATIS software was used to perform this geostatistical analysis. ISATIS was developed by Geovariances and the Center of Geostatistics at the Paris School of Mines (Geovariances 1997). This program includes extensive estimation and simulation options combined with an efficient data management system. ISATIS results have been extensively validated by research work and practical applications in an increasing variety of new fields.

The geostatistical procedures used in this study conform to the American Society for Testing and Materials (ASTM) standard guides. The following ASTM standard guides were used:

- D 5549-94 for reporting geostatistical site investigations (ASTM 1994)

- D 5922-96 for analyzing spatial variation in geostatistical site investigations (ASTM 1996a)

- D 5923-96 for selecting kriging for use in geostatistical site investigations (ASTM 1996b)

Preliminary Analysis of the Data

Chloride data were available for 84 Upper Floridan aquifer wells in the De Land groundwater basin (Figure 3). If a well was sampled more than once, the mean of the data values was used in the analysis. The lowest chloride concentrations occurred in the upland ridge recharge areas of the Floridan aquifer system. The highest chloride concentrations occurred along the coast of the Atlantic Ocean due to the effects of seawater intrusion. High chloride concentrations also occurred in areas along the western edge of the groundwater basin due to an upwelling of residual seawater in discharge areas of the Floridan aquifer system near the St. Johns River, and in Flagler County due to the mixing of freshwater with residual formation water still present in the aquifer. The highest chloride values were reported in wells V-0200 (14,700.0 mg/L), V-0508 (4,430.0 mg/L), V-0129 (2,200.6 mg/L), V-0155 (871.0 mg/L), V-0810 (699.5 mg/L), V-0240 (626.6 mg/L), and V-0085 (551.0 mg/L) (Appendix B).

Descriptive statistics for the chloride data included minimum, quartile, median, and maximum concentration levels as well as mean and standard deviation values (Table 1). The mean and standard deviation were inflated by anomalous data and did not adequately describe the majority of the data. Therefore, the median and the quartile information were more appropriate measures of the location and spread of the data.

The distribution of the chloride concentrations is depicted in a box plot graphical summary, which displays the mean of the data set and the 25th, 50th (median), and 75th percentiles (Figure 4). The data falling below the 10th percentile and above the 90th percentile are also shown. The solid center line in the box plot is the median, or the central value of the data distribution when the data are ranked in order of magnitude. The dashed line represents the mean of the data. The box height is the interquartile range from the 25th percentile to the

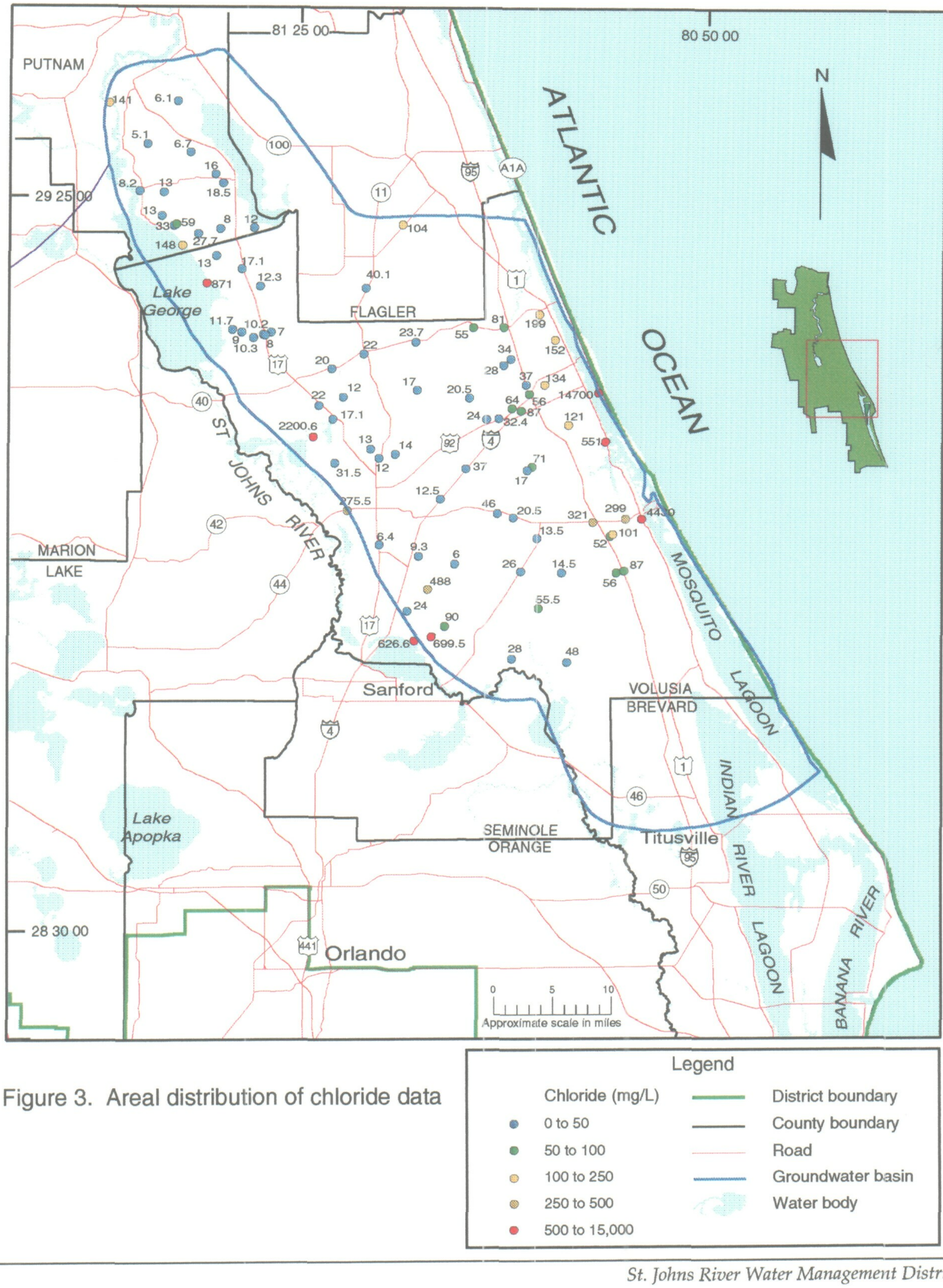


Figure 3. Areal distribution of chloride data

Table 1. Summary statistics of chloride data from 84 monitoring wells in the Upper Floridan aquifer

Statistical Factor	Chloride Value (mg/L)
Minimum	5.1
25th quartile	13.0
Median	28.0
75th quartile	87.0
Maximum	14,700.0
Mean	337.7
Standard deviation	1,667.9

Note: mg/L = milligrams per liter

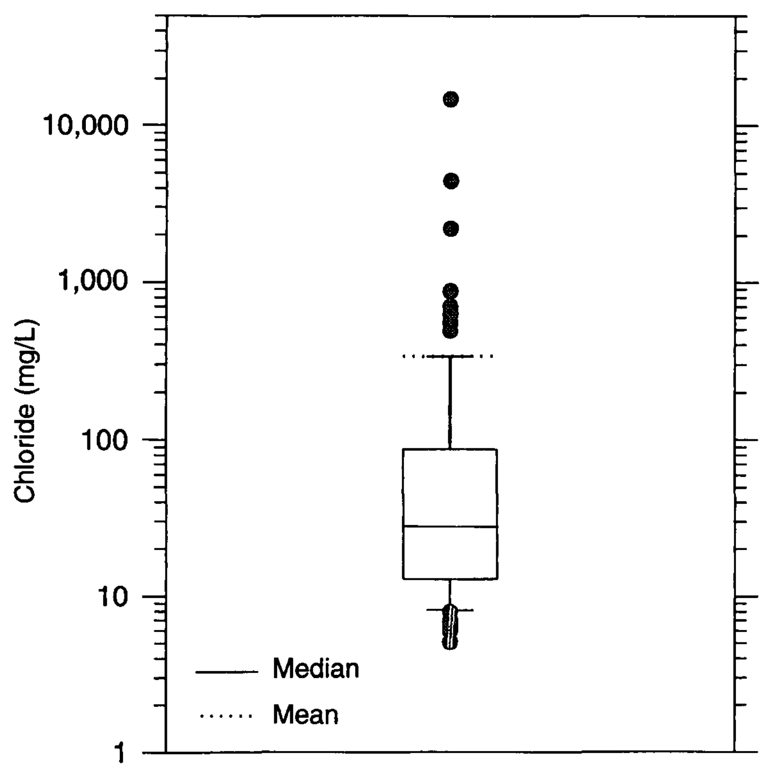


Figure 4. Box plot of chloride data

75th percentile and depicts the variation of the data. The lines extending below and above the box, called the box plot whiskers, represent data to the 10th and 90th percentiles, respectively. The dots below and above the whiskers indicate the presence of outlier values. The dots, the whiskers, and the relative size of the box halves provide an indication of the skewness of the data (Helsel and Hirsch 1993).

Due to the anomalous data, which were considerably higher than other reported values, the chloride data were nonnormally distributed, resulting in a positively skewed histogram (Figure 5). The histogram depicts the majority of the data clustered at low concentrations (less than 100 mg/L); it also shows the anomalous high chloride concentrations in wells V-0200, V-0508, and V-0129.

Using ISATIS, a natural logarithmic transformation of the data was performed. Although the low chloride concentrations occurred in the center of the basin and the high chloride concentrations occurred along the eastern and western boundaries of the basin, the transformed chloride data generated a single, normally distributed data set that is suitable for geostatistical analysis (Figure 6). The linear pattern of the probability plot of the transformed chloride data further confirms that the transformed values fit a normal distribution (Figure 7).

STRUCTURAL ANALYSIS OF THE DATA

A structural analysis was conducted to determine the spatial correlation of the investigated data. The process was accomplished through the computation and modeling of the variogram function. A variogram is a graph that depicts the average of one-half of the squared differences between data values as a function of the separation distance (ASTM 1996a). The use of a variogram allows one to assess how well a sample measurement at one location can represent the concentration at another location a certain distance and direction away. In this analysis, the transformed chloride data values were used to calculate the experimental variogram and to select an appropriate model. The model was used to estimate chloride concentrations and the standard deviations of the estimated concentrations.

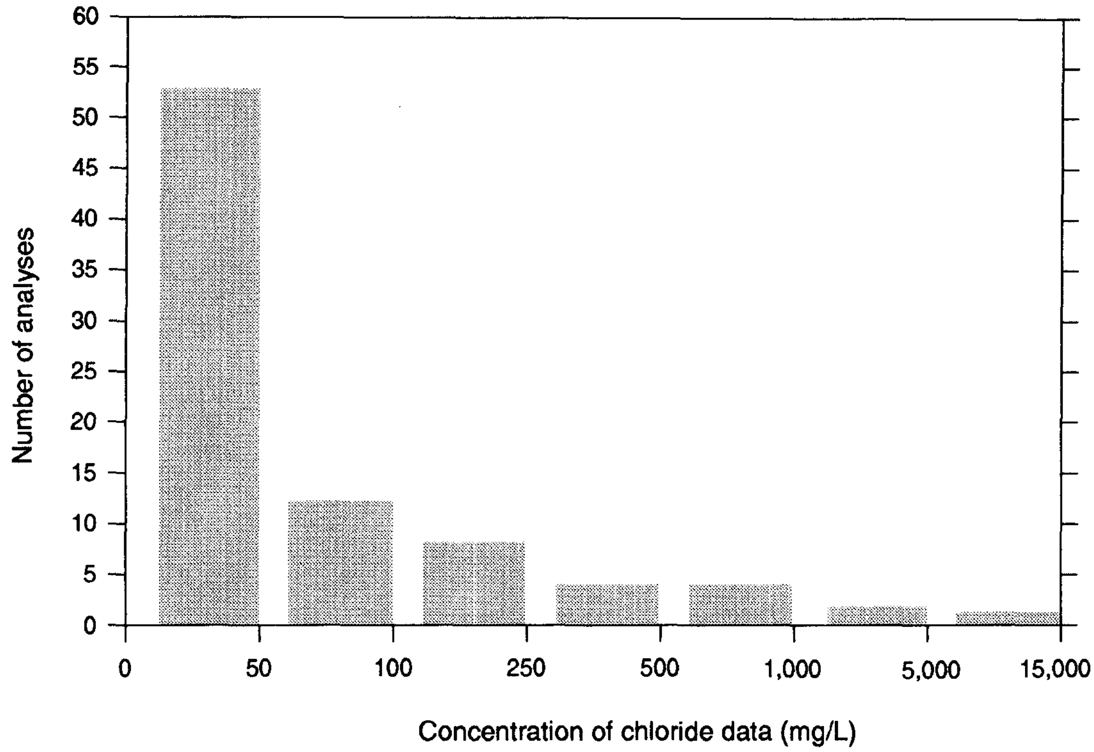


Figure 5. Frequency histogram of chloride data. *The high values over 1,000 mg/L come from samples taken at wells V-0200, V-0508, and V-0129.*

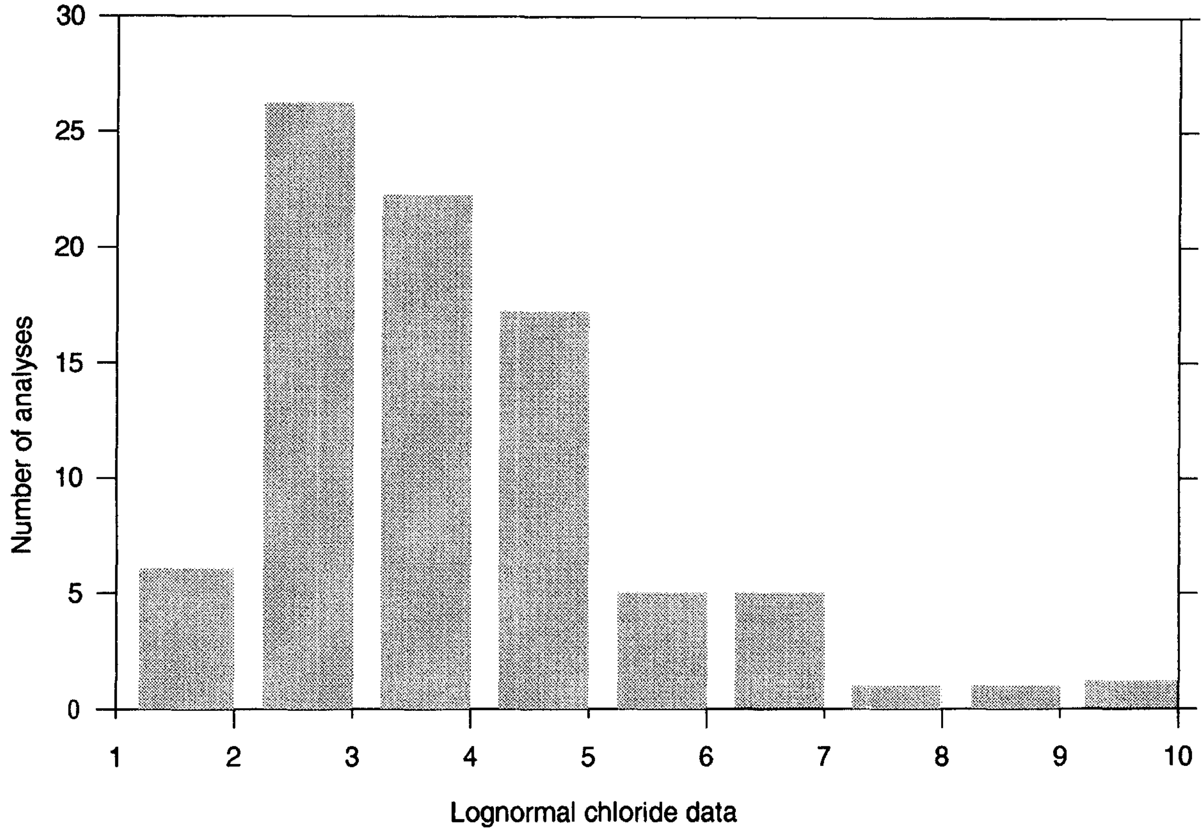


Figure 6. Frequency histogram of transformed chloride data

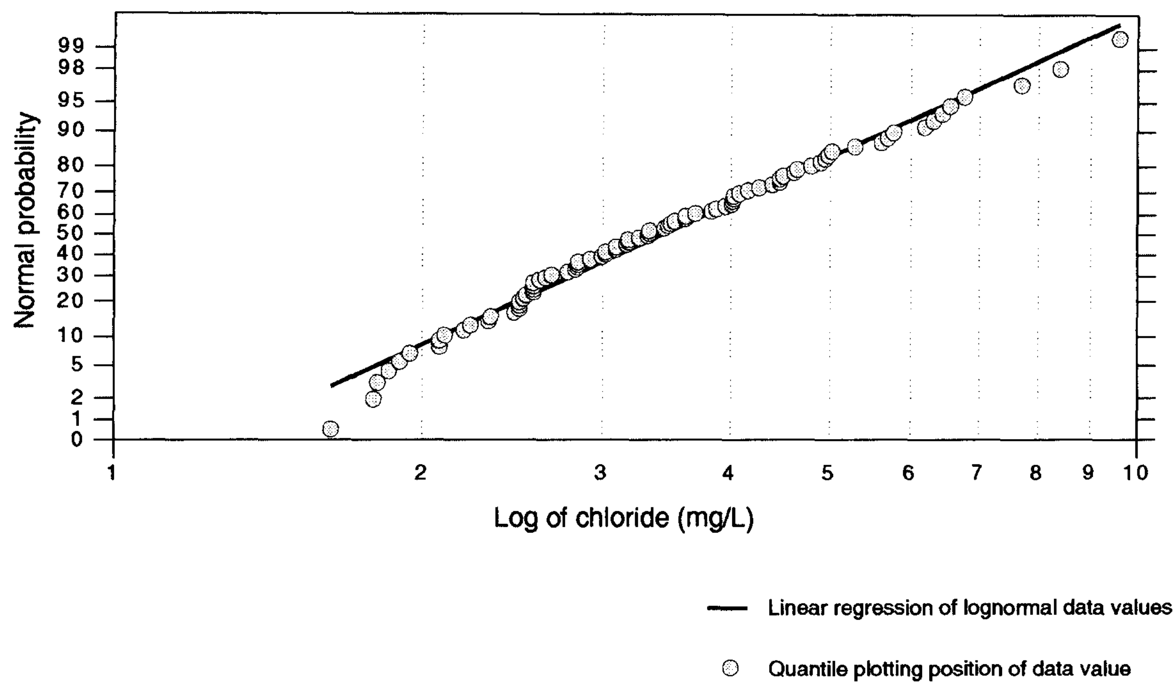


Figure 7. Probability plot of transformed chloride data

Variogram Cloud

A variogram cloud is a diagram of one-half of the squared difference between all pairs of data values along a given direction plotted against their corresponding separation distances (Geovariances 1997). The variogram cloud was used to create a variogram, which depicts the spatial variability between samples and the distance between samples.

The presence of anomalous values in the variogram cloud causes distortion and masks the underlying variogram structure. To avoid these problems, the high chloride measurements were masked during the ensuing variogram analyses. A review of the variogram cloud for the transformed chloride data indicates that the majority of the high pair differences were associated with the high chloride values for wells V-0200 (14,700.0 mg/L), V-0129 (2,200.06 mg/L), and V-0155 (871.0 mg/L) (Figure 8). In subsequent cross-validation and estimation procedures, the entire data set—including the high measurements—was used.

Experimental Variograms

For modeling purposes, the pair results in the variogram cloud plot are grouped into a number of distance groups, or lags. The lag is the distance at which sample differences are compared. In each lag, the average of one-half the squared differences is computed and plotted against its corresponding separation distance. The resulting plot is referred to as the experimental variogram (ASTM 1996a).

Omnidirectional and directional experimental variograms were examined with lag distances ranging from 10,000 to 30,000 feet (ft) and lag counts ranging from five to ten lags. An omnidirectional variogram is one in which the spatial correlation structure of the data set depends only on the variability of the separation distance between data values and not on the direction (e.g., northeast-southwest). A directional variogram has a structure dependent on both distance and direction.

A lag value of 16,000 ft and a lag count of nine were selected as input values to the omnidirectional experimental variogram (Figure 9). The number of data pairs for each lag interval, as enumerated in Figure 9, ranged from 25 to 326 pairs. Generally, a variogram is considered

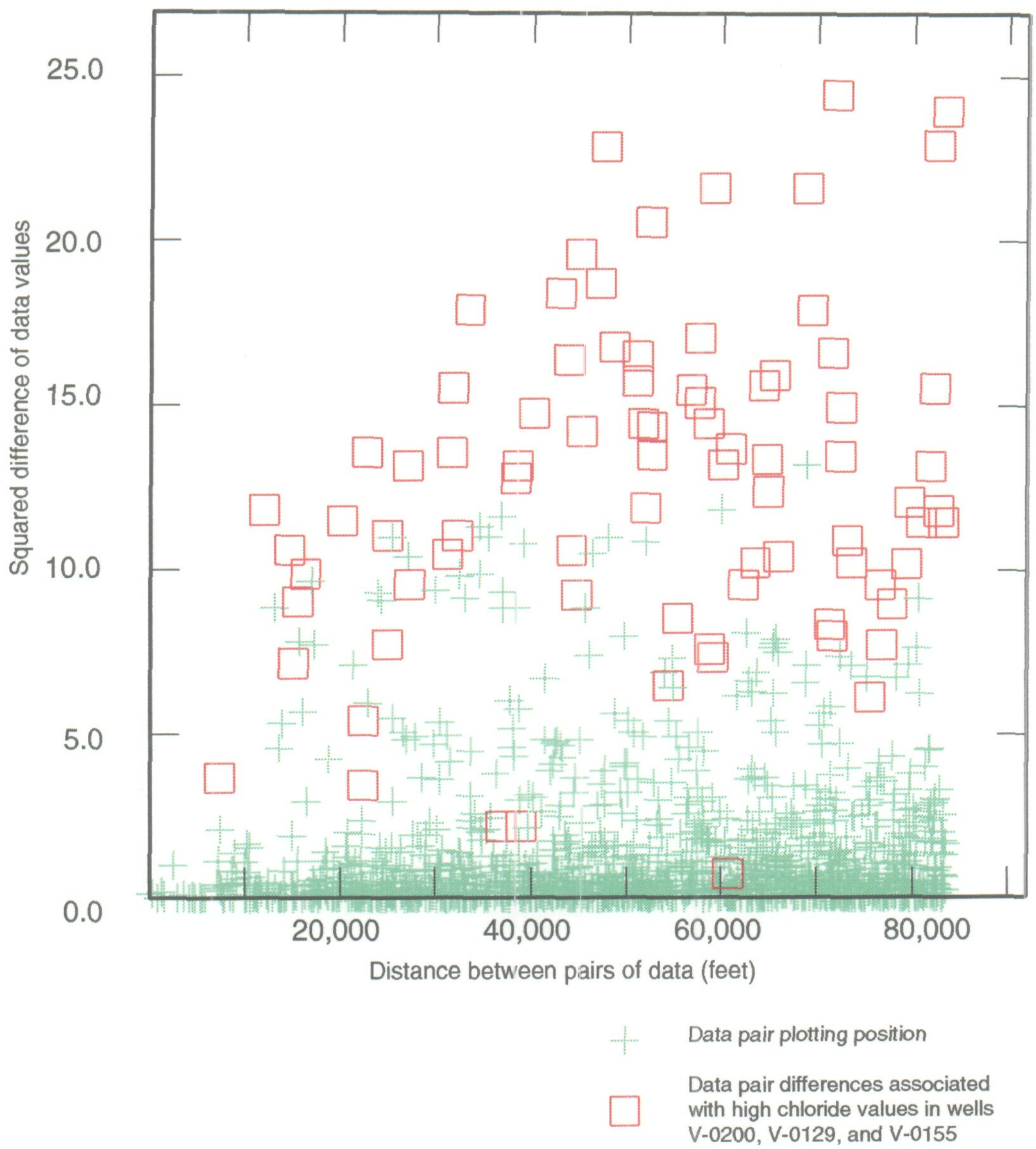


Figure 8. Variogram cloud of transformed chloride data

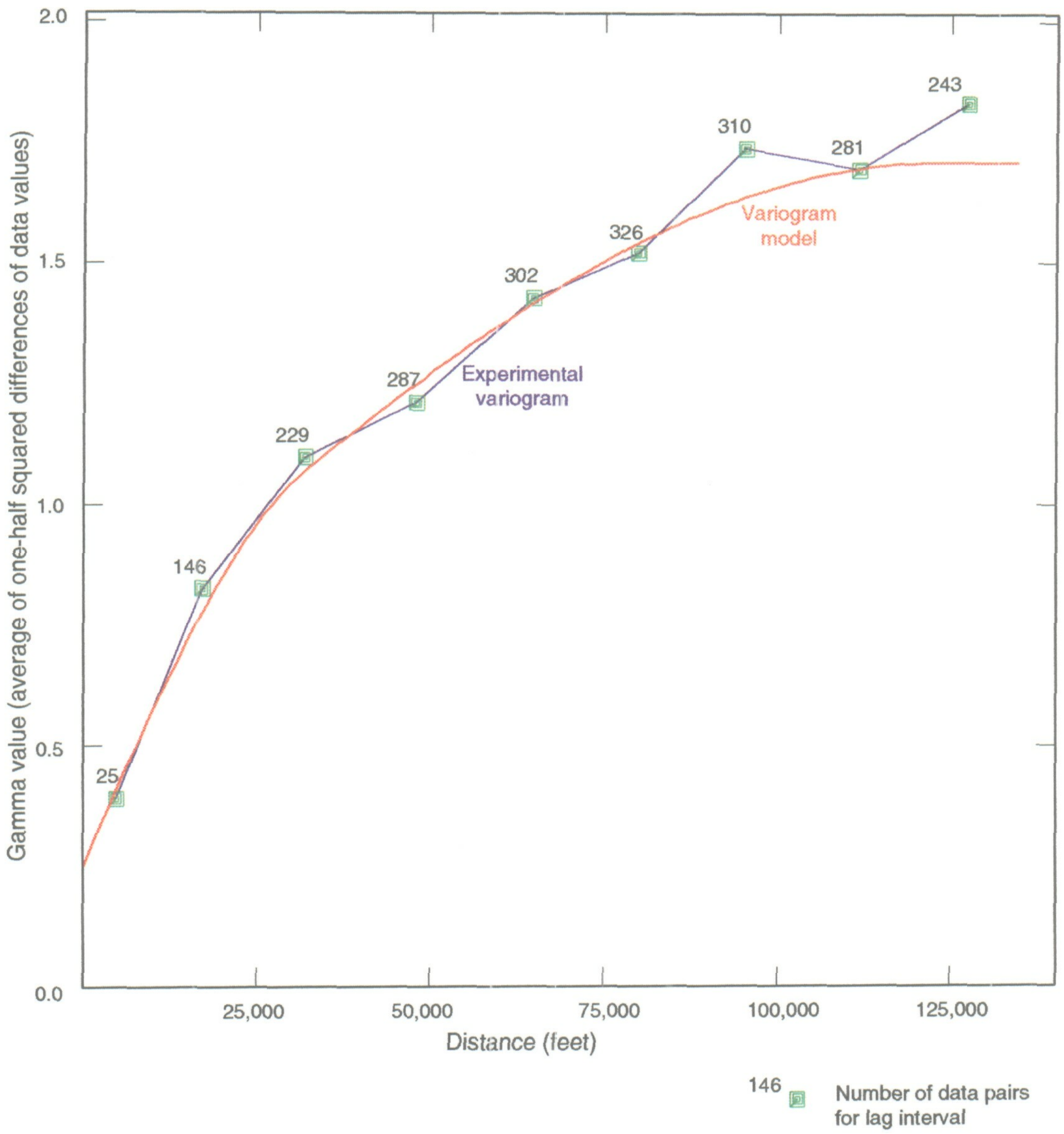


Figure 9. Isotropic (omnidirectional) variogram model of transformed chloride data in relation to the experimental variogram

reliable if the number of pairs in each lag exceeds 20 (S. Rouhani, NewFields, Atlanta, Ga., pers. com. 1998).

Variogram Model—Isotropic

An isotropic model was fitted to the omnidirectional experimental variogram (Figure 9). The model-fitting procedure was performed graphically in order to find a structure that would be as close as possible to the experimental variogram curve. The final isotropic model of the experimental variogram was configured with a nested nugget and two spherical structures.

Sill, nugget, and range are parameters that describe the variogram model. The variogram is said to have reached a sill where the variogram plot levels off. The sill represents the population variance of the investigated data (ASTM 1996a).

A jump up the y axis from the origin of the variogram plot is called a nugget. The nugget represents micro-scale variations and/or measurement errors. The ratio of the nugget to the sill represents the level of unexplained variations (ASTM 1996a). A nugget-to-sill ratio of less than 0.3 indicates a well-structured variogram, while a nugget-to-sill ratio over 0.7 indicates a poorly structured variogram (S. Rouhani, pers. com. 1998). For the omnidirectional variogram model, the nugget was 0.22 and the sill was 1.5, with a nugget-to-sill ratio of 0.15, which indicates a well-structured model.

The range is the distance (feet) from the origin to a point where the variogram model reaches the sill. When a variogram is well structured (i.e., has a low nugget-to-sill ratio), the range is a measure of the extent of the spatial correlation exhibited by the investigated data, or the maximum distance over which the data exhibit spatial correlation (ASTM 1996a).

Sensitivity Analysis

To confirm the suitability of the selected variogram model, experimental variograms were computed using various lag values. For this purpose, the mean minimum distance between wells in this study (11,225 ft) and the median minimum distance between these wells (10,470 ft) were used as a starting point for the sensitivity analysis of lag values. Variograms with lag values ranging from 10,000 to 20,000 ft were examined at 2,000-ft increments. The model adequately captured the main features of the experimental variograms regardless of the corresponding lag values (Figure 10).

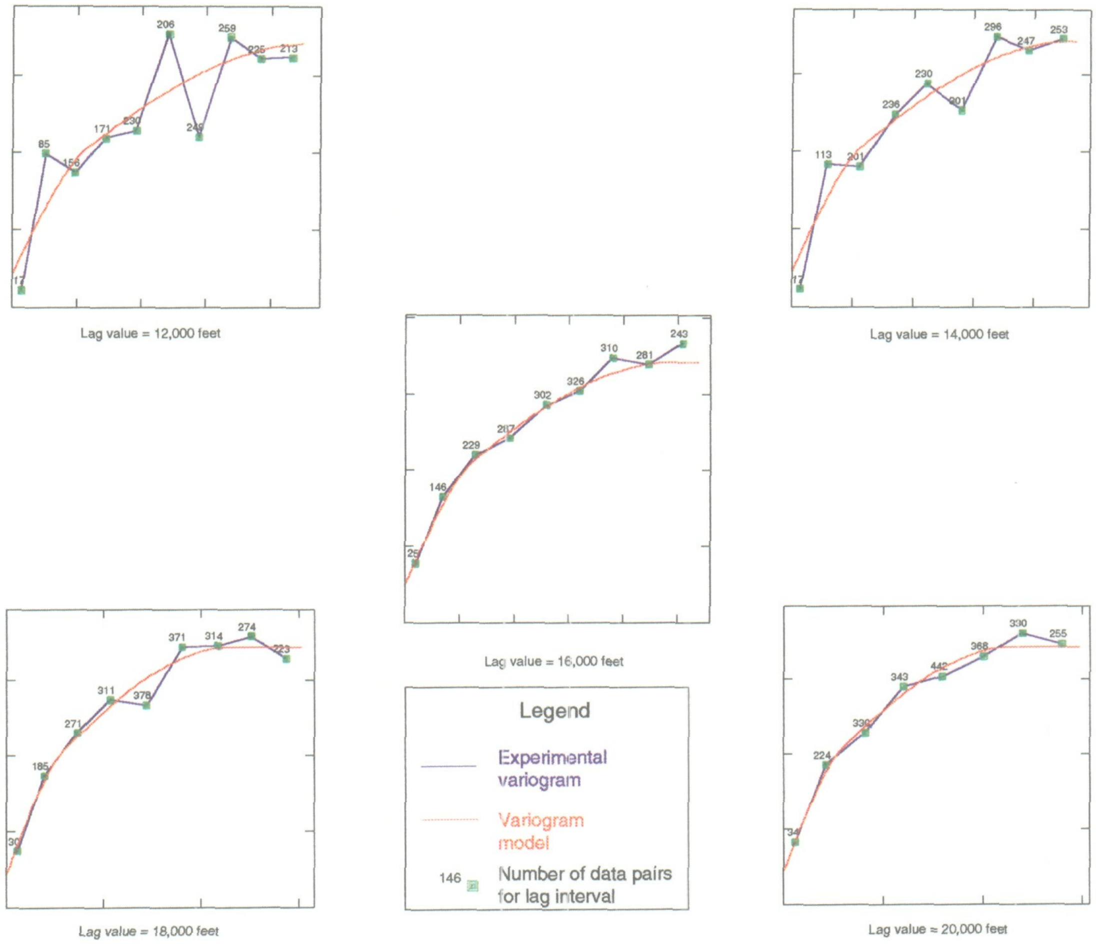
Variogram Map

A variogram map was used to determine if the spatial correlation structure of the data is dependent upon direction (Figure 11). A variogram map is calculated by laying the center of a grid over each data location one at a time. For each cell where data exist, the squared difference of the values between the center and the cell are accumulated. The average of the accumulated differences is the value for that cell of the variogram map (Chu et al. 1994). For the investigated chloride data, the variogram map suggested anisotropy in a northwest-southeast direction.

Variogram Model—Anisotropic

Based on the results of the variogram map, an anisotropic model was fitted to an anisotropic experimental variogram (Figure 12). The anisotropic model consists of two directions perpendicular to one another. The primary direction is northwest-southeast, and the secondary direction is northeast-southwest. First, the model was adjusted to obtain the best fit to the experimental variogram in the primary direction, then the model was adjusted to obtain the best fit in the secondary direction. The number of data pairs for each lag interval of the anisotropic experimental variogram ranged from 10 to 207 pairs in the primary northwest-southeast direction (D1 on Figure 12) and from 15 to 120 pairs in the northeast-southwest direction (D2 on Figure 12).

The lag value, number of lags, nugget, and sill used in the isotropic variogram model were also used for the anisotropic variogram model. In addition, azimuth (i.e., direction of trend) and range values were used as parameters for the anisotropic model (Table 2). For the primary direction, the nugget was 0.22 and the sill was 1.08, with a nugget-to-sill ratio of 0.20. In the secondary direction, the nugget-to-sill ratio was 0.52. These nugget-to-sill ratios indicated that the anisotropic model was well structured. The anisotropic model was used for the cross-validation and estimation procedures.



The *x* axis for each of the above = distance (feet)
The *y* axis for each of the above = gamma value (average of one-half squared differences of data values)

Figure 10. Lag value sensitivity analysis for the isotropic variogram model

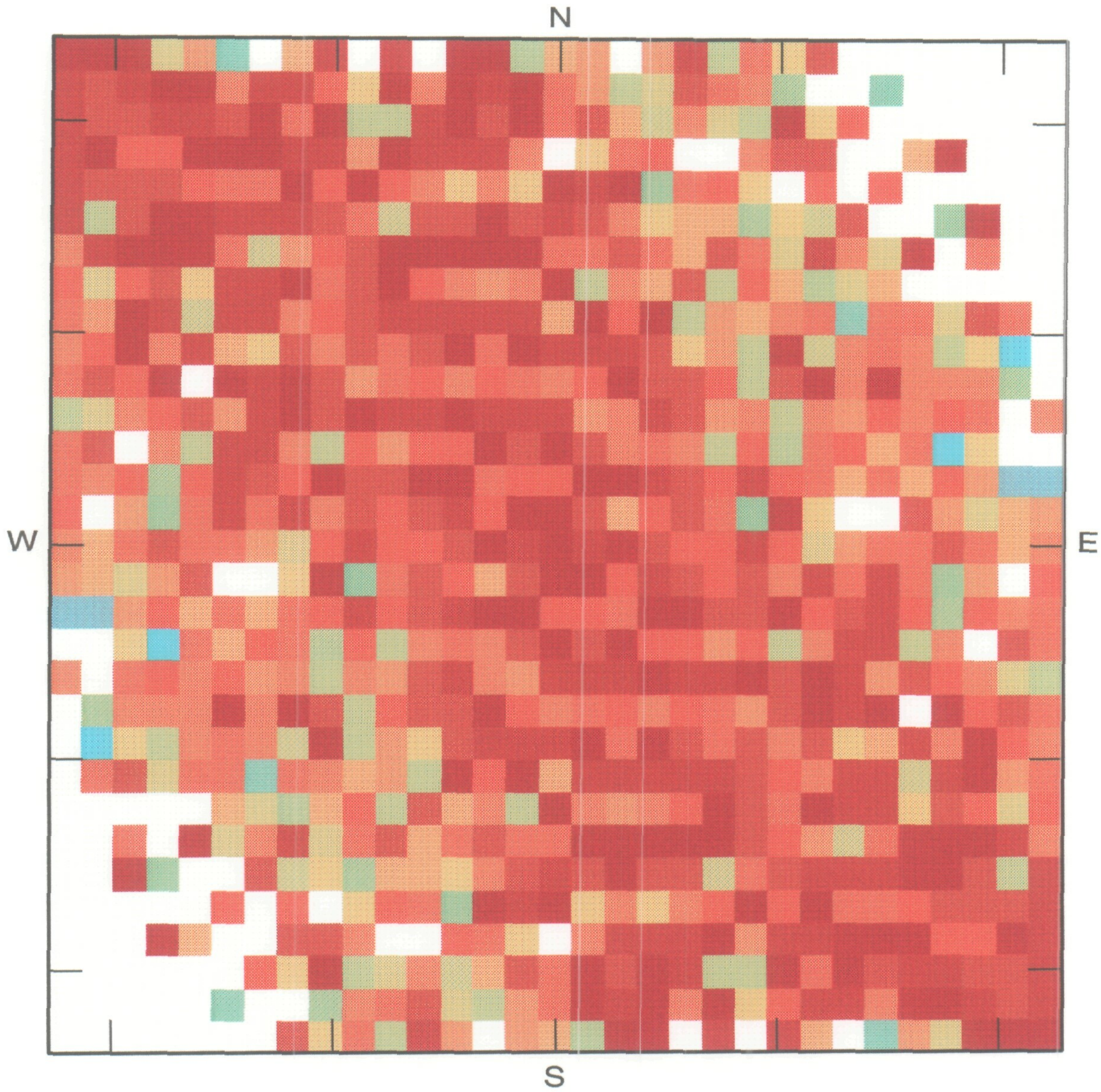


Figure 11. Variogram map of transformed chloride data. *The primary direction of anisotropy is indicated by the alignment of darker colors trending northwest-southeast.*

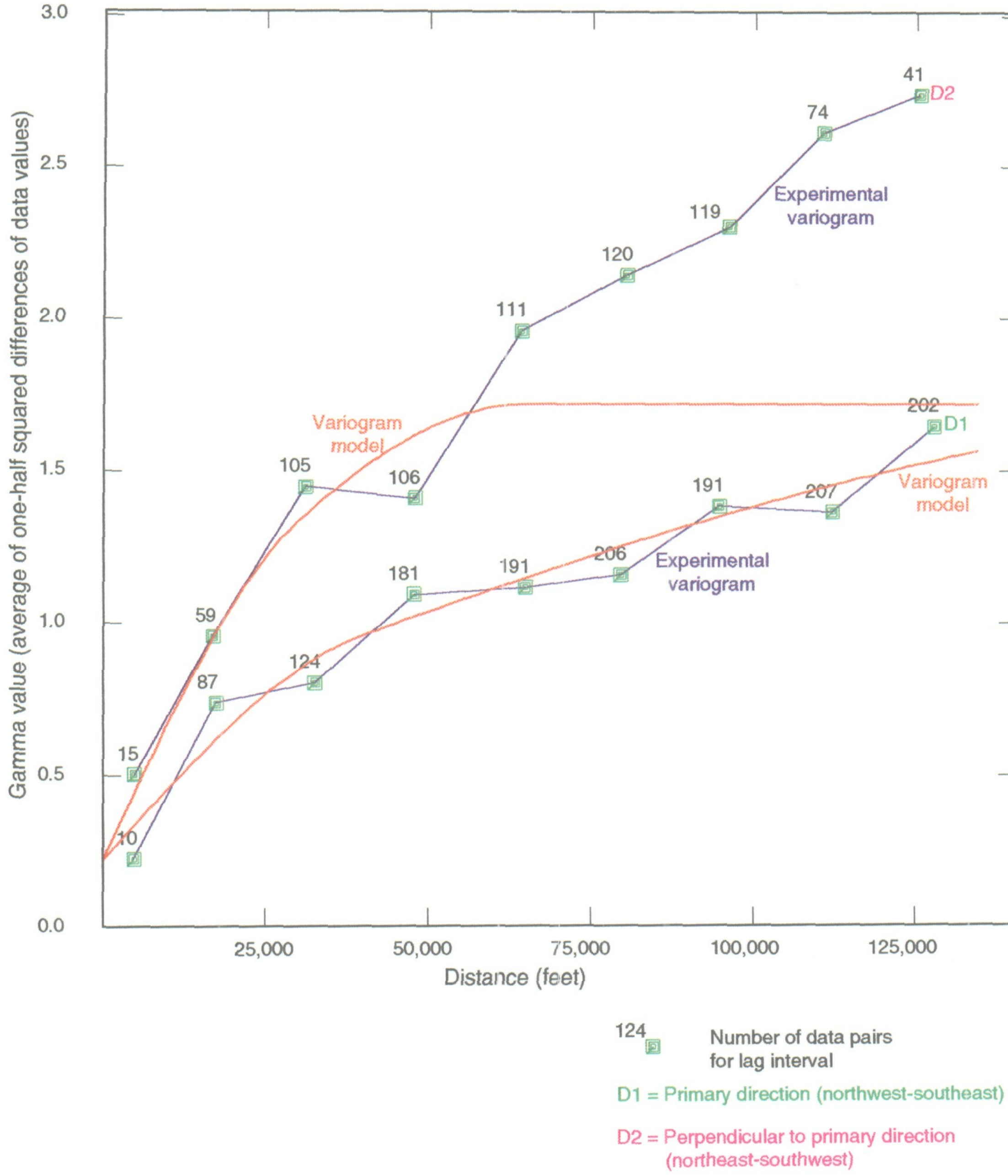


Figure 12. Anisotropic (directional) variogram model of transformed chloride data in relation to the experimental variogram

Table 2. Parameters for the anisotropic variogram model

Parameter	Numerical Value
Lag value	16,000 feet
Number of lags	9
Angular tolerance	45 degrees
	Spherical Structure 1
Azimuth	135 degrees (northwest-southeast direction)
Range	65,000 feet
Sill	1.08
	Spherical Structure 2
Azimuth	45 degrees (northeast-southwest direction)
Range	35,000 feet
Sill	0.42
	Nugget Structure
Sill	0.22

Neighborhood

Neighborhoods must be defined in order to cross-validate the data values and to estimate chloride data in areas where the data have not been collected. Due to the observed anisotropy of the variogram model, an elliptical search neighborhood was chosen. The neighborhood search area of 70,000 ft in the northwest-southeast direction (the primary correlation orientation) and 35,000 ft in the northeast-southwest direction (secondary orientation) was chosen based on the good fit of the model to these distances (Figure 12). The minimum number of samples used in the calculations for each neighborhood was three and the maximum number was ten. An example of a search neighborhood for chloride, showing the weights assigned to the data points surrounding the point of interest, is provided in Figure 13.

CROSS-VALIDATION

Cross-validation assesses the overall quality of the spatial analysis and estimation procedures. Validation involves sequentially removing each data value, estimating the value using the variogram model and the neighborhood information, and then comparing the resulting pairs of estimated and actual values (ASTM 1994).

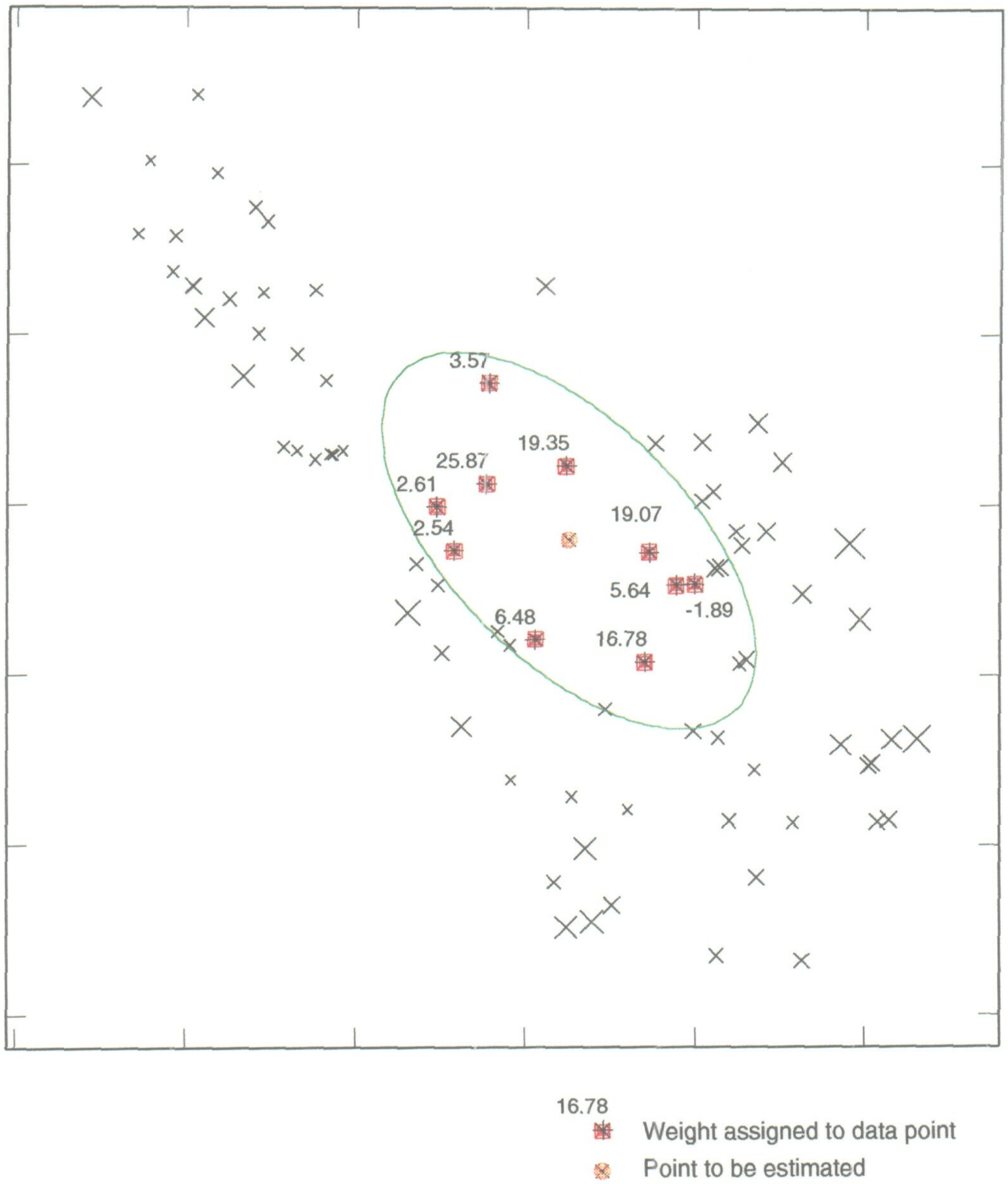


Figure 13. An example of a search neighborhood for estimating the chloride concentration for a location without data. *The magnitude of the actual chloride concentration is reflected in the size of the X.*

The difference between the true value (Z) and the cross-validation estimated value (Z*) is the estimation error (Z – Z*). The standard deviation of the estimation (σ) was also computed. The estimation error divided by the standard deviation is the cross-validation standardized error $\left(\frac{Z-Z^*}{\sigma}\right)$, also known as the *Z* score (Geovariances 1997; Englund and Sparks 1988). Standardized errors between –2.5 and 2.5 represent robust data, signifying a model that can yield correct predictions in spite of errors in data collection or model parameters (Olea 1991). Standardized errors less than –2.5 or greater than 2.5 represent nonrobust data, or values that lie outside the 95% confidence limit of a normal distribution.

A base map showing the standardized errors, a histogram of the standardized errors, and a scatter diagram of the true data value (*Z* on the *y* axis) versus the estimated value (Z* on the *x* axis) were used to display the cross-validation results (Figure 14). The base map (Figure 14, part A) depicts the data with standardized errors less than –2.5, the underestimated data, and the overestimated data. The standardized errors were all less than 2.5. Based on the distribution of the overestimated and underestimated data on the base map, the data were spatially unbiased. The normally distributed histogram of standardized errors (Figure 14, part B) supports the assumption that the transformed chloride data approximated a normal distribution as well as the validity of the variogram model that was used. Based on the scatter diagram (Figure 14, part C), the data were numerically unbiased.

The cross-validation procedure for chloride resulted in only four nonrobust data points. So few nonrobust data points imply that the estimates for chloride concentrations were reliable. The nonrobust data points were all located along the boundary of the groundwater basin at wells V-0200, V-0129, V-0155, and V-0772. The cross-validation procedure resulted in estimated data values lower than the actual chloride concentration for each well. Nearby wells with lower chloride concentrations influenced the cross-validation procedure.

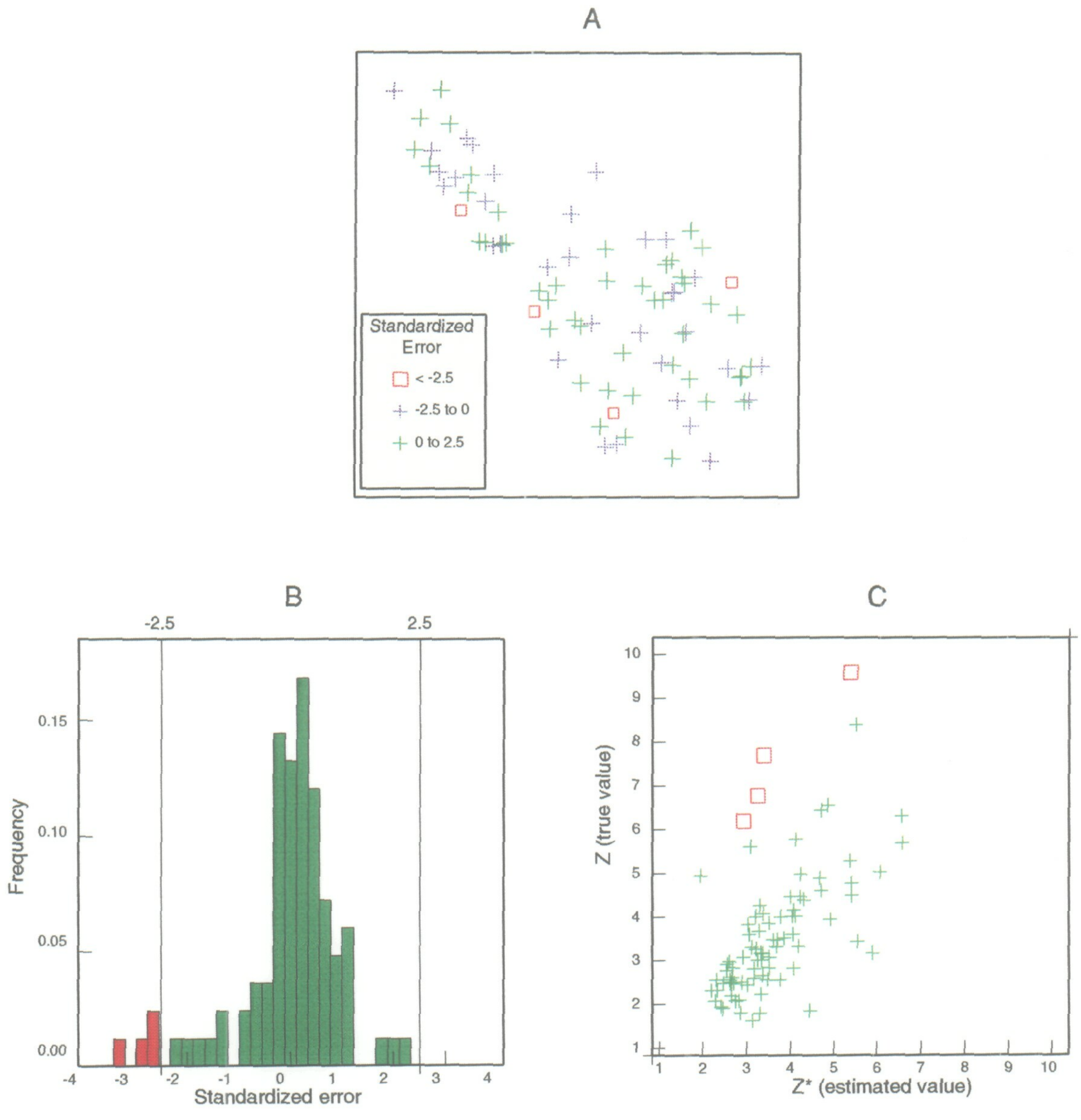


Figure 14. (A) Base map, (B) histogram, and (C) scatter diagram for the cross-validation procedure. *Red symbols indicate nonrobust data.*

ESTIMATION

Estimation is a procedure by which the value of the investigated variable at an unsampled location is predicted using sample values from the neighborhood of that location. Kriging is a collection of linear estimation methods in which sample values are weighted using a linear least-squares optimization procedure based on the variogram model and the neighborhood data (ASTM 1996b). This study used the lognormal form of kriging. The estimation procedure in ISATIS automatically transforms the values in an estimation grid back to milligrams per liter.

Point kriging was used to estimate the chloride concentration on the nodes of the estimation grid. Each grid cell represents a distance of 1,000 by 1,000 ft on the earth's surface. To encompass the entire De Land groundwater basin, the grid had 350 nodes extending in an east-west direction and 370 nodes extending in a north-south direction.

A contour map of chloride concentrations was produced using kriging (Figure 15). This map portrays the water quality conditions in the Upper Floridan aquifer for the De Land groundwater basin. Areas of high chloride concentrations were estimated along the western boundary of the groundwater basin and along the Atlantic Ocean. Low chloride concentrations were estimated on the ridge areas. Data values were temporarily superimposed on the map to verify the contour locations.

A map of the relative standard deviations of estimated chloride concentrations (Figure 16) depicts the relative accuracy of the estimated values. In the northern and southern parts of the groundwater basin, data are insufficient to estimate chloride concentrations with a high degree of certainty. The mean relative standard deviation of the estimated chloride concentrations, 2.92, was used in the network design analysis.

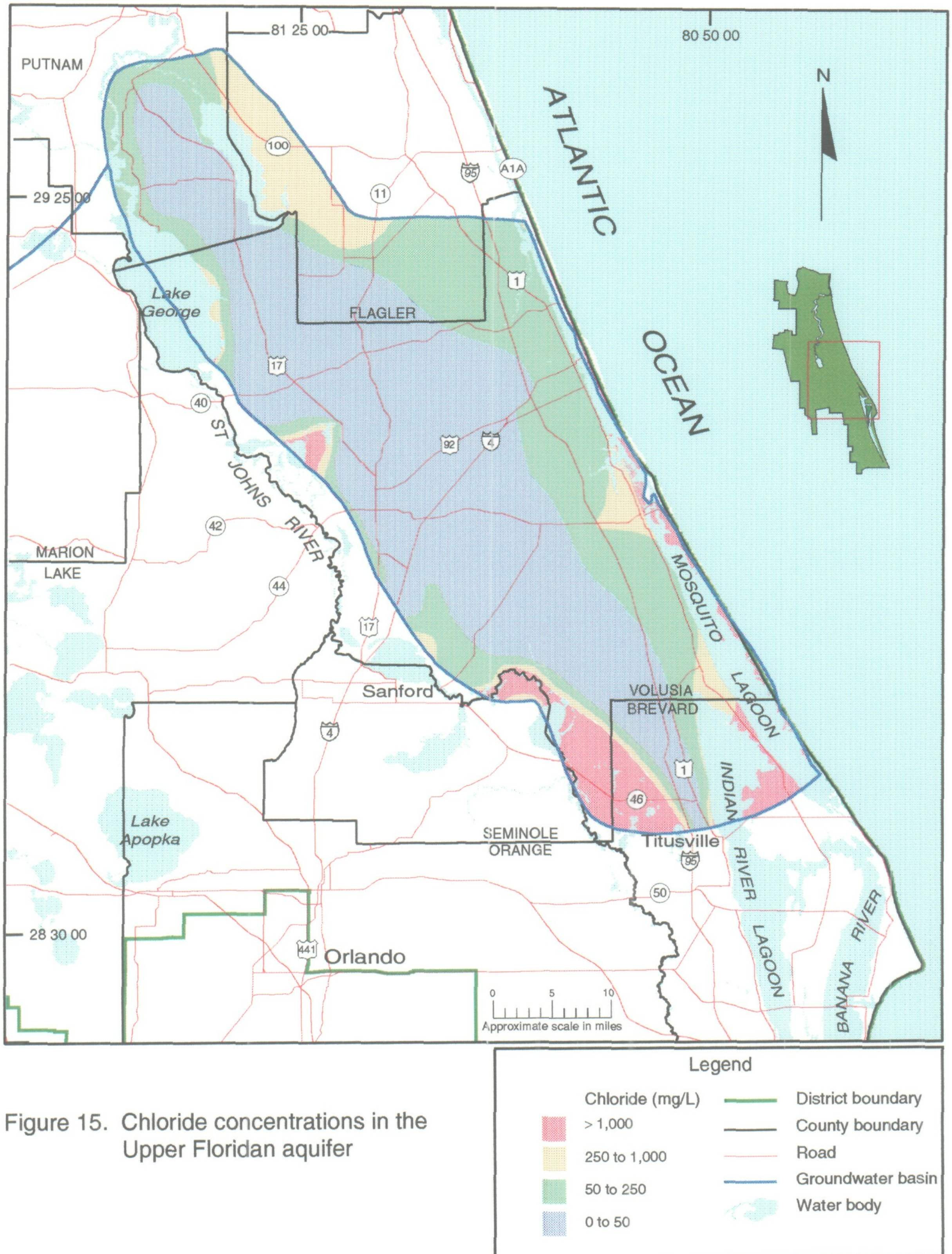


Figure 15. Chloride concentrations in the Upper Floridan aquifer

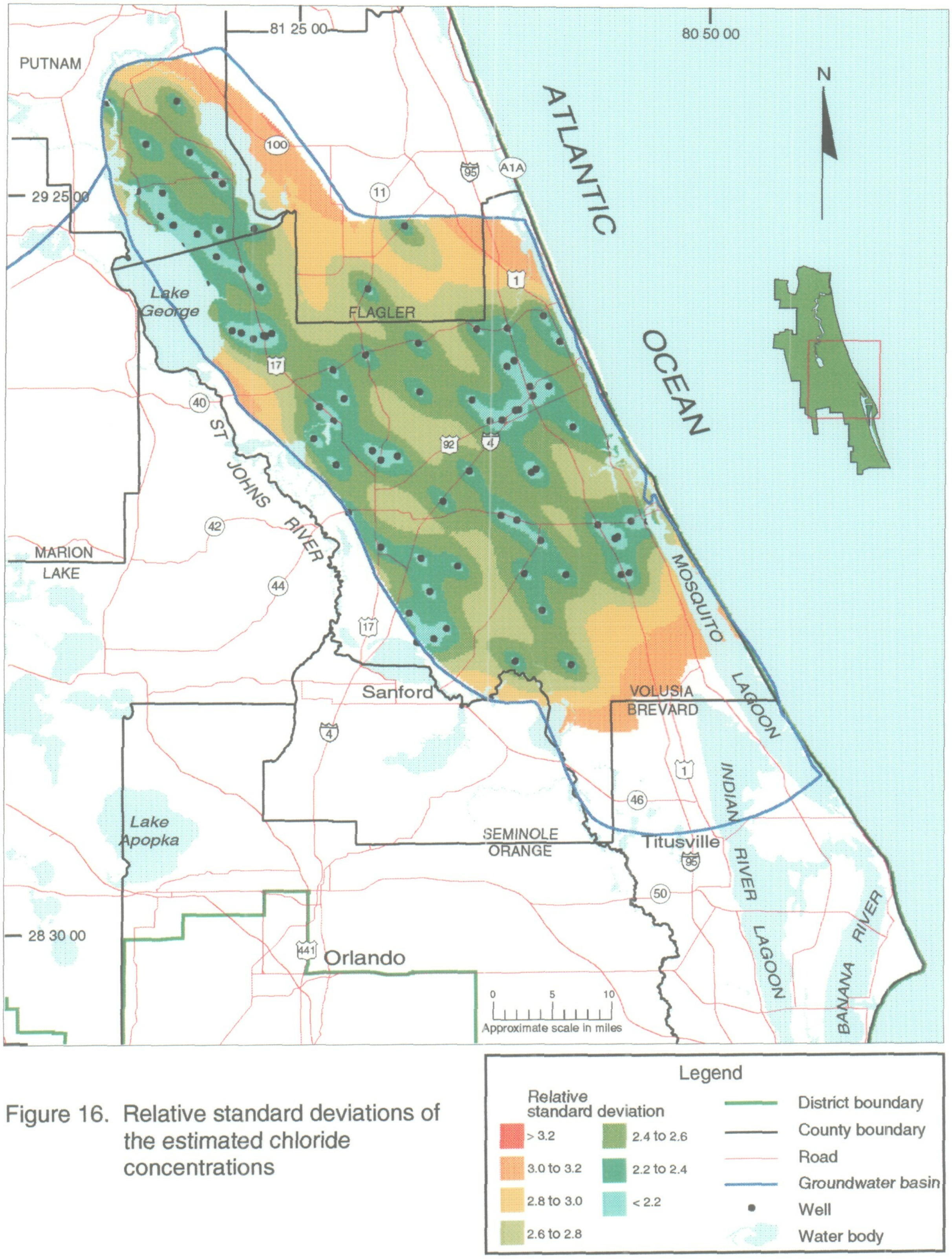


Figure 16. Relative standard deviations of the estimated chloride concentrations

NETWORK DESIGN

Once the geostatistical analysis of the chloride data was completed, the analysis was used to design an improved regional monitoring well network for the De Land groundwater basin. This improved network design will allow resources to be reallocated and wells to be added where needed, particularly in critical concern areas.

On a subregional level, primary and secondary areas of critical concern were identified (Figure 17). Areas in the Upper Floridan aquifer with a projected water level drawdown of greater than 3 ft by the year 2010 (Vergara 1994) were identified as primary critical concern areas. Areas of high chloride concentrations were identified as secondary critical concern areas. In the secondary critical concern areas, the high chloride concentrations result from the mixing of freshwater in the Floridan aquifer system with intruded seawater from the Atlantic Ocean, upwelling residual seawater along parts of the St. Johns River, and residual formation water in parts of Flagler County (Figure 17). These areas were identified based on the estimate of chloride concentrations (Figure 15) and from Vergara 1994.

Olea (1984) determined that spatial networks with uniform hexagonal spacing were the most efficient. Because well data are not uniformly distributed, a stratified sampling design was used. In stratified sampling, an area is divided into grid cells and one data point per grid cell is selected for sampling. A well network based on a stratified hexagonal grid is considered to be regional in nature.

Well locations were plotted on a series of four hexagonal polygon grids with diameters of 10,000 ft, 20,000 ft, 30,000 ft, and 40,000 ft. The 10,000-ft hexagonal grid was chosen as the starting grid size because the median and mean distances among all 84 wells were 10,470 and 11,225 ft, respectively.

In this investigation, all wells located within or near primary or secondary areas of critical concern were selected for each grid. However, because this investigation is regional, the results cannot be used to determine the exact number of wells required to address the subregional data needs of the critical concern areas. Increased spatial

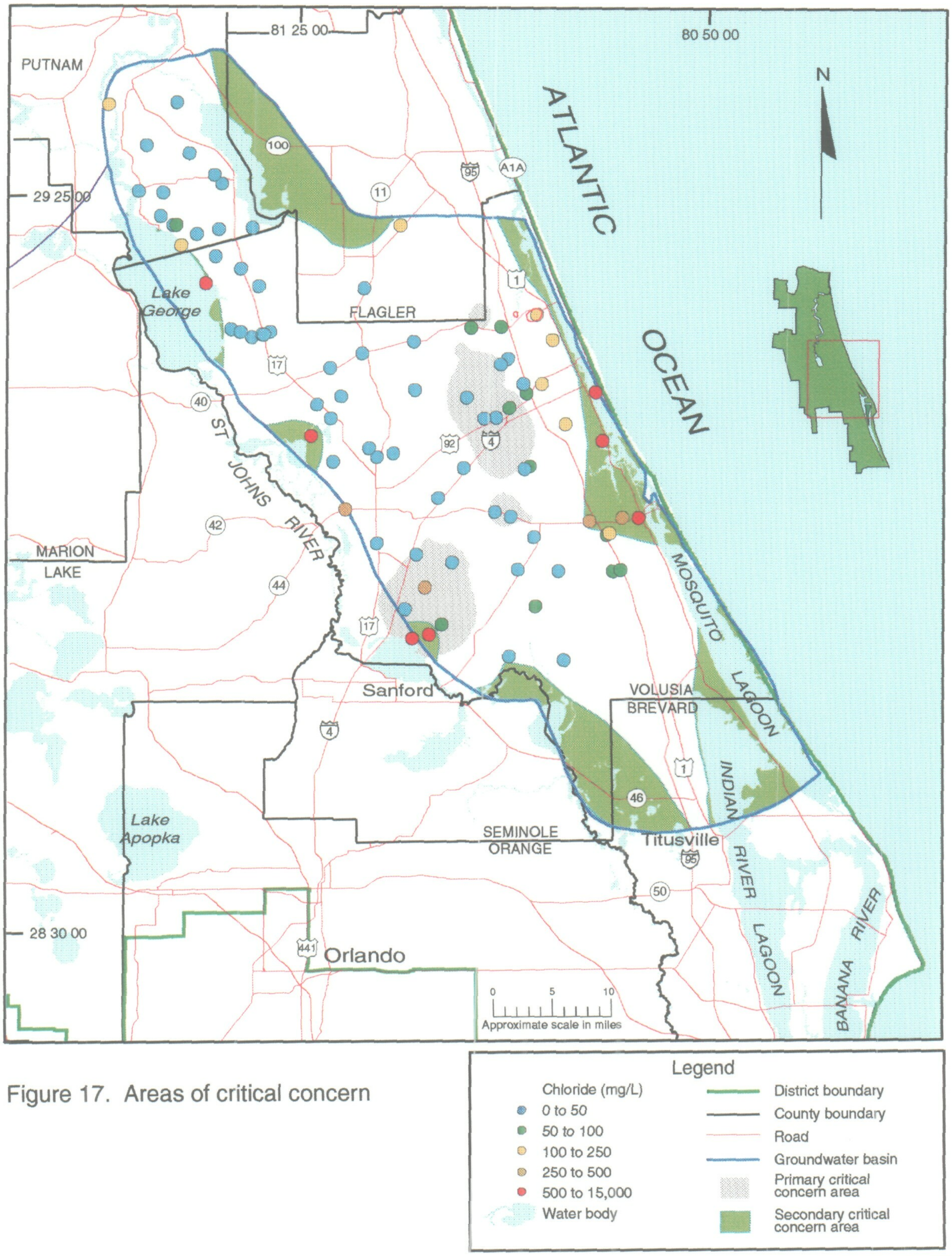


Figure 17. Areas of critical concern

and temporal monitoring may be needed in primary critical concern areas because of the changes in water quality that might occur due to the drawdowns in and near public supply wellfields. Secondary critical concern areas require a spatial well network denser than is needed to evaluate regional water quality conditions but less dense than is needed for the primary critical concern areas.

Of the wells not located within or near critical concern areas, a representative well was selected in each grid cell. Selection criteria were used to select the best well if a grid cell had more than one well. The selection criteria included current sampling frequency and status of the well, history of water quality data collection at the well, location of the well relative to critical concern areas, well construction, and well use. For example, monitoring wells currently sampled on a quarterly basis and with a relatively long data history were selected.

This investigation used chloride data from 84 wells. The resultant 10,000-, 20,000-, 30,000-, and 40,000-ft hexagonal grid networks consisted of 77, 71, 68, and 63 wells, respectively. Kriging was applied to each data subset from each of the four stratified hexagonal grids using the same anisotropic variogram model and neighborhood as was used with the original data set to obtain the mean relative standard deviation of each grid network.

The mean relative standard deviation can be used to assess the effectiveness of each hexagonal grid network. There is no guideline for an acceptable mean relative standard deviation. Because there is no guideline, the mean relative standard deviation of each hexagonal grid was compared to the mean relative standard deviation which resulted from the analysis of all data in order to select a reasonable size for the regional grid network.

The mean relative standard deviation of the estimated chloride data for all 84 wells was 2.92 (p. 27). In comparison, the mean relative standard deviations of the 10,000-, 20,000-, 30,000-, and 40,000-ft hexagonal networks were 3.05, 3.31, 3.40, and 3.61, respectively. The mean relative standard deviation of the 10,000-ft grid network was only 5% greater than the mean relative standard deviation of all the wells. However, the spacing of the 10,000-ft grid network was not practical for a regional well network. The mean relative standard deviation of the 20,000-ft grid was 13% greater than that of all the wells. The mean relative standard deviation of the 30,000-ft grid was 16% greater than that of all the wells. The 40,000-ft grid had a mean relative standard deviation 24% greater than that of all the wells. Because the mean relative standard deviation of the 30,000-ft-diameter hexagonal grid was only slightly higher than that of the 20,000-ft grid, the 30,000-ft grid was selected as the well network spacing for the regional assessment of water quality conditions (Figure 18). At least one well should be located in each 30,000-ft-diameter hexagonal grid to adequately assess the regional water quality conditions in the Upper Floridan aquifer.

The grid configuration in the De Land groundwater basin contains 81 grid cells. A grid cell that was more than 50% water or that was more than 50% outside the basin boundary was not included in the network unless the cell contained a monitoring well. Ideally, each one of the 81 grid cells should contain at least one well. Of the 81 cells, 30 had no well data. Locations without well data occur mainly in southeastern Volusia County, northern Brevard County, and southern Flagler County.

Using all wells within or near the primary and secondary areas of critical concern and the wells selected for the regional network resulted in a network of 68 wells. Sixteen wells not located in critical concern areas were considered redundant and were eliminated from the existing network.

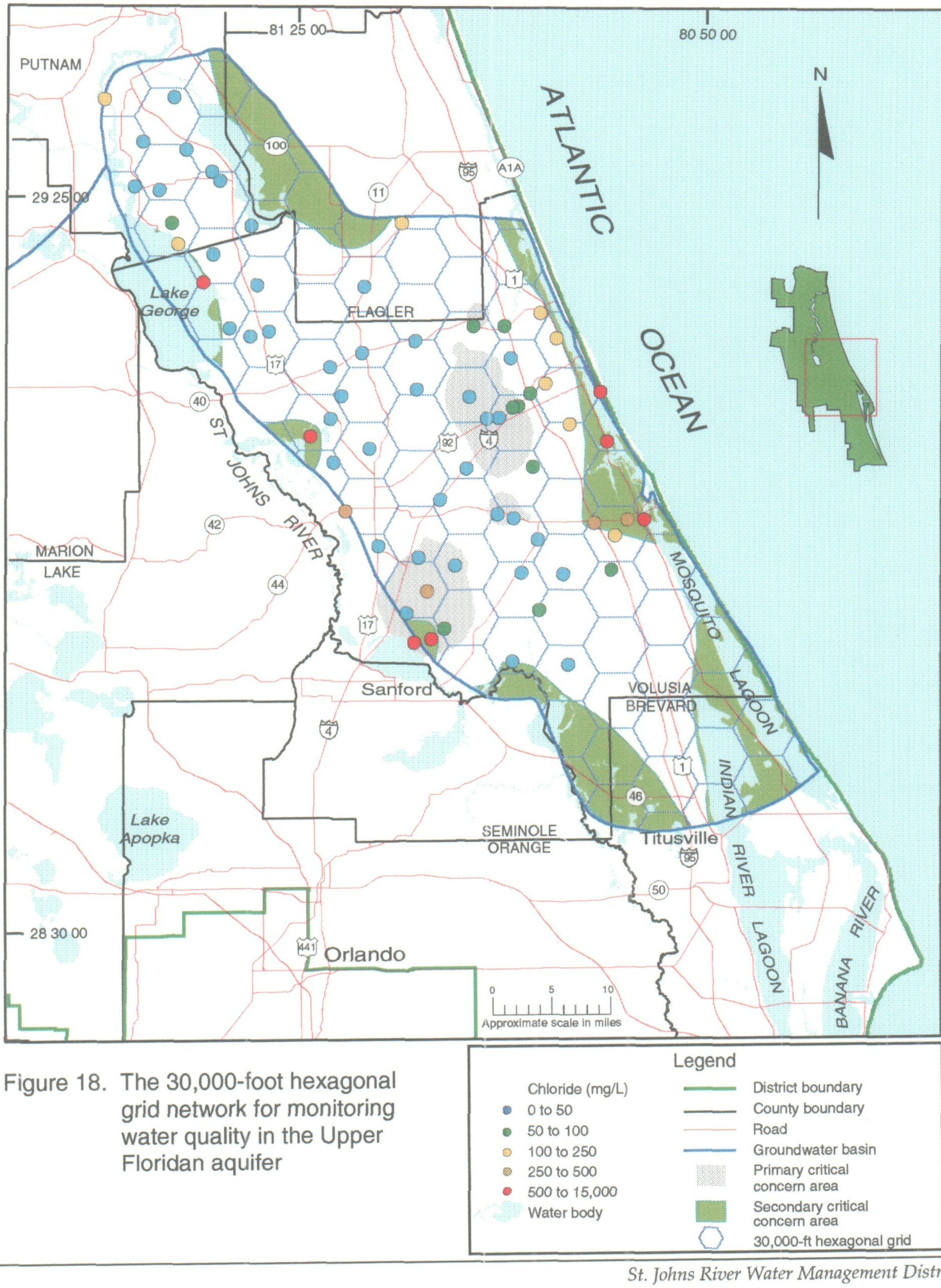


Figure 18. The 30,000-foot hexagonal grid network for monitoring water quality in the Upper Floridan aquifer

CONCLUSIONS AND RECOMMENDATIONS

This geostatistical analysis was undertaken to evaluate the current network of wells used to monitor water quality in the Upper Floridan aquifer in the De Land groundwater basin. This refined network will retain the objectives of the original network—to assess regional water quality conditions and to detect changes in water quality that may occur over time—and it will increase monitoring in areas of critical concern. Following are the major conclusions of the geostatistical analysis:

- The chloride data from the 84 wells in the Upper Floridan aquifer were nonnormally distributed. Anomalous data that were considerably higher than most of the data displayed a positively skewed distribution. A natural logarithmic transformation of the measured values resulted in a more lognormally distributed data set, which was suitable for geostatistical analysis.

- The spatial analysis of the chloride data was best represented by an anisotropic variogram model. The major direction of anisotropy was northwest-southeast; the minor direction was northeast-southwest. The model is composed of a nested nugget and two spherical structures.

- The neighborhood used to perform the cross-validation and the estimation used a moving elliptical search area of 70,000 ft in the northwest-southeast direction and 35,000 ft in the northeast-southwest direction.

- A sensitivity analysis of lag values validated the model parameters.

- Cross-validation resulted in four nonrobust data points, all of which were located along the boundary of the groundwater basin. The cross-validation procedure resulted in estimated data values lower than the actual chloride concentration for the wells because of the influence of nearby wells with low chloride values.

- The contour map of chloride concentrations produced using kriging displayed a zone of high chloride concentration along the coast of the Atlantic Ocean. The high concentrations are due to the effects of seawater intrusion. The map also displayed areas of high chloride concentrations along the western edge of the groundwater basin. These elevated concentrations result from the upwelling of residual seawater in discharge areas of the Floridan aquifer system near the St. Johns River. An area of high chloride concentration also was displayed in Flagler County where freshwater mixes with residual formation water that has not been replaced by fresh recharge water.

- The areas of low chloride concentrations were located in the upland ridge recharge areas of the Floridan aquifer system.

The geostatistical analysis was used to devise a more efficient monitoring network which reduces the number of wells required to assess regional water quality conditions. Identification of redundant wells frees resources to be reallocated for sampling wells to be added to the network. The redesigned well network for the Upper Floridan aquifer in the De Land groundwater basin has the following components:

- For the regional network, a 30,000-ft-diameter hexagonal grid composed of 81 grid cells was selected. If a grid cell had more than one well, selection criteria were used to select a representative well. Sixteen wells not located in critical concern areas were considered redundant and were eliminated from the existing network. Thirty grid cells had no well data.

- On a subregional level, primary and secondary areas of critical concern may require a dense monitoring network to address specific concerns. All wells located in these areas were selected. However, because this investigation is regional, the results cannot be used to determine the exact number of wells required to address the subregional data needs of the critical concern areas.

Based upon the geostatistical analysis and the resultant well network, the following actions are recommended:

- Add new or existing monitoring wells to the regional 30,000-ft hexagonal network in the grid cell locations that are currently not being monitored (30 grid cells). These locations occur mainly in southeastern Volusia County, northern Brevard County, and southern Flagler County.

- Evaluate the primary and secondary areas of critical concern to determine additional monitoring required to address the subregional data needs. Although the proposed network includes all available wells in these areas, more intensive spatial well coverage will likely be needed.

- Perform trend analyses to determine if changes have occurred in water quality over time. A benefit that might be gained from such analyses would be the ability to determine the optimal sampling frequency of the wells in the regional water quality monitoring network and in the critical concern areas.

GLOSSARY

Bias. A purposeful or accidental distortion of observations, data, or calculations in a nonrandom manner.

Estimation. A procedure by which the value of the investigated variable at an unsampled location is predicted using sample values from the neighborhood of that location.

Geostatistics. A collection of statistical methods for the analysis and estimation of spatial data for use in the earth sciences. These techniques incorporate the spatial characteristics of actual data into statistical estimation processes.

ISATIS. A geostatistical software program that includes extensive estimation and simulation options combined with an efficient data management system. Developed by Geovariances and the Center of Geostatistics at the Paris School of Mines, ISATIS is widely used in mining and oil and gas technologies.

Kriging. A collection of linear estimation methods in which sample values are weighted using a linear least-squares optimization procedure based on a variogram model and neighborhood data.

Lag. The distance at which sample differences are compared.

Nugget. A jump up the y axis from the origin of the variogram plot. A nugget represents micro-scale variations and/or measurement errors. The ratio of the nugget to the sill represents the level of unexplained variations.

Range. The distance from the origin to a point where the variogram reaches the sill. If a variogram is well structured, the range can be viewed as a measure of the extent of the spatial correlation exhibited by the investigated data, or the maximum distance over which the data exhibit spatial correlation.

Robust. The characteristic of a model to persist in yielding correct predictions in spite of errors in the data (bias).

Sill. The point at which the variogram plot levels off.

Variogram. A graph depicting the spatial variability between samples and the distance between samples.

REFERENCES

[ASCE] American Society of Chemical Engineers. 1990. Review of geostatistics in geohydrology I, basic concepts. *Journal of Hydraulic Engineering* 116(5).

[ASTM] American Society for Testing and Materials. 1994. *Standard guide for content of geostatistical site investigations*. D 5549-94. Philadelphia, Pa.

———. 1996a. *Standard guide for analysis of spatial variation in geostatistical site investigations*. D 5922-96. Philadelphia, Pa.

———. 1996b. *Standard guide for selection of kriging methods in geostatistical site investigations*. D 5523-96. Philadelphia, Pa.

Bates, R.L., and J.A. Jackson, eds. 1997. *Glossary of geology*. 3rd edition. Alexandria, Va.: American Geological Institute.

Chu, J., W. Xu, and A.G. Journel. 1994. Chapter 16: 3-D implementation of geostatistical analysis—the Amoco case study. In *Stochastic modeling and geostatistics: Principles, methods, and case studies*. Edited by J.M. Yarus and R.F. Chambers. Tulsa, Okla.: American Association of Petroleum Geologists.

Englund, E., and A. Sparks. 1988. *GEO-EAS (Geostatistical Environmental Assessment Software) user's guide*. EPA600/4-88/033. Environmental Monitoring Systems Laboratory. Las Vegas, Nev.: U.S. Environmental Protection Agency.

Geovariances. 1997. *ISATIS, the geostatistical key: User's guide*. Avon, France.

Helsel, D.R., and R.M. Hirsch. 1993. *Statistical methods in water resources*. Studies in Environmental Science, No. 49. Reston, Va.: U.S. Geological Survey.

Hem, J.D. 1985. *Study and interpretation of the chemical characteristics of natural water*. Water-Supply Paper 2254. Alexandria, Va.: U.S. Geological Survey.

Krajewski, S.A., and B.L. Gibbs. 1993. *A variogram primer*. Special Publication No. 8. Boulder, Colo.: Gibbs Associates.

Olea, R.A. 1984. *Systematic sampling of spatial functions*. Series on Spatial Analysis, No. 7. Lawrence, Kans.: Kansas Geological Survey.

———. 1991. *Geostatistical glossary and multilingual dictionary*. New York: Oxford University Press.

U.S. Environmental Protection Agency. 1990. *Guidance for data usability in risk assessment*. EPA/540/G-90/008. Office of Emergency and Remedial Response.

Vergara, B., ed. 1994. *Water supply needs and sources assessment*. Technical Publication SJ94-7. Palatka, Fla.: St. Johns River Water Management District.

APPENDIX A—WELL CHARACTERISTICS

Key to Appendix A abbreviations

ft	feet
Galv	galvanized
HS	high school
I-95, I-4	Interstate 95, Interstate 4
in.	inches
Latitude	latitude—for example, 292302 is 29°23'02"
Longitude	longitude—for example, 811559 is 81°15'59"
MS	middle school
MW	monitoring well
OBS	observation well
PS	public supply
PVC	polyvinyl chloride
SR	state road
US 1	United States highway 1

Table A1. Characteristics for wells in the De Land groundwater basin

Well Number	Location	Latitude	Longitude	Casing Depth (ft)	Total Depth (ft)	Diameter (in.)	Material
DB10	Daytona Beach PS 10	290831	810840	100	340	14	Steel
DB45*	Daytona Beach PS 45	291107	810519	96	255	16	Fiberglass
DL6	Deltona PS 6	285405	811522	110	240	8	Steel
DL22	Deltona PS 22	285257	811211	105	230	12	Steel
DL24	Deltona PS 24	285737	811119	125	255	12	Steel
EW10	Edgewater PS 10	285709	815650	103	200	12	Iron
F-0240	Near Codys Corner	292302	811559	92	155	4	Steel
F-0251	Relay tower	291818	811904	78	147	4	PVC
HH7	Holly Hill PS 7	291429	810248	95	250	10	Steel
HH13*	Holly Hill PS 13	291235	810714	95	250	10	Steel
NS1	New Smyrna Beach PS 1	285952	805748	100	210	12	Steel
NS8*	New Smyrna Beach PS 8	285945	805801	104	183	12	Steel
NS12*	New Smyrna Beach PS 12	290042	810508	107	249	12	Steel
NS15	New Smyrna Beach PS 15	290126	810741	110	253	12	Steel
OB19	Ormond Beach PS 19	291623	810411	88	200	8	Steel
OB28	Ormond Beach PS 28	291526	810714	89	203	8	Steel
P-0102*	Near Georgetown	292337	813639	48	53	2	
P-0242	Gautier, Lake Stella	292606	813124	105	135	4	Iron
P-0246	Thunderbird Airport	292824	813415	104	144	4	Steel
P-0270	Fruitland Handyway	292528	813835	91	124	6	Iron
P-0395	Hamilton	293203	814115		320	6	Iron
P-0408	Fruitland	292856	813757	127	148	4	PVC
P-0410*	Jumping Gulley Road	292218	813331	81	156	4	PVC
P-0413	Near Lake Broward	293214	813522	89	182	4	PVC
P-0468*	Paradise Lakes, west	292257	813533	92	168	4	PVC
P-0469	Paradise Lakes	292256	813526	105	190	4	PVC
P-0495	Clifton Road	292246	812843	132	246	6	Iron
P-0691	Near Fruitland	292522	813630	62	100	4	
P-0696*	Silver Pond Road	292239	813137	80	400	6	PVC
P-0719	Near Crescent City	292646	813205	94	472	8	
P-0736	Middle Road	292124	813452	70	100	6	PVC
V-0008	Near Daytona	290926	810602	480	496	2	Galv steel
V-0028*	Near De Land, SR 11	290536	811749	245	259	4	Iron
V-0062	SR 40, east of Barberville	291218	812154	131	200	4	Iron
V-0064	Cowarts Road	291823	812808	113	158	4	Iron
V-0065	Truck road #3	291508	813028	97	180	4	PVC
V-0066	Pierson	291433	812842	246	367	4	Iron
V-0068*	West of Pierson	291459	812939	63	125	4	Iron
V-0080	Near Daytona	290920	810630	102	235	6	Galv steel
V-0085	Harbor Oaks	290651	805828	104	146	4	Iron
V-0086	Tiger Bay 4A	291006	811010	122	222	4	Steel
V-0099	I-95 Daytona	291023	810501	152	498	6	Iron
V-0101	Alamana	285705	810540	113	121	6	Iron
V-0103	Maytown Cow Creek	285016	810141	102	107	4	PVC

Table A1—*Continued*

Well Number	Location	Latitude	Longitude	Casing Depth (ft)	Total Depth (ft)	Diameter (in.)	Material
V-0106	West Samsula	290107	810620	105	111	4	Iron
V-0111	South Samsula	285934	810418	58	105	4	Iron
V-0113	Lake Ashby	285700	810210	90	261	3	Iron
V-0115	SR 40, west of De Land	290138	812032	252	350	4	Iron
V-0118	5 miles east of De Land	290230	811234	72	241	3	Iron
V-0120	I-4 east of De Land	290447	811023	92	241	3	Steel
V-0123	W Allandale, Guava Road	290456	810444	90	261	3	Iron
V-0127	11th Street	291302	810638	84	240	3	Iron
V-0129	Jones Island	290708	812331	100	165	4	Iron
V-0130	SR 40, west Ormond Beach	291523	810950	82	242	3	Iron
V-0147	Franklin Street	291457	812709	128	140	4	PVC
V-0155	Pine Island	291835	813242	120	155	6	Iron
V-0156	Glenwood	290512	812136	65	195	4	PVC
V-0162	Port Orange OBS #2	290806	810139	105	224	3	Iron
V-0164	New Smyrna, Jungle Road	290102	805642		220	4	Iron
V-0165	Took farm	285031	810623	58	255	4	PVC
V-0184*	Seville tower	291941	812943	75	100	4	PVC
V-0187	Daytona Beach Airport	291107	810342	97	817	8	PVC
V-0188	Tomoka tower	290834	810737	92	150	4	PVC
V-0198	Lake Ashby tower	285419	810410	88	122	4	PVC
V-0200	Daytona Beach Shores	291031	805904	98	160	4	PVC
V-0213*	Southeast Deep Creek	290930	812302	143	145	2	Steel
V-0215	Blackwelder	291009	812058	191	450	10	Iron
V-0240	Fortner	285153	811442	197	243	6	Iron
V-0253	De Land Country Club	285903	811747	210	372	6	Iron
V-0381	SR 44 and I-95	290047	805931	107	130	4	Iron
V-0508	US 1 and Smith Street	290103	805519	170	210	3	PVC
V-0531*	Pierson Airport	291449	812748	130	210	6	PVC
V-0567	Silver Pond Road	292038	813153	86	120	6	PVC
V-0569*	Pierson PS, Pierson HS	291445	812740	150	200	10	Steel
V-0614*	Edgewater PS, well #6	285700	805730	103	250	10	Steel
V-0700	Ormond Beach, Dan Ford Road	290615	811833	85	300	12	Iron
V-0742	Bob Lee Airport	291323	811912	140	460	6	PVC
V-0769	SR 40 and SR 11	291040	811437	85	440	6	PVC
V-0772	Galaxy MS	285543	811338	100	140	6	PVC
V-0777	Lake Helen Cemetery	285813	811424	115	193	6	PVC
V-0788	Ormond Beach MW-1	291417	811446	111	300	4	PVC
V-0808*	Lake Daugharty	290552	811626	90	140	6	PVC
V-0810	Snook Road	285211	811316	290	312	6	PVC
V-1030	Ponce De Leon Springs	290828	812151	120	200	6	PVC

Note: Blank cells indicate no information.

*Well removed from the redesigned water quality monitoring network in the De Land groundwater basin.

APPENDIX B—CONCENTRATIONS AND MEASUREMENTS OF WATER QUALITY VARIABLES FOR THE UPPER FLORIDAN AQUIFER IN THE DE LAND GROUNDWATER BASIN

Key to Appendix B abbreviations

°C	degrees Celsius
Alk	alkalinity
Ca	calcium
Cl	chloride
Hard	hardness
HS	high school
I-95, I-4	Interstate 95, Interstate 4
K	potassium
Mg	magnesium
mg/L	milligrams per liter
µmhos/cm	micromhos per centimeter
MS	middle school
MW	monitoring well
Na	sodium
OBS	observation well
PS	public supply
S	sulfate
SC	specific conductance
SR	state road
TDS	total dissolved solids
Temp	temperature
US 1	United States highway 1

Table B1. Mean concentrations and measurements of selected water quality variables for the Upper Floridan aquifer in the De Land groundwater basin

Well Number	Location	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl* (mg/L)	S (mg/L)	Alk (mg/L)	TDS (mg/L)	Hard (mg/L)	Temp (°C)	pH	SC (µmhos/cm)
DB10	Daytona Beach PS 10					24.0							
DB45†	Daytona Beach PS 45					37.0							
DL6	Deltona PS 6					24.0							
DL22	Deltona PS 22					90.0							
DL24	Deltona PS 24					6.0							
EW10	Edgewater PS 10					87.0							
F-0240	Near Codys Corner	132.0	12.3	52.0	2.4	104.0	6.0	323	515		22.6	6.84	838
F-0251	Relay tower	133.0	10.0	25.4	1.6	40.1	1.1	375	478		22.9	7.01	788
HH7	Holly Hill PS 7					152.0							
HH13†	Holly Hill PS 13					28.0							
NS1	New Smyrna Beach PS 1					101.0							
NS8†	New Smyrna Beach PS 8					52.0							
NS12†	New Smyrna Beach PS 12					17.0							
NS15	New Smyrna Beach PS 15					46.0							
OB19	Ormond Beach PS 19					199.0							
OB28	Ormond Beach PS 28					81.0							
P-0102†	Near Georgetown	70.0	12.2	8.0	1.2	13.0		228	277		20.9	7.17	543
P-0242	Gautier, Lake Stella	47.0	4.5	12.5	2.0	18.5	11.4	126	181	138	22.6	7.41	341
P-0246	Thunderbird Airport	39.0	4.1	5.2	0.8	6.7	0.2	113	132	110	23.6	7.58	243
P-0270	Fruitland Handyway	45.5	7.9	6.2	0.9	8.2	0.2	148	181	150	22.9	7.49	319
P-0395	Hamilton	46.0	19.0	64.5	1.8	141.0		97	396		22.8	7.75	751
P-0408	Fruitland	19.0	6.5	8.1	0.9	5.1	3.8	79	101	75	23.9	8.34	188
P-0410†	Jumping Gulley Road	75.3	12.0	15.7	1.6	27.7	0.9	230	284	239	22.5	7.24	526
P-0413	Near Lake Broward	21.0	1.3	4.5	0.7	6.1	5.3	53	80	58	25.3	8.09	139
P-0468†	Paradise Lakes, west	96.0	15.0	16.0	1.2	33.0	0.2	282	347	300	22.1	7.07	633
P-0469	Paradise Lakes	85.0	17.5	25.5	1.2	59.0	0.3	270	393	285	22.9	6.88	677
P-0495	Clifton Road	56.0	9.4	7.5	1.2	12.0		195	225		22.7		400
P-0691	Near Fruitland	32.0	2.9	6.0	1.2	13.0							
P-0696†	Silver Pond Road	49.3	4.4	5.3	1.0	8.0		248	178	151			
P-0719	Near Crescent City	39.0	5.8	9.0	0.9	16.0		120	161				
P-0736	Middle Road	114.0	17.3	82.5	9.4	146.0		182	471		21.9		845
V-0008	Near Daytona	99.0	12.7	48.0	1.8	87.0		269	478		23.2		764
V-0028†	Near De Land, SR 11	62.5	9.0	6.5	1.1	12.0		200	223		21.8		380
V-0062	SR 40, east of Barberville	43.5	8.6	11.3	1.6	20.0	1.8	153	203	154	22.9	7.66	373
V-0064	Cowarts Road	46.3	6.6	7.9	1.1	12.3	7.6	138	181	141	23.3	7.41	320
V-0065	Truck road #3	50.6	8.3	6.6	1.9	11.7	8.3	154	194	158	22.5	7.47	346

Table B1—*Continued*

Well Number	Location	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl* (mg/L)	S (mg/L)	Alk (mg/L)	TDS (mg/L)	Hard (mg/L)	Temp (°C)	pH	SC (µmhos/cm)
V-0066	Pierson	43.9	13.3	6.0	0.9	10.3	2.2	166	194	164	23.1	7.51	347
V-0068[†]	West of Pierson	49.0	9.9	5.9	0.9	9.0	2.1	161	174	160	22.8	7.51	345
V-0080	Near Daytona	99.5	10.2	38.8	1.4	64.0		276	437		23.2		673
V-0085	Harbor Oaks	106.0	39.4	232.0	6.9	551.0		254	856		22.8		2,020
V-0086	Tiger Bay 4A	112.0	2.8	14.0	1.8	20.5	3.2	297	355	260	21.9	6.91	633
V-0099	I-95 Daytona	95.6	12.1	32.5	1.4	56.0		273	397		23.4		707
V-0101	Alamana	113.0	4.5	15.3	1.5	26.0		322	348		22.6	7.13	670
V-0103	Maytown Cow Creek	133.0	7.0	30.5	0.8	48.0	2.3	337	430	347	22.1	6.97	780
V-0106	West Samsula	115.0	2.4	13.5	1.5	20.5	0.2	310		302	22.3	7.11	655
V-0111	South Samsula	92.5	1.5	8.5	1.0	13.5	2.6	258	297	296	22.6	7.01	546
V-0113	Lake Ashby	91.5	4.5	10.0	0.9	14.5	2.6	233	299	242	22.2	7.12	502
V-0115	SR 40, west of De Land	71.2	20.4	134.0	5.2	275.5	44.0	152	669	190	22.9	7.50	1,140
V-0118	5 miles east of De Land	37.4	6.1	8.4	0.9	12.5	2.2	122	148	116	22.7	7.92	286
V-0120	I-4 east of De Land	116.0	7.1	26.5	1.2	37.0	2.6	308	414	310	21.7	7.01	695
V-0123	West Allandale, Guava Road	102.0	8.8	38.9	1.7	71.0	2.1	277	399	284	22.6	7.10	731
V-0127	11th Street	87.0	12.8	20.0	1.7	34.0		266	340		23.0		562
V-0129	Jones Island	284.4	175.2	1,036.0	9.4	2,200.6		161	4,542		22.3	6.80	6,691
V-0130	SR 40, west Ormond Beach	98.5	9.9	29.5	1.9	55.0	0.2	289	413	266	23.1	6.96	693
V-0147	Franklin Street	31.6	5.9	5.4	0.7	7.0		110	135		23.0		256
V-0155	Pine Island	107.0	52.9	393.0	9.1	871.0		195	1,200		23.6		2,280
V-0156	Glenwood	70.3	5.1	10.7	5.4	31.5	61.5	72	356	212	22.6	7.81	1,260
V-0162	Port Orange OBS #2	92.0	12.1	72.3	3.4	121.0		257	485		22.8		850
V-0164	New Smyrna, Jungle Road	101.0	24.7	140.0	4.8	299.0		286	785		23.3		1,410
V-0165	Took farm	131.0	4.6	16.0	1.2	28.0	3.1	329	402	341	22.9	7.01	694
V-0184[†]	Seville tower	70.7	2.0	10.0	0.9	17.1	2.0	183	232	187	21.1	7.25	417
V-0187	Daytona Beach Airport	69.8	26.0	70.2	4.1	134.0	12.0	215	485	285	23.9	7.48	897
V-0188	Tomoka tower	94.5	7.6	18.6	1.1	32.4	3.1	271	285	279	22.5	7.29	614
V-0198	Lake Ashby tower	98.5	4.9	32.5	2.1	55.5	9.2	240	374	271	22.7	7.14	648
V-0200	Daytona Beach Shores	538.0	750.0	7,310.0	240.0	14,700.0	1,730.0	131	18,200	4,470	24.4	7.20	34,200
V-0213[†]	Southeast Deep Creek	41.0	7.8	10.0	1.4	22.0		126	166		22.1		284
V-0215	Blackwelder	36.3	11.2	6.0	2.5	12.0		106	140		22.7		279
V-0240	Fortner	65.0	29.1	310.3	8.9	626.6		173	1361		22.5	7.60	2,191
V-0253	De Land Country Club	22.1	6.0	3.0	1.2	6.4		80	91		22.8	8.00	173
V-0381	SR 44 and I-95	144.0	21.9	136.0	2.7	321.0		307	917		23.2	6.99	1,630
V-0508	US 1 and Smith Street	249.0	307.0	2,570.0	76.9	4,430.0			7,970		24.5		14,600
V-0531[†]	Pierson Airport	42.2	6.3	7.2	3.8	10.2	6.3	113	148	221	23.3	7.98	281
V-0567	Silver Pond Road	56.0	12.5	8.0	1.6	13.0		206	209		22.5	7.47	365

Table B1—*Continued*

Well Number	Location	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl* (mg/L)	S (mg/L)	Alk (mg/L)	TDS (mg/L)	Hard (mg/L)	Temp (°C)	pH	SC (µmhos/cm)
V-0569†	Pierson PS, Pierson HS	36.0	5.6	4.7	0.7	8.0	1.8	110	134	113	24.1	8.07	250
V-0614†	Edgewater PS, well #6	120.0	11.0	35.0	1.4	56.0	0.5	330	440	336	22.1	7.24	771
V-0700	Ormond Beach, Dan Ford Road	96.0	4.2			16.8		249	303		21.6	7.23	467
V-0742	Bob Lee Airport	40.0	7.9	8.1	2.1	13.0	3.7	133	162	121	22.8	7.60	302
V-0769	SR 40 and SR 11	42.7	9.5	13.0	1.3	22.0	4.1	138	190		23.4	7.90	321
V-0772	Galaxy MS	63.0	36.1			488.0		118	1,050		22.5	8.19	1,690
V-0777	Lake Helen Cemetery	33.5	1.7			9.3		95	124		23.7	8.11	224
V-0788	Ormond Beach MW-1					23.7		279	342		22.6	7.10	553
V-0808†	Lake Daugharty					14.0		307	262		22.0		416
V-0810	Snook Road					699.5		196	1,460		23.7		373
V-1030	Ponce de Leon Springs	36.6	6.9	9.7	2.7	17.1	2.6	127	168		22.4	7.87	289

Note: Blank cells represent no data.

*Chloride was selected for geostatistical analysis. The column is shaded to highlight the data set used in the modeling procedures.
†Well removed from the redesigned water quality monitoring network in the De Land groundwater basin.