

Geostatistical Analysis of Effective Vertical Hydraulic Conductivity and Presence of Confining Layers in the Shallow Glacial Drift Aquifer, Oakland County, Michigan

By E.G. Bissell and S.S. Aichele

In cooperation with Oakland County, Michigan

Scientific Investigations Report 2004-5167

**U.S. Department of the Interior
U.S. Geological Survey**

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2004

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: <http://www.usgs.gov/>

Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:

Bissell, E.G., and Aichele, S.S., 2004, Geostatistical analysis of effective vertical hydraulic conductivity and presence of confining layers in the shallow glacial drift aquifer, Oakland County, Michigan: U.S. Geological Survey Scientific Investigations Report 2004-5167, 19 p.

Contents

Abstract.....	1
Introduction	1
Approach and Methods	3
Calculation of Effective Vertical Hydraulic Conductivity	4
Identification of Distinct Geologic Settings	4
Quality Assurance of Well Logs	5
Prediction of Effective Vertical Hydraulic Conductivity	5
Prediction of Confining Layer Presence.....	6
Error Analysis.....	7
Results	7
Conclusions and Limitations.....	17
Acknowledgments	18
References Cited.....	18
Glossary.....	19

Figures

1. Map showing surficial geology of Oakland County, Michigan.....	2
2–4. Graphs showing:	
2. Sample variogram showing the nugget, sill, and range, and the random and structured parts of the variation	3
3. Driller-specific sample variogram showing spatial structure in well-log data	5
4. Driller-specific sample variogram showing lack of spatial structure in well-log data	6
5. Map showing till and outwash settings in Oakland County	8
6–9. Graphs showing:	
6. Sample variogram and model variogram for outwash setting.....	9
7. Sample variogram and model variogram for till setting	10
8. Sample variogram and model variogram for indicator kriging of confining layers in outwash setting.....	10
9. Sample variogram and model variogram for indicator kriging of confining layers in till setting	11
10–13. Maps showing:	
10. Predicted effective vertical hydraulic conductivity in the shallow glacial drift aquifer, Oakland County	12
11. Predicted probability of confining-layer (10 ft thick or greater) presence in the shallow glacial drift aquifer, Oakland County	13
12. Uncertainty associated with prediction of effective vertical hydraulic conductivity in the shallow glacial drift aquifer, Oakland County	15
13. Uncertainty associated with prediction of confining-layer presence in the shallow glacial drift aquifer, Oakland County.....	16

Tables

1. Results of Student-Newman-Keuls Multiple Comparison Test 7
2. Cross-validation results for ordinary kriging and indicator kriging 14

Conversion Factors

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	0.4047	hectare (ha)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Geostatistical Analysis of Effective Vertical Hydraulic Conductivity and Presence of Confining Layers in the Shallow Glacial Drift Aquifer, Oakland County, Michigan

By E.G. Bissell and S.S. Aichele

Abstract

About 400,000 residents of Oakland County, Mich., rely on ground water for their primary drinking-water supply. More than 90 percent of these residents draw ground water from the shallow glacial drift aquifer. Understanding the vertical hydraulic conductivity of the shallow glacial drift aquifer is important both in identifying areas of ground-water recharge and in evaluating susceptibility to contamination. The geologic environment throughout much of the county, however, is poorly understood and heterogeneous, making conventional aquifer mapping techniques difficult. Geostatistical procedures are therefore used to describe the effective vertical hydraulic conductivity of the top 50 ft of the glacial deposits and to predict the probability of finding a potentially protective confining layer at a given location.

The results presented synthesize the available well-log data; however, only about 40 percent of the explainable variation in the dataset is accounted for, making the results more qualitative than quantitative. Most of the variation in the effective vertical hydraulic conductivity cannot be explained with the well-log data currently available (as of 2004). Although the geologic environment is heterogeneous, the quality-assurance process indicated that more than half of the wells in the county's Wellkey database (statewide database for monitoring drinking-water wells) had inconsistent identifications of lithology.

Introduction

Oakland County encompasses 910 mi² in southeastern Michigan (fig. 1). The suburbs of Detroit have been rapidly expanding across Oakland County from southeast to northwest since World War II. Oakland County is home to approximately 1.2 million residents, of whom about 400,000 rely on ground water for their domestic water supply (Aichele, 2000). More than 95 percent of the water wells in Oakland County draw water from the shallow glacial drift aquifer. Such glacial drift

aquifers can be highly permeable and typically are at a higher risk than deeper bedrock aquifers for contamination from anthropogenic sources such as fertilizers, septic tanks, pesticides, and accidental spills.

Oakland County is committed to protecting the quantity and quality of ground-water resources in general and drinking water in particular. The county has recently supplemented the statewide drinking-water well database (Wellkey) with previously unavailable information for more than 8,000 wells. This database can be analyzed to predict which areas are sensitive to changes in recharge and potential contamination, as well as areas where confining layers inhibit recharge but result in some protection from surface contamination to the underlying aquifer. This approach may be applicable to other areas in Michigan.

The configuration of the shallow glacial drift aquifer in Oakland County is the result of approximately 60,000 years of glacial history (Leverett and Taylor, 1915). The upland area in the center of the county formed the dividing line between the Saginaw Lobe and the Huron-Erie Lobe during the retreat of the Wisconsin glaciers approximately 12,000 years ago (Winters and others, 1985). This dividing line is shown in figure 1. As each lobe retreated, an ice-free area opened through the center of the county, where a succession of outwash plains, kames, and periglacial lakes formed. During successive small advances and retreats over thousands of years, these features were formed, overridden, and then reformed, resulting in a very complex subsurface environment.

After glaciation, glacial Lake Maumee (predecessor to modern Lake Erie) covered the southeastern part of the county from approximately Rochester through Farmington (Eschman and Karrow, 1985). All or part of the current townships of Avon, Troy, Bloomfield, Royal Oak, Southfield, and Farmington were submerged (fig. 1). The thick, fine-textured sediment deposited under glacial Lake Maumee constitutes an effective confining layer at the land surface. These townships are also almost entirely served by surface-water supplies from the Detroit Water and Sewer Department (Aichele, 2000) and are excluded from this study.

2 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

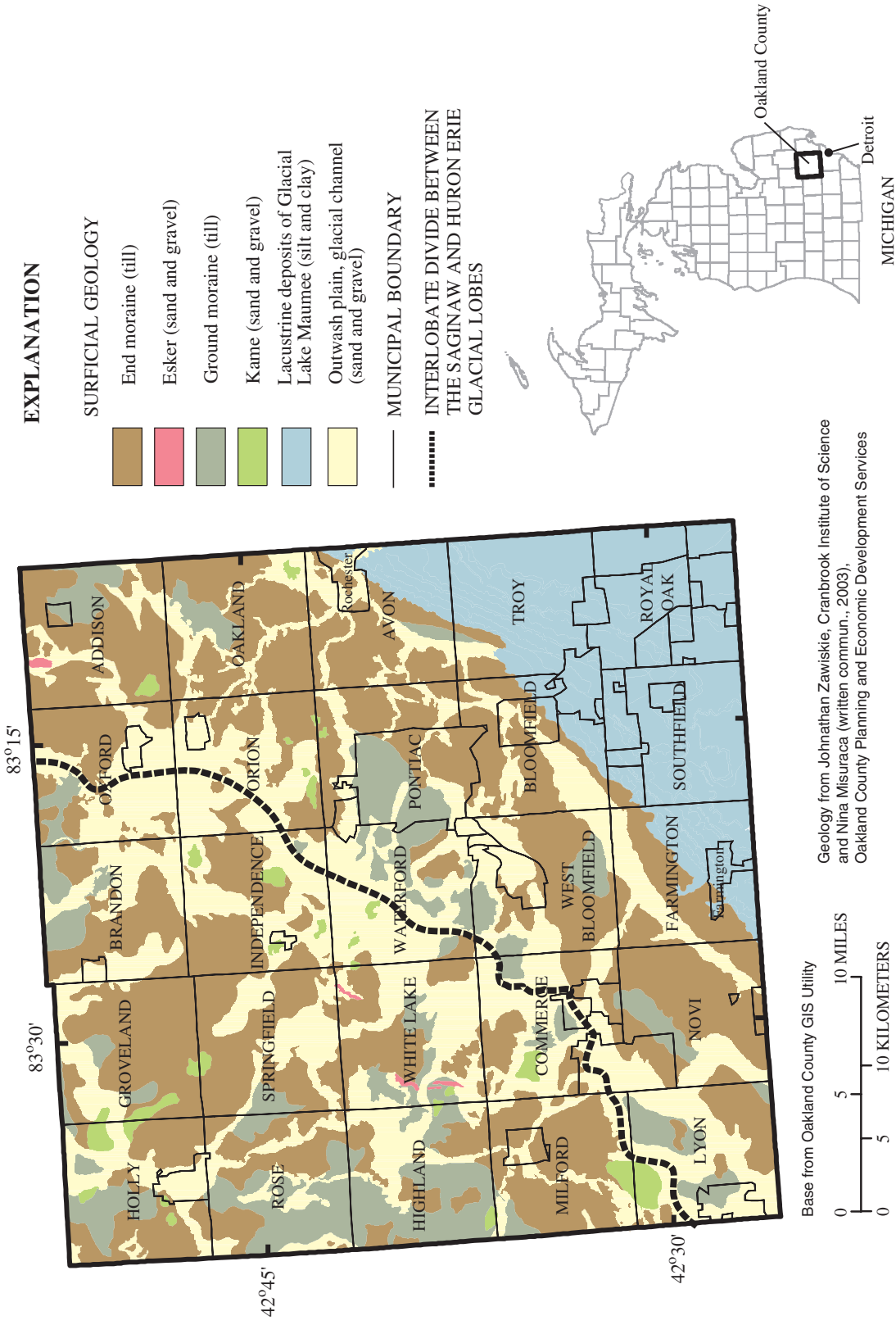


Figure 1. Surficial geology of Oakland County, Michigan (from Aichele, 2000).

In 2001, the U.S. Geological Survey and Oakland County agreed to cooperate to update the 1972 publication “Water for a rapidly growing urban community—Oakland County, Michigan” by Floyd Twenter and Robert Knutilla. This report is one of a series of publications describing quality and quantity of water resources in Oakland County. This report describes a series of geostatistical procedures that were used to (1) assure the quality of well logs used in the analysis, (2) generate estimates of effective vertical hydraulic conductivity, and (3) generate a map of probabilities predicting the existence of confining layers. Resulting maps of predicted effective vertical hydraulic conductivity and confining layer presence, and assessments of their accuracy also are included. Only estimations of specific physical properties of the glacial drift aquifer based on data from the county Wellkey database are presented. Transport or fate of specific contaminants is not discussed.

Approach and Methods

This study uses a geostatistical approach to predict effective vertical hydraulic conductivity and presence of confining layers, two specific properties of the subsurface environment important to the transport of recharge and contaminants to ground water. The study also provides

measures of the uncertainty associated with each estimate. Although this approach is not as definitive as a process-based, contaminant-specific model, the approach does result in a clear, scientifically and statistically credible synthesis of observed geologic properties.

Geostatistical analysis is built on the principle of spatial autocorrelation; as distance increases, similarity in some observed property decreases. Another way of expressing this concept is that as the distance increases, the variance, or dissimilarity, in the observed property increases. The interaction of distance (d) and variance (γ) is represented graphically on a variogram. At some infinitely short distance from an observation point, some amount of random variation exists in the measured property. This feature is called the nugget and may be considered a combination of natural heterogeneity and measurement error. As the separation distance increases, the difference in the measured property increases, until it reaches some threshold, known as the sill. The distance at which the sill forms is called the range. The difference in variance between the nugget (the random variation caused by heterogeneity and measurement error), and the sill (the total variation in the dataset) is the explainable part of the variation. Variograms with longer ranges are indicative of more homogeneous datasets. These features of the variogram are shown in figure 2.

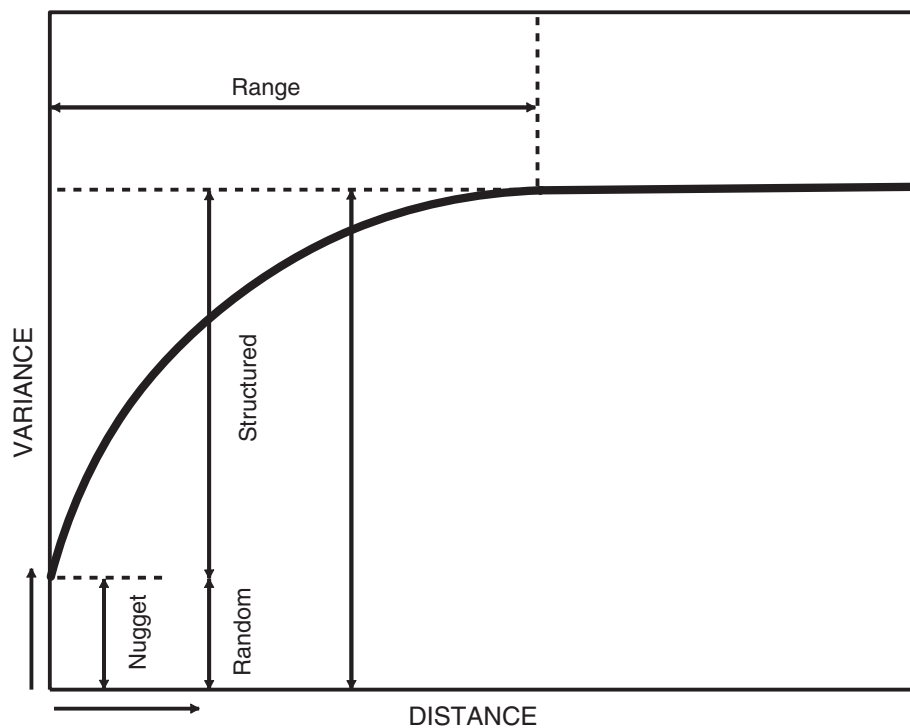


Figure 2. Sample variogram showing the nugget, sill, and range, and the random and structured parts of the variation.

4 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

A key assumption of geostatistics is that the observations used to construct the variogram are all members of the same population; in other words, they share similar characteristics such as mean and standard deviation for the property studied. The spatial extent of the observations and predictions must coincide with an appropriate region of stationarity, an area over which predictions are to be made where the statistical properties of the modeled phenomena do not change across space. Many geostatistical techniques are based on the assumption that the property exhibits second-order stationarity or weak stationarity, which implies that the mean for the property to be modeled is constant and the covariance exists and is a function of separation distance and not absolute location. To satisfy these assumptions, predictions must be limited to the geographic area that elicits similar values for the population to be modeled. For example, the depositional environments of glacial landforms can vary considerably and result in a wide range of hydraulic properties. Consequently, the heterogeneous nature of the glacial geology in Oakland County makes the selection of an appropriate region of stationarity crucial to ensure that predictions are derived from the same population of observations.

Hydraulic-property data in the Wellkey database vary considerably. Similarly, the accuracy and detail of 36,192 logs submitted by 540 drillers over a period of 14 years also vary, potentially adding error and uncertainty to the predictions. Therefore, prior to developing predictive geostatistical models, the database of driller logs must be inspected for distinct geologic populations and for drillers whose observations do not exhibit increased variance with increased separation distance.

Calculation of Effective Vertical Hydraulic Conductivity

Wellkey is the statewide ground-water database managed by the State of Michigan to record information pertaining to drinking-water wells. Records of 36,192 wells were geocoded (located in geographic space using address information) and entered into Wellkey by the Oakland County Health Division from paper well logs submitted by drillers (D. Beemer, Oakland County Health Division, written commun., 2003). The lithologic descriptions have been standardized for entry into the database. Effective vertical hydraulic conductivities were computed for the upper 50 ft by use of the equation described in Fetter (1994, p. 124).

$$K_{v,eff} = \frac{b}{\sum_{m=i}^n \frac{b_m}{K_{vm}}} \quad (1)$$

where

- $K_{v,eff}$ is the effective vertical hydraulic conductivity;
- K_{vm} is the vertical hydraulic conductivity of the m th layer;
- b_m is the thickness of the m th layer; and
- b is the total aquifer thickness.

Because of increased inconsistencies in well drillers' lithologic identifications with increased well depths, effective vertical hydraulic conductivity was calculated only for the first 50 ft for each well. Estimated vertical hydraulic conductivities (K_{vm}) for each lithology were derived from Holtschlag and others (1996), who used similar well logs from the same standardized database to develop a ground-water flow model. The vertical hydraulic conductivities used for each lithology are average values calculated from ranges of hydraulic conductivity values published in the literature, not the results of actual material tests. A range of possible values exists for each lithology but only the average of that range was entered in the database. The errors resulting from simplifying hydraulic conductivities from ranges to simple arithmetic means are not considered in this study.

Identification of Distinct Geologic Settings

Homogeneous depositional environments were identified by classifying wells into groups on the basis of a glacial-landform map provided by Johnathan Zawiskie of the Cranbrook Institute of Science and Nina Misuraca of Oakland County Planning and Economic Development Services (Johnathan Zawiskie, written commun., 2003). Once the wells were classified, the within-group and between-group variation was identified. The map description included the surficial texture and the geomorphologic context; for instance, coarse-textured end moraine or lacustrine sand and gravel. The Kruskal-Wallis Rank Sum Test was selected to determine whether a difference in the means for the hydraulic-conductivity data was associated with the different surficial geologic settings. The Kruskal-Wallis Rank Sum Test is similar to a one-way analysis of variance test except it is nonparametric (Burt and Barber, 1988). A unique value for each geologic environment was assigned to the dataset to serve as a grouping variable. The Kruskal-Wallis rank sum test was then applied, and the test statistic was interpreted. The Student-Newman-Keuls (SNK) multiple comparison test (Kuehl, 2000) was then applied to identify the appropriate groupings of surficial geologic settings and subsequently the well data located within them. The rank-sum means from the Kruskal-Wallis rank sum test were used to calculate the test statistic for the SNK test. With $\alpha = 0.05$ (probability of rejecting the null hypothesis when it is true), the test statistic was compared to the difference between the rank-sum means, and the results were interpreted. Vertical effective hydraulic conductivities of wells drilled in the two identified distinct geologic settings were considered to be from distinct populations. The spatial extents of these geologic settings were identified as the appropriate regions of stationarity to be modeled in subsequent geostatistical analysis.

Quality Assurance of Well Logs

Variography was done to ensure that well drillers provided consistent data. Holtschlag and others (1996) described the general approach for this procedure. For each driller with more than 100 wells drilled in either region, a geology-specific variogram was constructed. The sample variogram (Cressie, 1993) was used to qualitatively identify spatial autocorrelation inherent in the distribution of effective vertical hydraulic conductivities.

Lithologic interpretations by well drillers within stationary depositional environments should exhibit spatial autocorrelation, similar to that shown in figure 2. Because the process of kriging relies on spatial autocorrelation, wells drilled by drillers whose logs did not yield visible spatial autocorrelation were excluded from further analysis. Examples of sample variograms for a driller whose well logs were included in the analysis and a driller whose well logs were not included are presented in figures 3 and 4, respectively. Variography tested the consistency of lithologic descriptions submitted by the driller, but a consistent error could not be identified through this process. Wells drilled by drillers without 100 wells in either geologic setting also were excluded because the reliability of the well logs could not be verified.

Prediction of Effective Vertical Hydraulic Conductivity

The effective vertical hydraulic conductivity data were aggregated by the surficial geologic setting, and sample variograms were constructed. Values of effective vertical hydraulic conductivity were natural-log transformed to reduce the skew of the data because ordinary kriging prediction performance tends to improve if the distribution of the data is not highly skewed (Saito and Goovaerts, 2000).

Predictions were posted to a grid of 50-m by 50-m cells by means of GSTAT geostatistical software (Pebesma, 1999). The ordinary kriging algorithm was selected because it relies on a relaxed assumption of stationarity. This means that predictions are affected less by extremely heterogeneous data than predictions from other kriging methods such as simple and universal kriging would be (Pebesma, 1999). Through a process known as block kriging, 100 random locations were selected within each 50-m cell. Values of effective vertical hydraulic conductivity for these 100 points were then averaged to compute a best estimate for the cell. Block kriging was used to obtain an average value for a grid cell containing multiple wells that should have similar effective vertical hydraulic conductivities but do not because of inconsistencies in the input data.

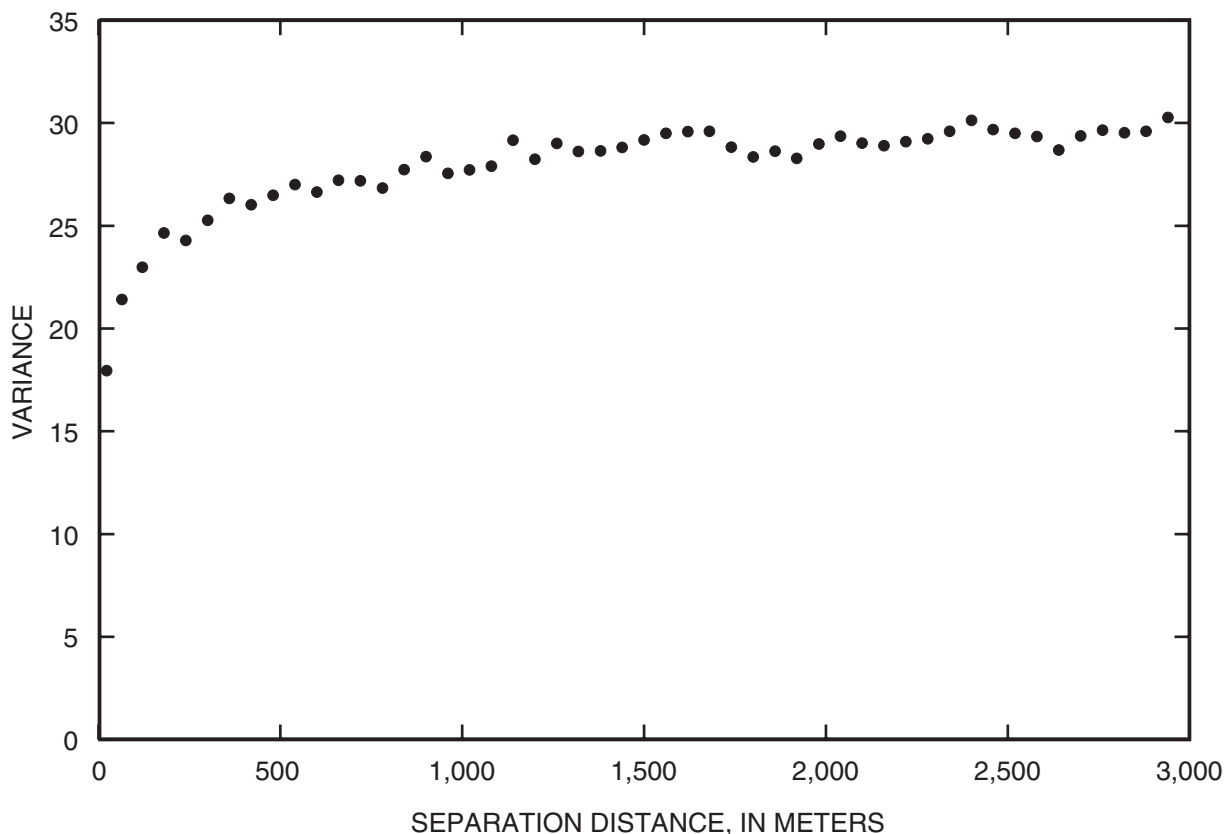


Figure 3. Driller-specific sample variogram showing spatial structure in well-log data.

6 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

By default, the block kriging algorithm employed by GSTAT discretizes a block based on 10 sample points in the x and y directions; therefore, 100 points are used. This does not imply that the use of 100 points to compute an estimate for a 50-m grid cell improves the overall prediction accuracy. Block kriging, however, may prevent proximate outlier data values from exerting undue influence on the prediction for a cell.

Prediction of Confining Layer Presence

The Oakland County Health Division (OCHD) and the Michigan Department of Environmental Quality (MDEQ) have recognized that confining layers in this region, which are typically composed of poorly permeable clay, can provide protection for ground-water supplies. Both OCHD and MDEQ recommend installing a well screen below a 10-ft-thick layer of clay. However, the complex depositional processes that formed the shallow glacial drift aquifer in Oakland County make conventional approaches to mapping aquifers and confining layers (such as fence diagrams) impractical. Indicator kriging

(Isaaks and Srivastava, 1989) is a probabilistic approach that can be used to identify areas that are either more likely or less likely to be underlain by a protective clay layer.

The same drillers logs identified as having spatial structure for the prediction of effective vertical hydraulic conductivity were used in this analysis. Logs showing a clay layer 10-ft-thick or thicker between a depth of 25 ft and 100 ft were coded 1, and all other logs were coded as 0. Layers between 25 ft and 100 ft were examined because 25 ft was determined to be the minimum depth at which most wells are drilled in Oakland County (based on the Wellkey database), and 100 ft was judged to be the maximum depth at which well drillers are likely to accurately record the presence of a clay confining layer. This binary coding became the basis for kriging a new predictive surface, with estimates ranging from zero, where logs can demonstrate absence of a 10-ft-thick clay layer, to 1, where logs can demonstrate presence of a 10-foot-thick clay layer. Because the data set being interpolated is binary, the Cressie robust variogram estimator was used (Cressie, 1993). This variogram estimator is designed to apply to nonparametric, nonnormal datasets and damps the noise created in the variogram by the binary dataset.

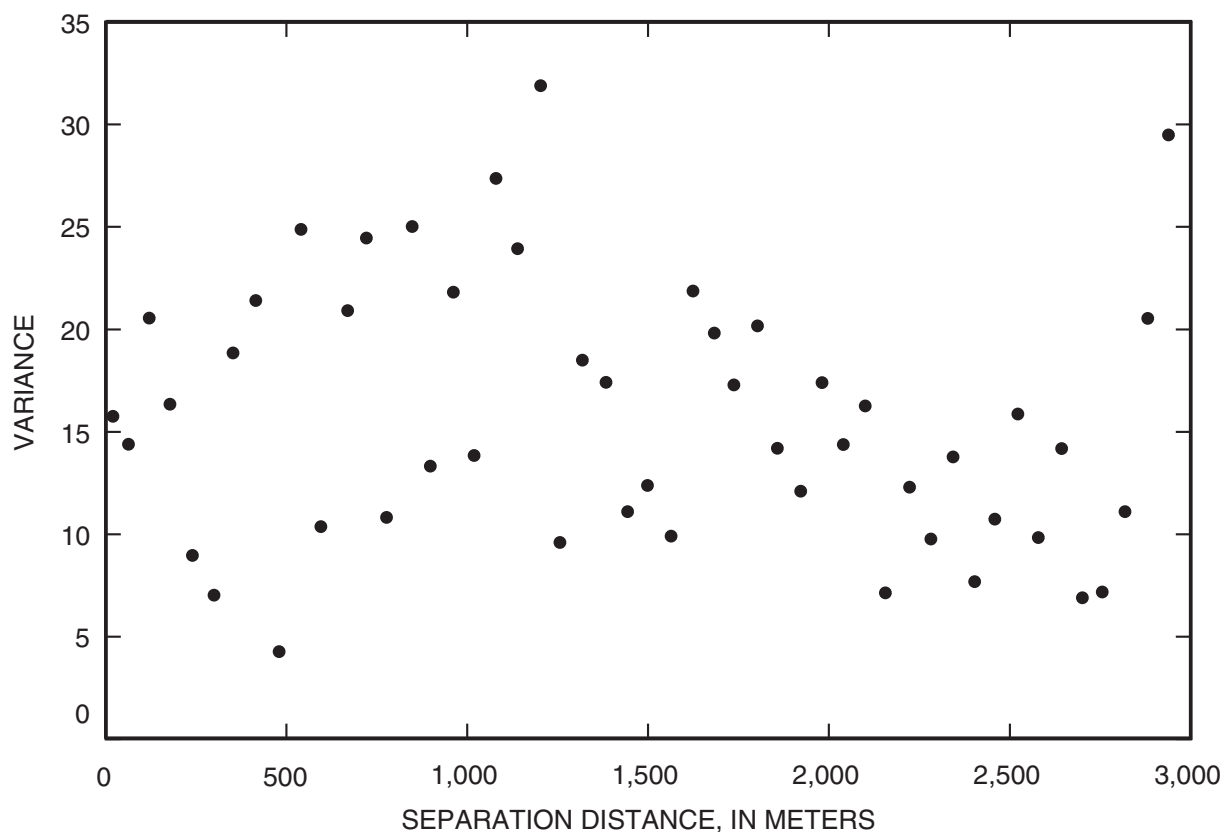


Figure 4. Driller-specific sample variogram showing lack of spatial structure in well-log data.

Error Analysis

The predictions were tested by cross-validation. Each input data point was withheld from the interpolation, and a value for the withheld point was calculated on the basis of surrounding points and the fitted variogram equation. The difference between the actual value and the predicted value was then calculated. This process was repeated for each point in the dataset, and a correlation coefficient (R) was calculated. The theoretical maximum R is equivalent to the structured portion of the empirical variogram (the difference between the nugget and the sill) divided by the sill.

Results

Of the 36,192 wells in the original data set, 5,908 wells drilled by 472 drillers were excluded because of insufficient sample size; 13,043 wells drilled by 36 drillers were excluded because of the absence of spatial structure in either glacial setting; and 136 wells were excluded because of inconsistencies in the reported depth and thickness information. A total of 17,105 wells drilled by 32 well drillers were included in this analysis.

Twelve distinct mapping descriptions were identified in Oakland County on the basis of the surficial geology map (Johnathan Zawiskie, Cranbrook Institute, written commun., 2003). These descriptions were refined to five classes (distinct groupings of surficial geologic texture based on the mapping descriptions) because many of the surficial geologic settings consisted of lacustrine sediments in the southeastern corner of the county. Records in this same part of the county were excluded from analysis because too few well logs were available to produce reliable predictions; southeastern Oakland County is predominately urban, and wells are scarce (as are well-log data that could be used in this analysis). The Esker

surficial geologic class was aggregated with the Outwash class because the land area and number of wells included in the Esker class were not significant enough to warrant separate treatment. To determine whether any of the four remaining classes represented statistically different populations of effective vertical hydraulic conductivity, the Kruskal-Wallis Rank Sum Test was employed. Based on a comparison between the test statistic and a two-tailed chi-square distribution, the null hypothesis was rejected, indicating that multiple populations of effective vertical hydraulic conductivity data existed. The ranked means from the Kruskal-Wallis test were used to calculate the difference in ranked means between groups and, also, the test statistic. The difference in means was compared to the test statistic to determine the appropriate groupings of effective vertical hydraulic conductivity data. Based on ($\alpha = 0.05$), the null hypothesis was rejected twice, indicating that four texture classes could be grouped into two mutually exclusive classes (table 1). The distinct groupings were termed Till, consisting of end moraine and ground moraine, and Outwash, consisting of outwash and kame deposits (fig. 5).

Table 1. Results of Student-Newman-Keuls multiple comparison test.

[α , Probability of rejecting the null hypothesis when it is actually true]

Surficial geology group	Mean rank sum	Similarity
End moraine	7,680	a*
Ground moraine	8,241	a
Kame	9,098	b
Outwash	9,277	b

*Means followed by same letter are not significantly different from each other [$\alpha = 0.05$, (SNK)].

8 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

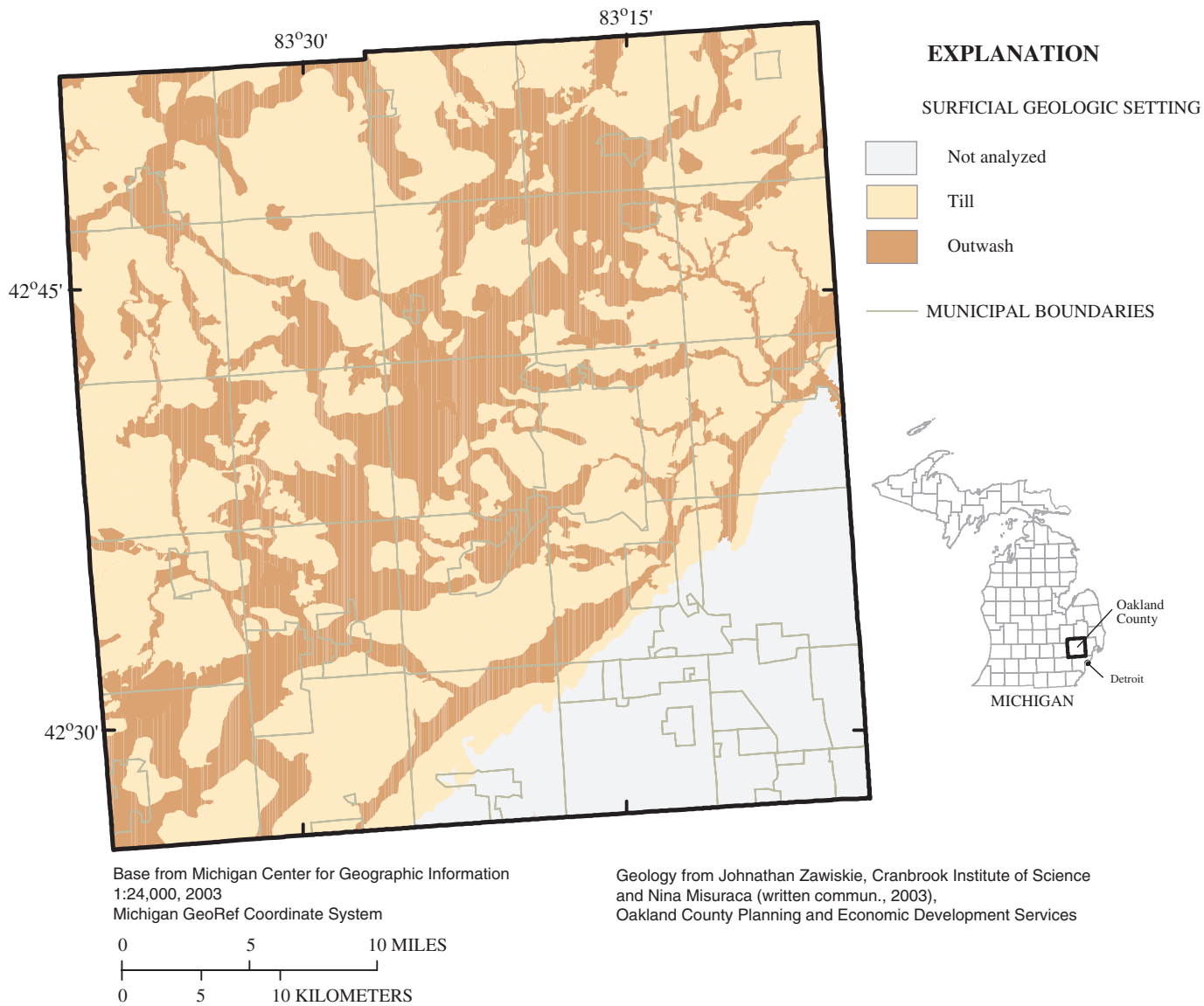


Figure 5. Modeled outwash and till settings in Oakland County, Michigan.

The effective vertical hydraulic conductivity data for each group were transformed to the natural log scale. After natural log transformation, the resulting data distributions were more normal and produced variograms that were considerably more interpretable. The modeled settings are shown in figure 5. The sample model variograms for outwash and till, respectively, are shown in figures 6 and 7. The model variograms used are listed below.

$$\text{Till equation: } \gamma(h) = 16 + 2(h)^{0.23} \quad (3)$$

where:
 $\gamma(h)$ is the model variogram; and
 h is the separation distance.

The sample and model variograms for prediction of confining layer existence in the outwash and till settings, respectively, are shown in figures 8 and 9.

$$\text{Outwash equation: } \gamma(h) = 17 + 2(h)^{0.26} \quad (2)$$

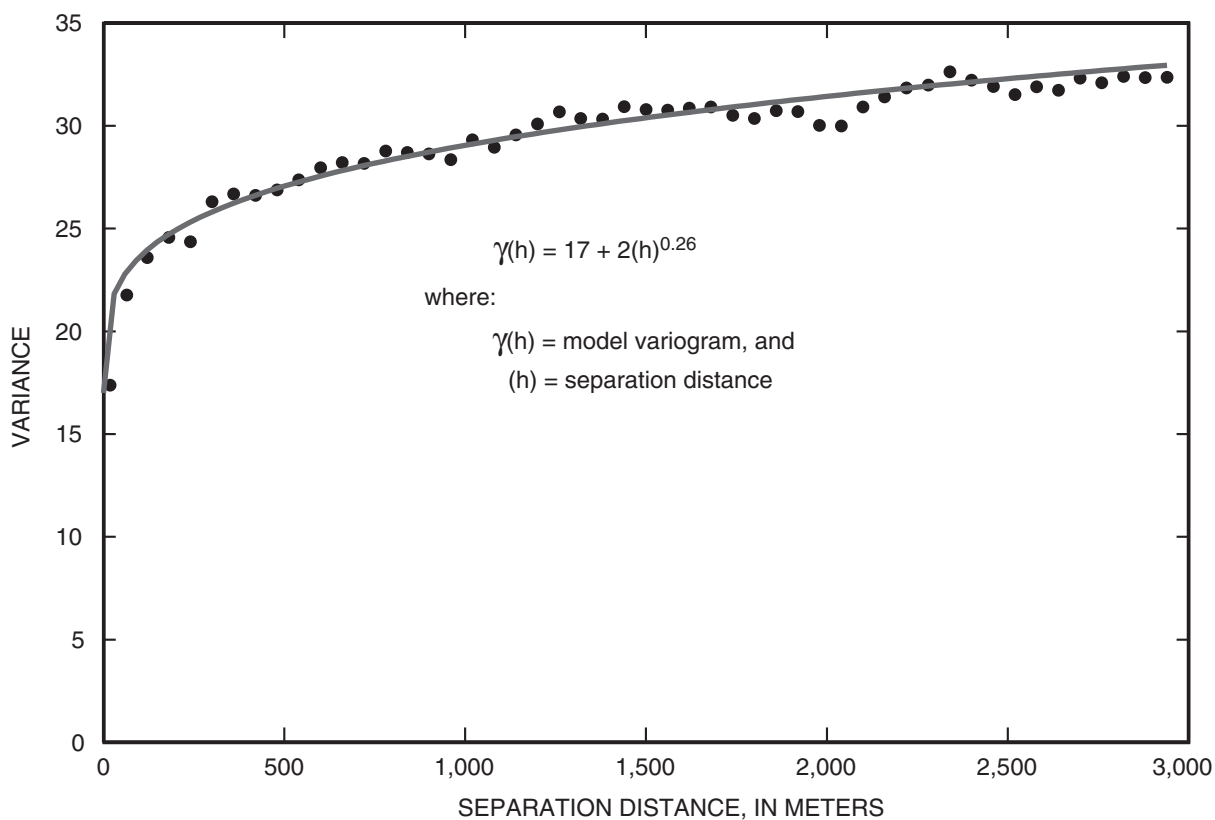


Figure 6. Sample variogram and model variogram for outwash setting.

10 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

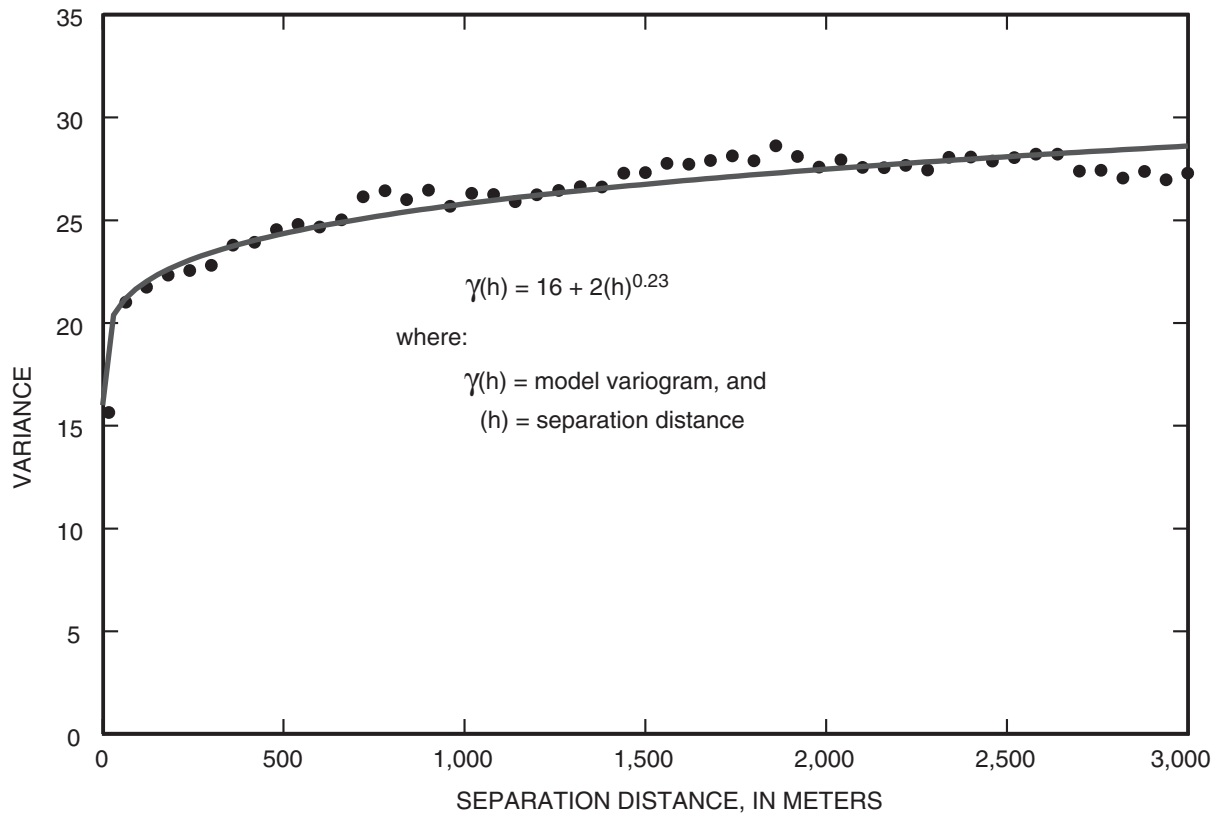


Figure 7. Sample variogram and model variogram for till setting.

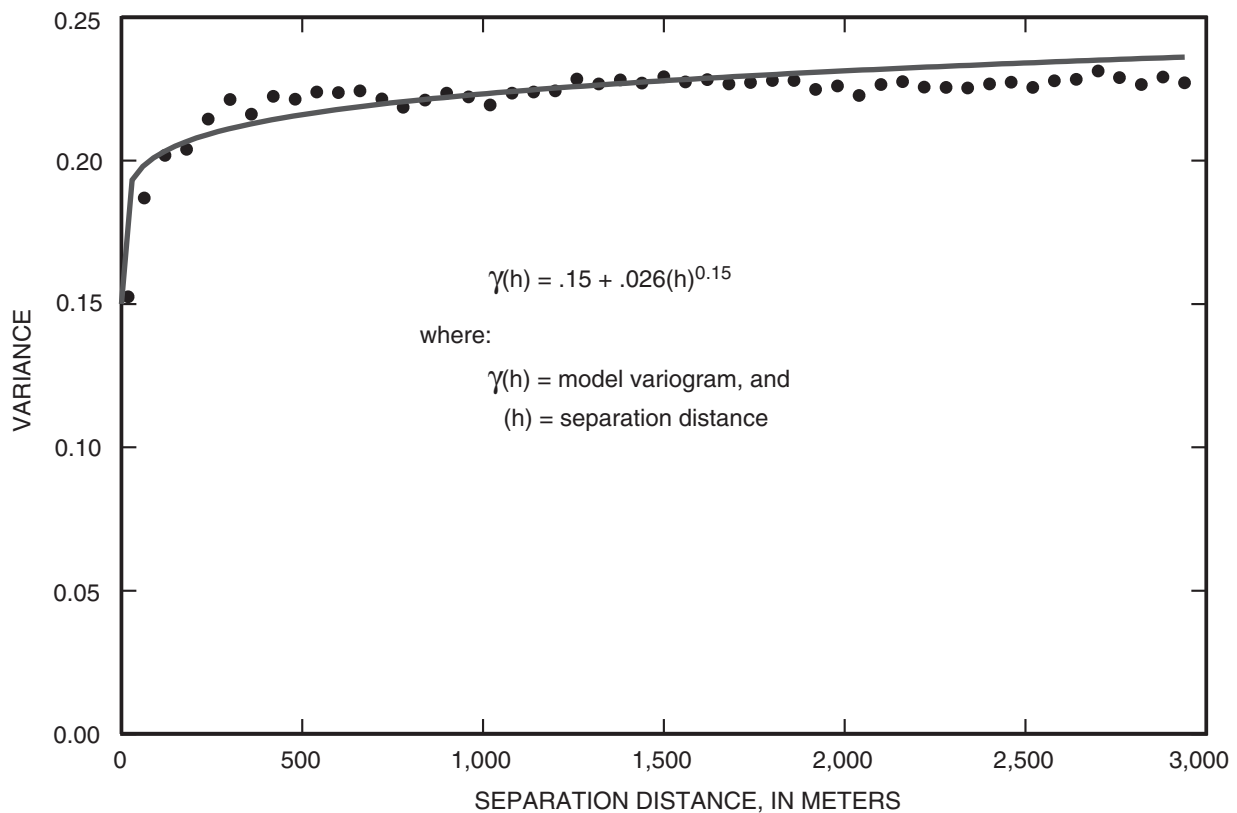


Figure 8. Sample variogram and model variogram for indicator kriging of confining layers in outwash setting.

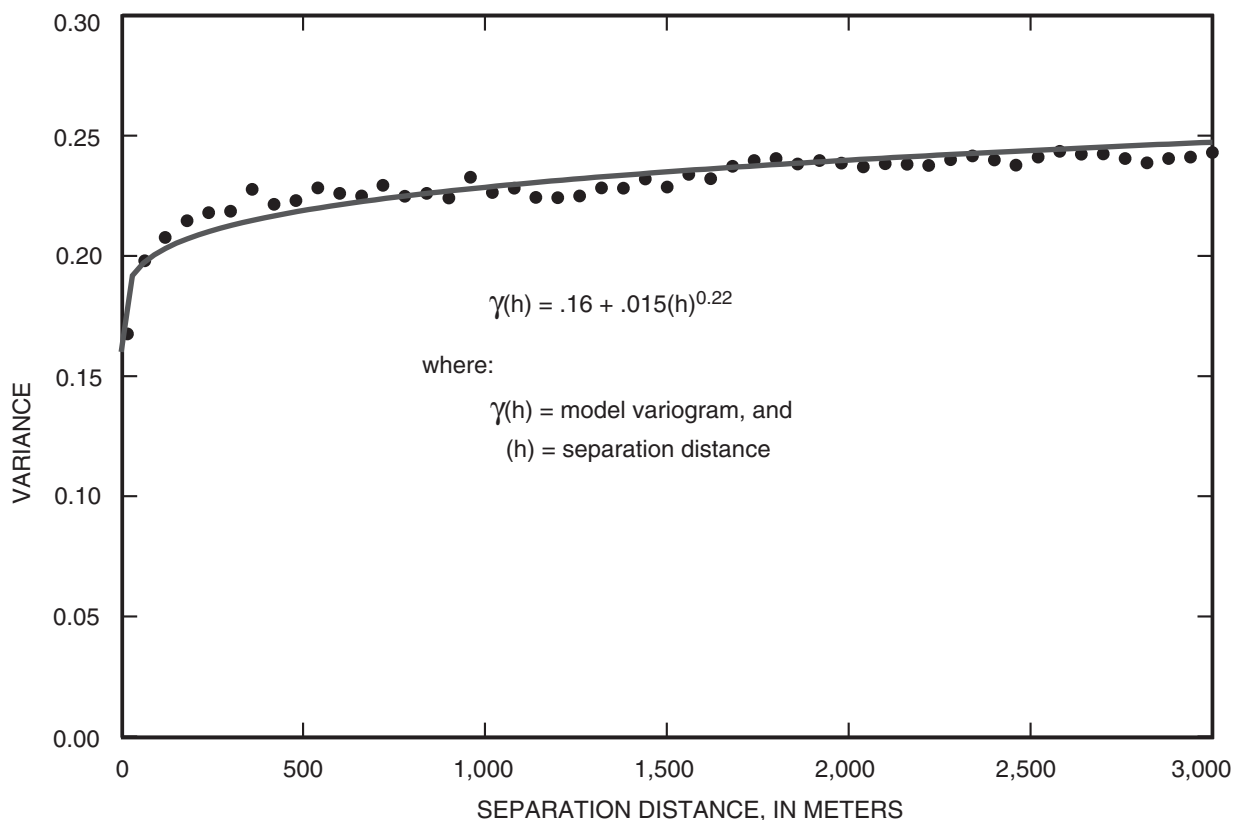


Figure 9. Sample variogram and model variogram for indicator kriging of confining layers in till setting.

The spatial distribution of predicted effective vertical hydraulic conductivity in Oakland County is presented in figure 10, which is a mosaic of the kriged estimates for the till and outwash settings. Several major features common to the effective vertical hydraulic conductivity map and the surficial geology map (fig. 1) are apparent, most notably the large area of high effective vertical hydraulic conductivity stretching up the center of the county from southwest to northeast, which corresponds to the large outwash plains through the center of the county. Even within the till settings, however, the predicted effective vertical hydraulic conductivity through this central part of the county is higher than in other till settings in the model area. Given that the till and outwash settings were modeled individually, this result may indicate an area of high effective vertical hydraulic conductivity within the till that may be more susceptible to contamination than other areas elsewhere in till. If the till and outwash settings had been

modeled together, the interpolation process would have obscured the variation between the two surficial geologic settings. Thus, the variation in predicted effective vertical hydraulic conductivity within a particular surficial geology class allows the comparison of the relative potential for ground-water contamination based on the physical characteristics of the subsurface environment not available from the surficial-geology map alone. The resulting map characterizes the relative potential for ground-water contamination of the shallow glacial drift aquifer in Oakland County.

The spatial distribution of the probability of confining layers that are 10 ft thick or greater is shown in figure 11. Clay layers are much more likely to underlie till settings, and the predicted probability of the existence of a clay layer corresponds to the distribution of till settings throughout the county.

12 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

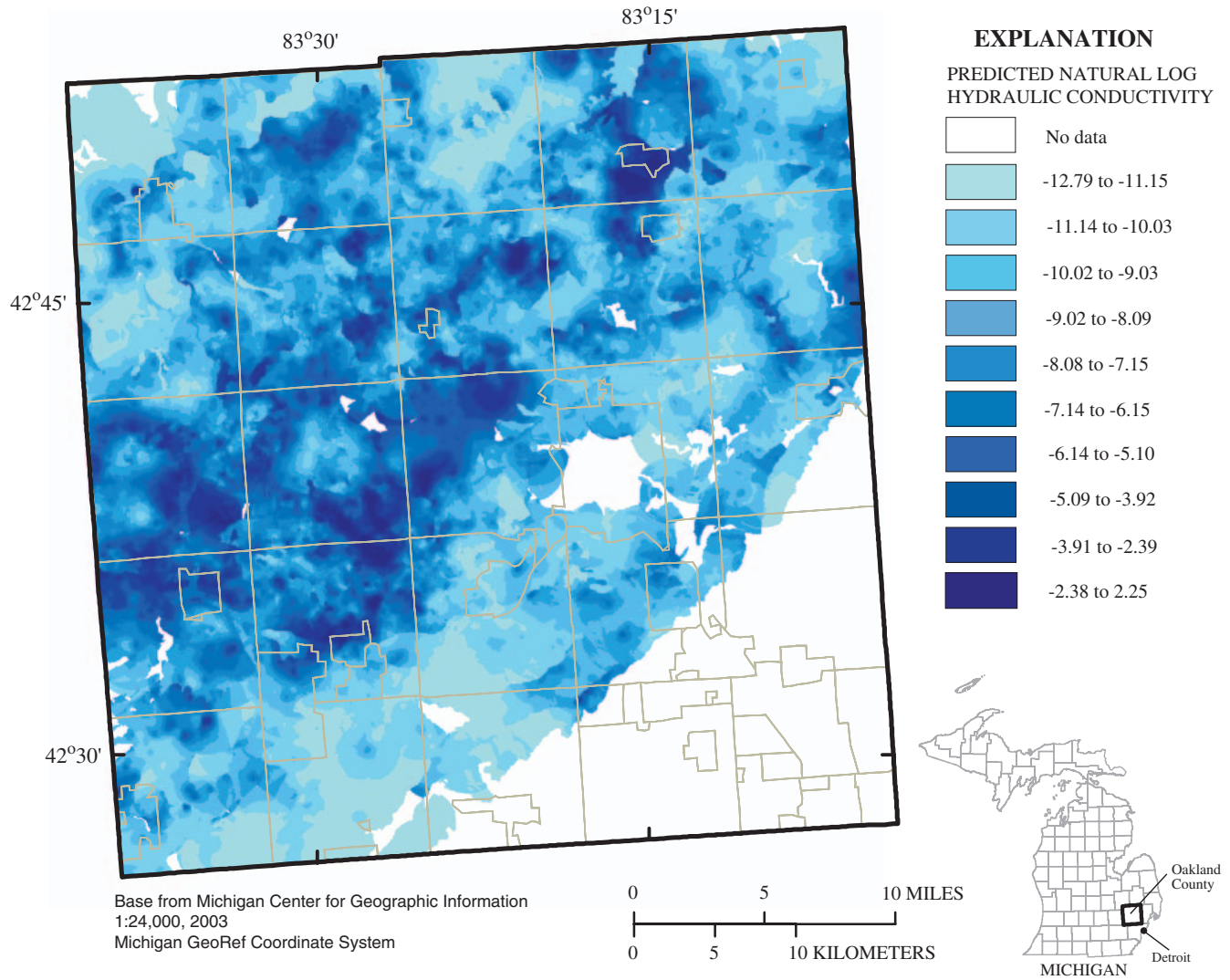


Figure 10. Predicted effective vertical hydraulic conductivity in the shallow glacial drift aquifer, Oakland County, Michigan.

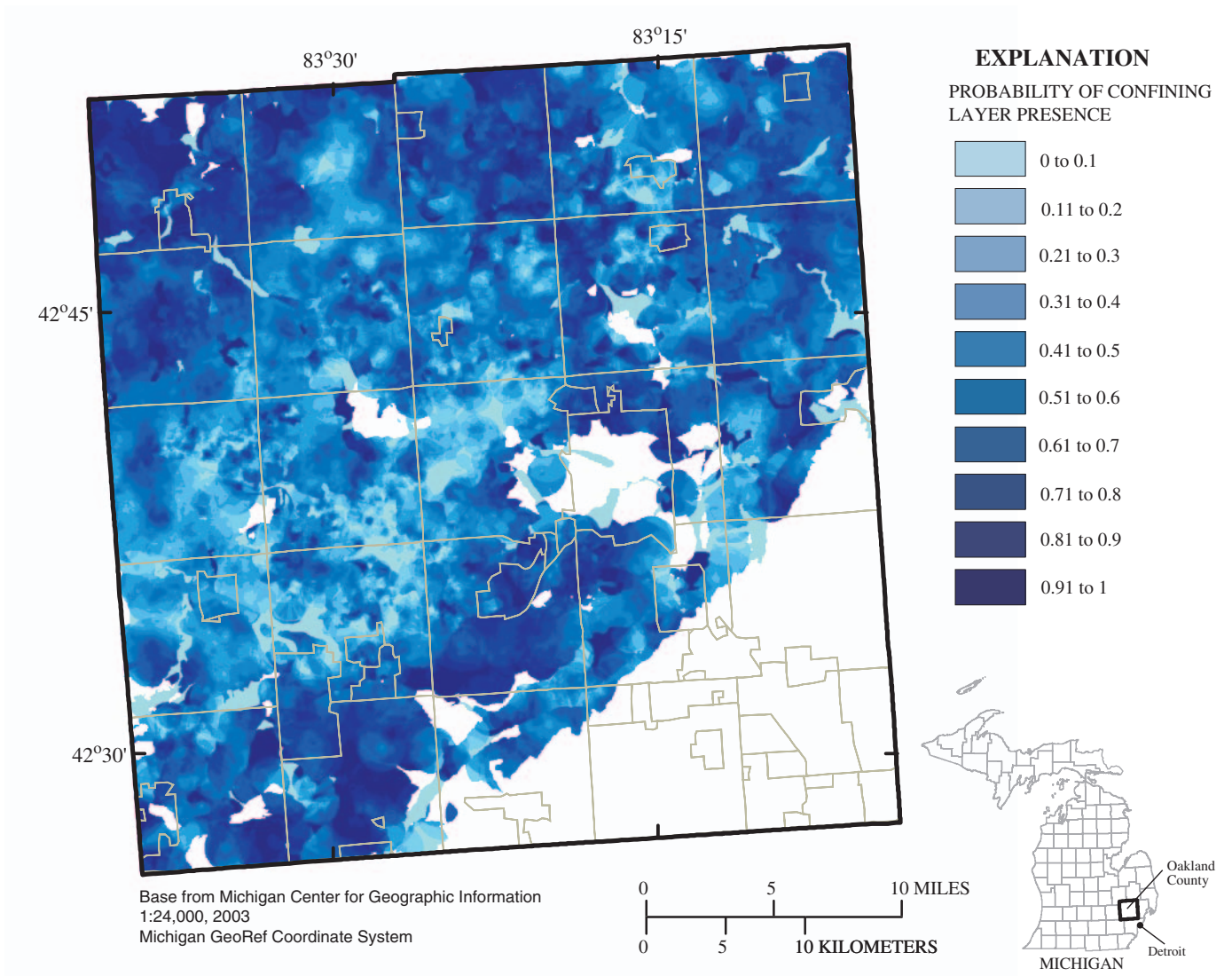


Figure 11. Predicted probability of confining-layer (10 ft thick or greater) presence in the shallow glacial drift aquifer, Oakland County, Michigan.

14 Effective Vertical Hydraulic Conductivity and Presence of Confining Layers, Shallow Glacial Drift Aquifer, Oakland Co., MI

The cross-validation process yields several metrics for assessing the quality and uncertainty of predictions. The first is the overall correlation coefficient, R. This was calculated individually in the till and outwash settings for both ordinary kriging (prediction of effective vertical hydraulic conductivity) and indicator kriging (prediction of confining layers). For the effective vertical hydraulic conductivity map, R is 0.417 and 0.435, in the till and outwash settings, respectively. For the prediction of confining layer presence map, R is 0.285 and 0.349 in the till and outwash settings, respectively. The lower R values may be the result of the noise introduced by converting the input data set to binary for use with indicator kriging. Based on the ratio of the nugget to the sill in the sample variograms, the percentage of the variance explained by the ordinary kriging

model was 58 percent in the till settings and 57 percent in the outwash setting. The correlation coefficient associated with each prediction as well as the Z-score (residual divided by the kriging standard error) are presented in table 2. These statistics serve as a relative measure of the uncertainty associated with each individual prediction.

Although these numbers are informative in a general sense, the uncertainty of the prediction also varies with data density. The uncertainty estimate, expressed as the variance of the kriged prediction, for the predicted effective vertical hydraulic conductivity, and prediction of confining layers presence are shown in figures 12 and 13. The locations of well logs used in the analysis also are shown.

Table 2. Cross-validation results for ordinary kriging and indicator kriging.

[Z-score indicates the residual/kriging error; std. dev., standard deviation]

Correlation coefficient	Summary statistic	Observed value	Predicted value	Predicted minus observed	Z-score
Ordinary kriging in outwash					
R = 0.4349	N	7,229	7,208	7,208	7,208
	Mean	-7.3770	-7.3650	.0024	-.0027
	Std. Dev.	5.5600	2.6200	5.0120	2.4100
Ordinary kriging in till					
R = 0.4171	N	9,379	9,369	9,369	9,369
	Mean	-8.3990	-8.4020	-.0031	-.0012
	Std. Dev.	5.2900	2.3830	4.8130	2.4430
Indicator kriging in till					
R = 0.2850	N	9,379	9,379	9,379	9,333
	Mean	.5582	.5564	-.0018	.0032
	Std. Dev.	.4960	.1900	.4779	2.7240
Indicator kriging in outwash					
R = 0.3491	N	7,229	7,229	7,229	7,209
	Mean	.4845	.4810	-.0035	-.0079
	Std. Dev.	.4987	.2585	.4749	2.4510

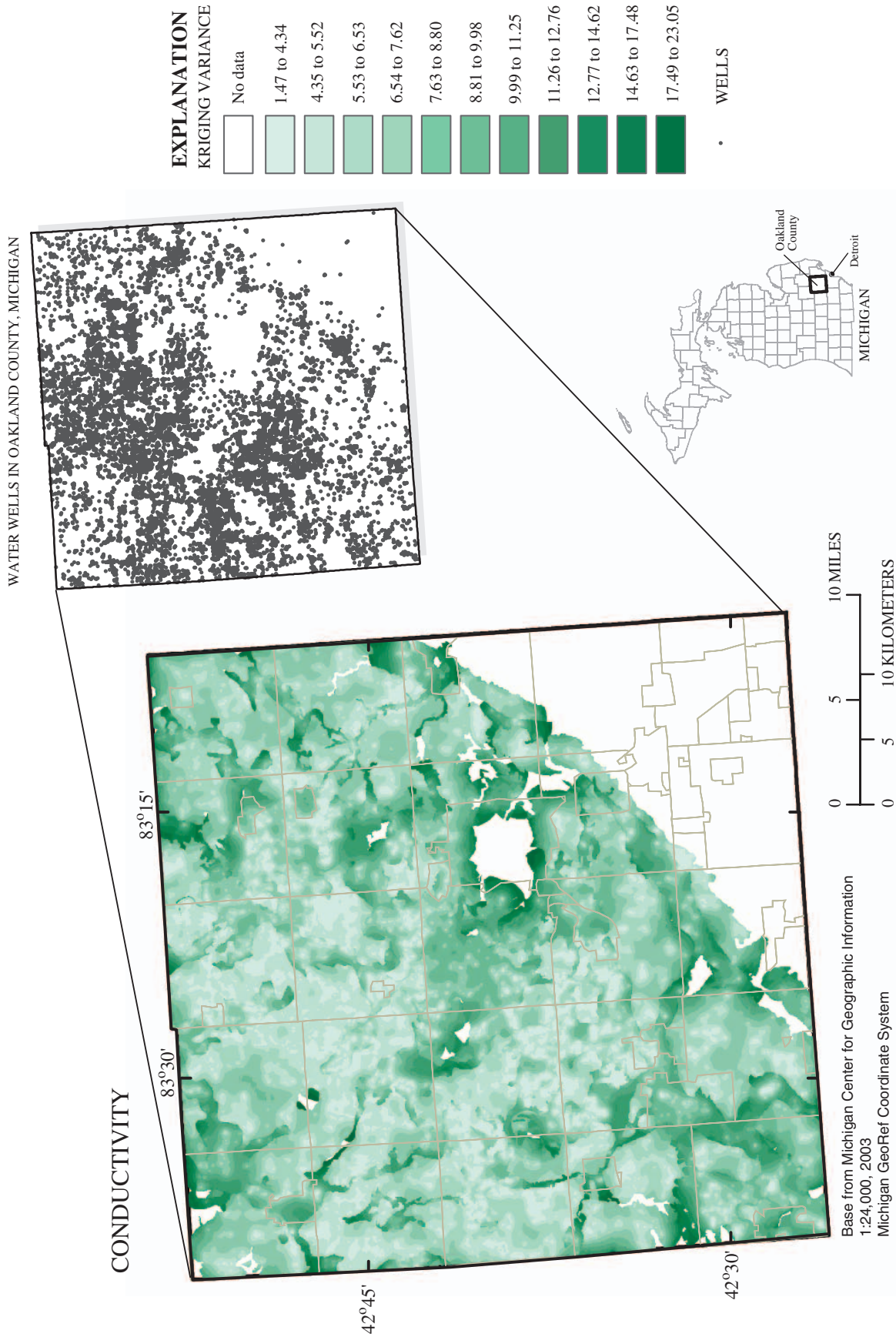


Figure 12. Uncertainty associated with prediction of effective vertical hydraulic conductivity in the shallow glacial drift aquifer, Oakland County, Michigan.

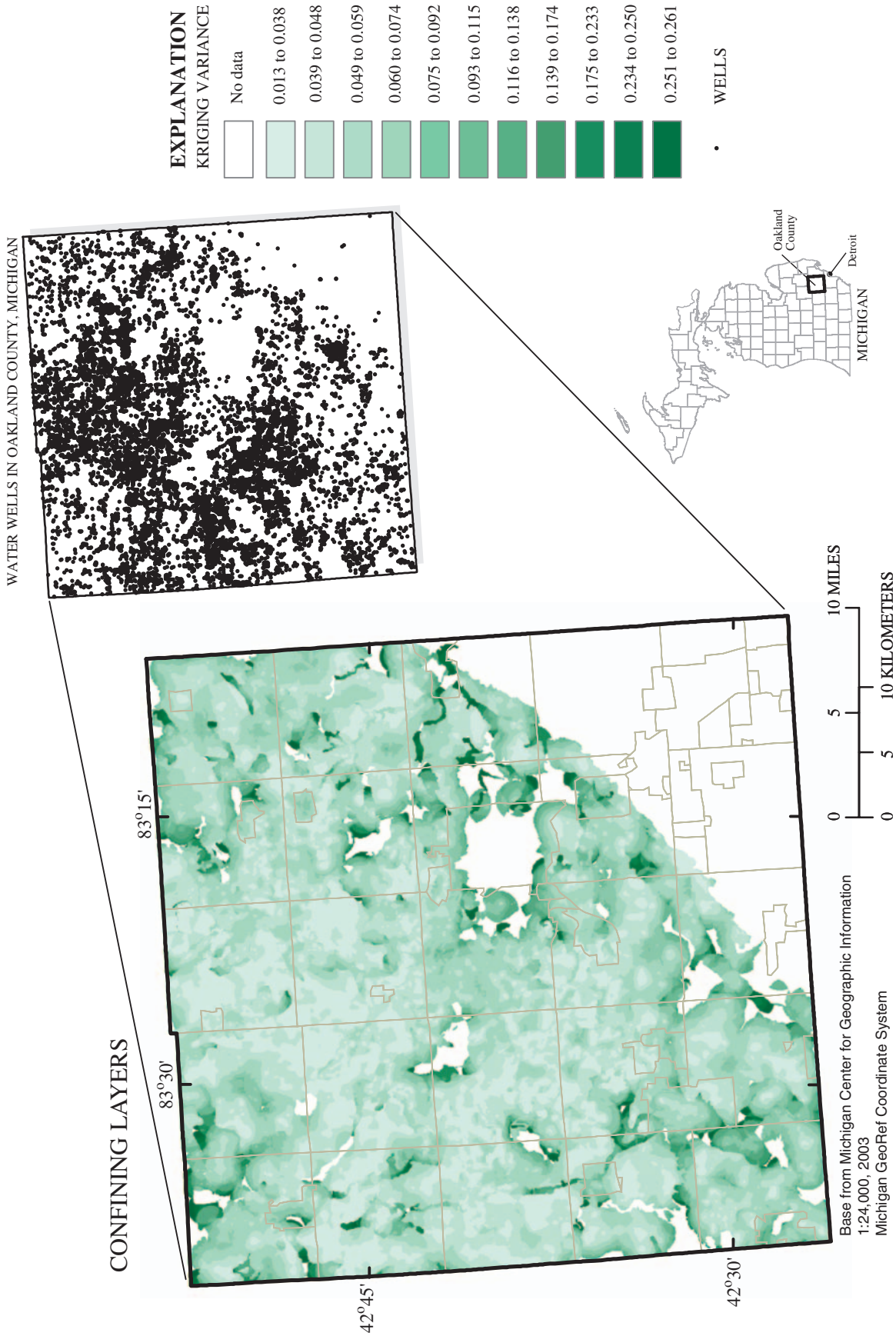


Figure 13. Uncertainty associated with prediction of confining-layer presence in the shallow glacial drift aquifer, Oakland County, Michigan.

Conclusions and Limitations

This report describes one aspect of a larger water resources assessment conducted cooperatively by the U.S. Geological Survey and Oakland County. Available lithologic data from the Wellkey database were used to create geostatistical models of the effective vertical hydraulic conductivity of the glacial deposits, and to predict the probability of encountering a clay layer with a thickness of 10 ft or more. While the accuracy of the predictions is limited because of both natural heterogeneity and the quality of the input data, these results provide a best estimate that can be used to prioritize ground-water protection programs in the county.

For the Oakland County Wellkey data, measurable spatial structure accounts for approximately 43 percent of the total variation in the computed effective vertical hydraulic conductivity dataset and 32 percent of the total variation in the confining layer dataset (both based on averages of R coefficients in the different settings). Overall, correlation coefficients were low for the four predictions that were done in this study. This relatively low level of prediction can be explained by the complexity of the glaciated landscape in Oakland County and by limitations of the input hydraulic-conductivity data derived from the Wellkey database. Although efforts were made to minimize the effects of complex geology and highly variable input data, their influence was still a significant factor contributing error in the well data, which ultimately limited the accuracy and reliability of predictions.

These predicted distributions are best estimates, and are limited not only by the quality of the source data but also by the complexity of glacial geology in this region. Estimates were posted to a raster grid with a resolution of 50 m for reasons related to computational efficiency, scale of the source data, and

the distribution of well locations. The variation in predictions cannot be identified for areas smaller than a 50-m cell. For this reason, the predictions are intended as screening tools and are not for site-specific use.

A natural log transformation was applied to hydraulic-conductivity data to reduce the skew of the data. Predictions are expressed on the natural log scale. A back-transformation, such as the inverse natural log transformation, was not applied because it would be biased. An unbiased back-transform requires knowledge of the Lagrange Multiplier, a coefficient developed in the kriging model that is not accessible when using GSTAT. Therefore, the results of the kriging algorithm should be viewed as relative rather than absolute because the units employed are not proportional to the observed values.

The extent of predictions is limited to areas that are within the search radius specified during the kriging operation. Areas that are devoid of wells (such as large water bodies, undeveloped areas, and municipalities with public water supplies) do not have predictions for effective vertical hydraulic conductivity and confining layer presence. These include the city of Pontiac, as well as a metropark and a state recreation area.

Only about 43 percent of the variation in effective vertical hydraulic conductivity and 32 percent of the variation in prediction of confining layers in Oakland County can be explained on the basis of available well-log data. Judging from this analysis, available well-log information is not sufficient to quantitatively characterize the subsurface environment in Oakland County by means of geostatistical methods. The maps in this report, however, give an indication of the relative susceptibility to contamination of ground-water sources (based on predicted effective vertical hydraulic conductivity and presence of clay layers) at a countywide scale.

Acknowledgments

The authors thank Dawn Beemer of the Oakland County Health Division for supplying the well data that are the basis of this report. Dr. Ashton Shortridge of Michigan State University Department of Geography gave valuable advice on the application of geostatistical techniques to data sets with highly skewed frequency distributions.

References Cited

- Aichele, S.S., 2000, Ground-water quality atlas of Oakland County, Michigan: U.S. Geological Survey Water-Resources Investigations Report 00-4120, 31 p.
- Burt, J.E., and Barber, G.M., 1988, Elementary statistics for geographers: New York, Guilford Press, 640 p.
- Cressie, N.A.C., 1993, Statistics for spatial data (revised ed.): New York, John Wiley and Sons, 802 p.
- Eschman, D.F., and Karrow, P.F., 1985, Huron basin glacial lakes—A review, *in* Karrow, P.F., and Calkin, P.E., Quaternary evolution of the Great Lakes: Geological Association of Canada, Special Paper 30, p. 79–94.
- Fetter, C.W., 1994, Applied Hydrogeology, (3d ed.): New York, MacMillan College Publishing, 616 p.
- Holtschlag, D.J., Luukkonen, C.L., and Nicholas, J.R., 1996, Simulation of ground-water flow in the Saginaw aquifer, Clinton, Eaton, and Ingham Counties, Michigan: U.S. Geological Survey Open-File Report 96-174, 48 p.
- Isaaks, E.H., and Srivistava, R.M., 1989, An introduction to applied geostatistics: New York, Oxford University Press, 552 p.
- Kuehl, R.O., 2000, Design of experiments—Statistical principles of research design and analysis: Pacific Grove, Calif., Brooks and Cole Publishing, 666 p.
- Leverett, Frank, and Taylor, F.B., 1915, The Pleistocene of Indiana, and Michigan and the History of the Great Lakes: U.S. Geological Survey Monograph 53, 529 p.
- Pebesma, E. J, 1999, GSTAT users manual: Utrecht, Netherlands, Department of Physical Geography, Utrecht University, 100 p.
- Saito, Hirotaka, and Goovaerts, Pierre, 2000, Geostatistical interpolation of positively skewed and censored data in a dioxin-contaminated site: Environmental Science & Technology, v. 34, no. 19, p. 4228–4235.
- Tobler, Waldo, 1979, A transformational view of cartography: The American Cartographer, v. 1, no. 2, p. 101–106.
- Twenter, Floyd, and Knutilla, Robert, 1972, Water for a rapidly growing urban community Oakland County, Michigan: U.S. Geological Survey Water-Supply Paper 2000, 150 p.
- Winters, H.A., Rieck, R.L., and Lusch, D.P., 1985, Quaternary geomorphology of southeastern Michigan, field trip guide for 1985 Annual Meeting of the American Association of Geographers: East Lansing, Mich., Department of Geography, Michigan State University, 98 p.

Glossary

Effective vertical hydraulic

conductivity Rate at which a material transmits water through its vertical profile based on its thickness and porosity.

Geostatistics Set of statistical tools used to analyze spatial data using inferences of the underlying spatial processes that determine the variability of attribute values.

Periglacial The area surrounding a glacier, from the Greek peri, meaning near or around. Periglacial environments are morphologically unstable, with frequent freeze/thaw cycles and abundant moisture.

Kriging Common term used to describe the general class of geostatistical tools used to predict attribute values and measures of uncertainty based on the spatial dependence of known sample values; named for the South African mining engineer D.G. Krige.

Spatial autocorrelation Statistical property of a spatial process describing the similarity of attribute values as a function of separation distance; based on Tobler's first law of geography; "measurements taken close together tend to be more similar than those taken far apart."

Stationarity Characteristic of a spatial process requiring a constant mean and variance for a defined spatial extent.

Variance A measure of the difference or spread between mean and predicted values.

Variogram A graph showing the average variance for groups of points separated by a specified lag distance.

