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Estimation of Leakage Potential of Selected Sites in Interstate and Tri-State Canals Using Geostatistical Analysis of Selected Capacitively Coupled Resistivity Profiles, Western Nebraska, 2004

Scientific Investigations Report 2009–5223

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

Front cover:
Capacitively coupled resistivity profiling of irrigation canals along adjacent access road.

Back cover:
Surveyed irrigation canals near Scotts Bluff, Nebraska.

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Conversion Factors, Datums, and Water-Quality Units

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
	Resistivity	
ohm-meter (ohm-m)	3.281	ohm-foot (ohm-ft)

Datums

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

Estimation of Leakage Potential of Selected Sites in Interstate and Tri-State Canals Using Geostatistical Analysis of Selected Capacitively Coupled Resistivity Profiles, Western Nebraska, 2004

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Abstract

With increasing demands for reliable water supplies and availability estimates, groundwater flow models often are developed to enhance understanding of surface-water and groundwater systems. Specific hydraulic variables must be known or calibrated for the groundwater-flow model to accurately simulate current or future conditions. Surface geophysical surveys, along with selected test-hole information, can provide an integrated framework for quantifying hydrogeologic conditions within a defined area. In 2004, the U.S. Geological Survey, in cooperation with the North Platte Natural Resources District, performed a surface geophysical survey using a capacitively coupled resistivity technique to map the lithology within the top 8 meters of the near-surface for 110 kilometers of the Interstate and Tri-State Canals in western Nebraska and eastern Wyoming. Assuming that leakage between the surface-water and groundwater systems is affected primarily by the sediment directly underlying the canal bed, leakage potential was estimated from the simple vertical mean of inverse-model resistivity values for depth levels with geometrically increasing layer thickness with depth which resulted in mean-resistivity values biased towards the surface. This method generally produced reliable results, but an improved analysis method was needed to account for situations where confining units, composed of less permeable material, underlie units with greater permeability.

In this report, prepared by the U.S. Geological Survey in cooperation with the North Platte Natural Resources District, the authors use geostatistical analysis to develop the minimum-unadjusted method to compute a relative leakage potential based on the minimum resistivity value in a vertical column of the resistivity model. The minimum-unadjusted method considers the effects of homogeneous confining units. The minimum-adjusted method also is developed to incorporate the effect of local lithologic heterogeneity on water transmission. Seven sites with differing geologic contexts were selected following review of the capacitively coupled resistivity data collected in 2004. A reevaluation of these sites using the mean, minimum-unadjusted, and minimum-adjusted methods was performed to compare the different approaches for estimating leakage potential.

Five of the seven sites contained underlying confining units, for which the minimum-unadjusted and minimum-adjusted methods accounted for the confining-unit effect. Estimates of overall leakage potential were lower for the minimum-unadjusted and minimum-adjusted methods than those estimated by the mean method. For most sites, the local heterogeneity adjustment procedure of the minimum-adjusted method resulted in slightly larger overall leakage-potential estimates. In contrast to the mean method, the two minimum-based methods allowed the least permeable areas to control the overall vertical permeability of the subsurface. The minimum-adjusted method refined leakage-potential estimation by additionally including local lithologic heterogeneity effects.

Introduction

Demands on water resources are increasing as population grows. Improved understanding of surface-water and groundwater systems can aid managing limited supplies of water. One method for understanding these systems is to develop a numerical groundwater-flow model. Groundwater-flow models can be used to establish theoretical relations between physical properties and model variables and to simulate the effects of stresses on an aquifer system (Appel and Bredehoeft, 1976). Specific hydrogeologic values must be known for the groundwater-flow model to accurately simulate current or future conditions (Merry and others, 2003). Test-hole data and surficial geologic mapping are commonly used to determine geologic and hydrogeologic conditions, such as the spatial distribution of water leakage between the surface-water and groundwater systems. Often, test-hole data are either unavailable or are spatially too sparse to adequately characterize the subsurface. This lack of information can increase uncertainties in estimating geologic and hydrogeologic properties, resulting in inadequate conceptualization of the simulated flow system and potential problems with simulation calibration.

Drilling additional test holes to acquire more information can be time-consuming and expensive. Furthermore, additional test holes only provide lithologic descriptions at spatially discrete points. In these situations an estimation of hydrogeologic properties, such as sediment grain-size distribution between distant points, is required (Ball and others, 2006). Surface geophysical surveys, along with test-hole information, can provide an integrated framework for determining the hydrogeologic conditions within a defined area. Surface geophysical methods measure the physical properties of the subsurface, such as electrical conductivity (or its inverse, electrical resistivity), dielectric permittivity, magnetic permeability, density, or elasticity (Grant and West, 1965). Results from geophysical surveys can be used to continuously characterize the hydrogeologic units in the subsurface.

In a previous study during 2004, the U.S. Geological Survey (USGS), in cooperation with the North Platte Natural Resources District (NRD), evaluated a continuous resistivity profiling technique to map the near-surface lithology of the Interstate and Tri-State Canals in western Nebraska and eastern Wyoming (Ball and others, 2006). Results from that study provided estimates of canal leakage for use in a groundwater-flow model developed to improve the general understanding of groundwater recharge (Ball and others, 2006). The upper 8 meters (m) along 110 kilometers (km) of these canals were mapped using a capacitively coupled resistivity (CCR) technique. Twenty-five test holes were drilled in close proximity to the CCR profiles to determine the relation between electrical resistivity and relative grain-size distribution. Using the test-hole information, an interpretation was developed associating different grain-size categories with resistivity values.

To interpret the CCR data, a vertical mean resistivity (referred to as the “mean method” in this report) was computed to classify leakage potential as either high, medium, or low (Ball and others, 2006). More weight was given to the resistivity values near the surface because it was assumed that leakage is affected primarily by the sediment directly underlying the canal bed. Although the mean method produced reliable interpretations for many of the surveyed canals, there were certain situations where an improved analysis method was needed. For example, in some situations highly resistive units (indicative of highly permeable material such as sand) overlie homogenous units of low resistivity (indicative of relatively impermeable material such as clay). Hydrologically, the deeper clay acts as a confining unit and impedes overall water transport regardless of the more permeable overlying unit (Smith and Wheatcraft, 1993). The mean method resulted in over-estimation of leakage potential for such situations because the average of the high- and low-resistivity units exceeds the effective permeability of the limiting unit. The present (2009) study, conducted by the USGS in cooperation with the North Platte NRD, provides a reevaluation of selected CCR profiles from the data collected in the Interstate and Tri-State Canals by using a new geostatistical approach to provide a more comprehensive estimation of leakage potential as compared to the mean method.

Purpose and Scope

This report presents descriptions of three geostatistical methods using selected CCR profiles for estimating leakage potential between surface-water and groundwater systems along the Interstate and Tri-State Canals. The CCR profiles were analyzed using the mean method, as used by Ball and others (2006), and two recently (2009) developed methods. Results from the three methods are compared to assess the effectiveness of incorporating hydrogeologic heterogeneity into leakage potential estimation. CCR data within the canal are selected on the basis of proximity to test-hole location and representation of differing geologic contexts.

This report does not present or reinterpret any of the test-hole data collected as part of the previous study. Furthermore, the three geostatistical methods presented in this report do not incorporate the test-hole data in their computations. The test-hole data were used only to provide information for selecting differing geologic contexts for the application of the geostatistical methods presented.

Description of Study Area

The study area is located in the western part of the North Platte NRD in the Nebraska Panhandle, in Scotts Bluff and Sioux Counties and extending into Goshen County, Wyo., and specifically consists of the Interstate and Tri-State Canals from about 10 km west of the Nebraska-Wyoming State line to about 4 km east of Scottsbluff, Nebr. (fig. 1) (Ball and others, 2006). The majority of the study site is underlain by Quaternary-age alluvial and eolian deposits with varying thicknesses. The predominant bedrock formation is the Brule Formation of Tertiary age, which is generally composed of siltstone and mudstone and crops out in the northern part of the study area.

The nearby land cover is dominated by rangeland and cropland. Major crops include irrigated corn, dry edible beans, sugar beets, and alfalfa (Verstraeten and others, 2001). Irrigation water is supplied predominantly from canals as surface water, although groundwater irrigation wells also are common (Ball and others, 2006). Recharge to the aquifer system is predominantly from the irrigation canals (Babcock and Visher, 1951; Verstraeten and others, 2001). A more detailed description of the study area is provided by Ball and others (2006).

For the present (2009) study, seven sites each consisting of a 600-m profile of CCR data were selected from the data evaluated by Ball and others (2006). The CCR data were selected on the basis of proximity of test holes exhibiting differing geologic contexts. Each CCR profile extends 300 m upstream and downstream from a specific test hole that

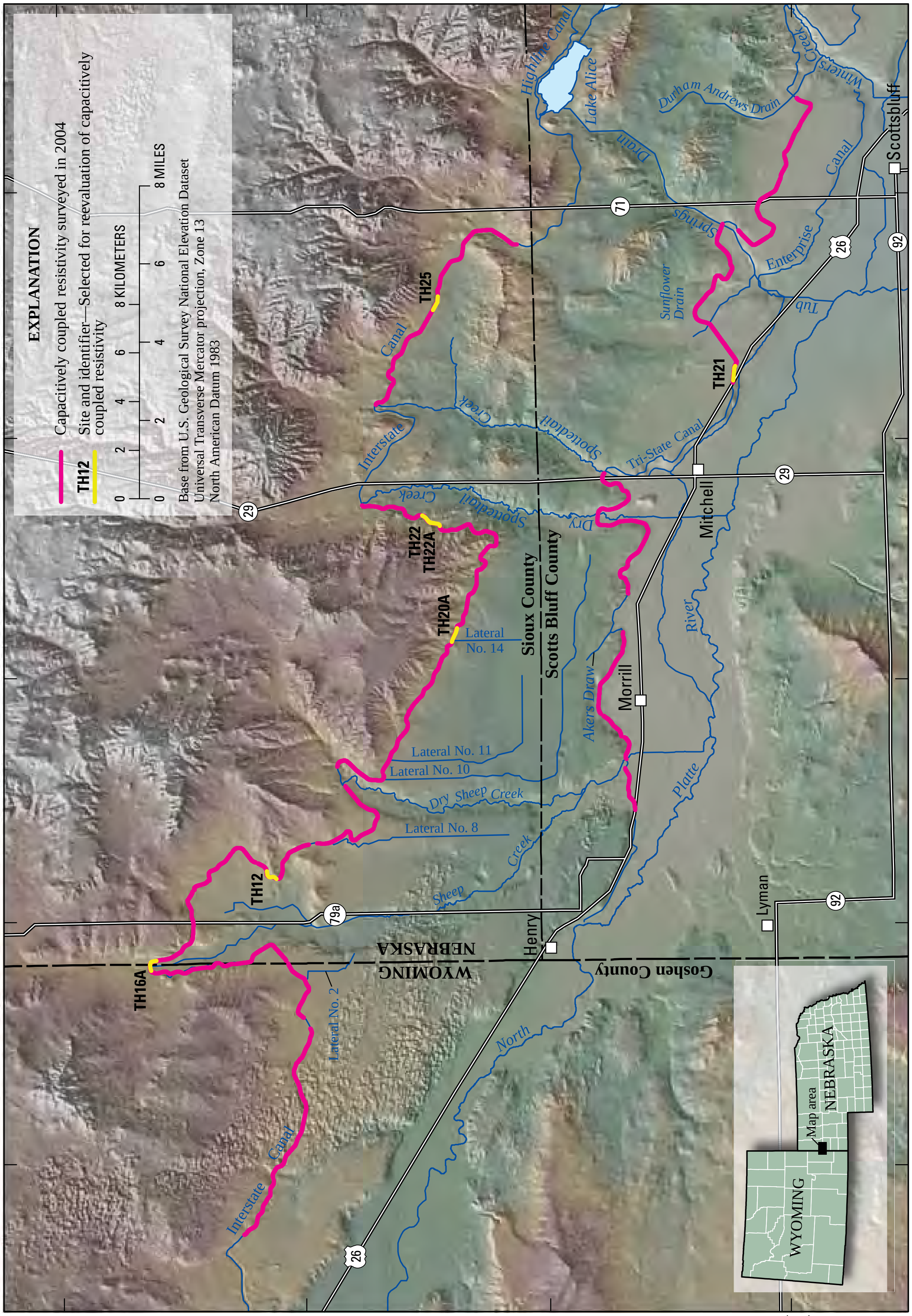


Figure 1. Location of capacitively coupled resistivity survey at selected sites in Interstate and Tri-State Canals, western Nebraska (modified from Ball and others, 2006).

anchors each of the seven sites. Each site is identified by the test hole anchoring the profile. Six of the selected test holes are located on the Interstate Canal: TH12, TH16A, TH20A, TH22, TH22A, and TH25. The seventh, TH21, is located on the Tri-State Canal (fig. 1).

Resistivity Methods

Surface geophysical resistivity techniques can be used to detect changes in the electrical properties of the subsurface (Zohdy and others, 1974). The electrical properties of soils and rocks are determined by water content, porosity, clay content, and conductivity (the reciprocal of electrical resistivity) of the pore water (Lucius and others, 2007). For example, resistivity values for clay minerals can be less than 1 ohm-meter (ohm-m), whereas the resistivity of dry sand and gravel can exceed several thousand ohm-meters (Zohdy and others, 1974). Resistivity measurements are collected by inducing a known current into the subsurface and measuring the change in voltage between two points on the land surface. Using Ohm's Law and an appropriate geometric factor, an apparent resistivity value can be computed (Zohdy and others, 1974). The resistivity survey method is described in further detail by Lucius and others (2007) and Zohdy and others (1974).

Capacitively Coupled Resistivity Profiling and Data Filtering

To make a CCR measurement, two transmitting antennas (transmitter) and two receiving antennas (receiver) are needed. By applying a known alternating current at a fixed frequency, the transmitter induces an electrical current in the subsurface through capacitive coupling with the earth (Ball and others, 2006). The receiver measures the resulting voltage change between receiving antennas. As the transmitter-receiver separation increases, greater depth penetration is achieved. Simultaneous use of multiple receivers positioned at different separation distances from a single transmitter acquires data at multiple depth levels with a single current transmission. With the CCR technique, several receivers and one transmitter are sequenced together and pulled slowly along the ground surface. A continuous two-dimensional (2D) profile of subsurface resistivity is obtained. An OhmMapper TR-5 (Geometrics, 2009) with one transmitter towed behind five receivers was used by Ball and others (2006) to collect the CCR profiles in 2004 along the study area canals.

Since the publication of Ball and others (2006), a new method for filtering CCR data has been developed. The CCR profiles evaluated by Ball and others were filtered and analyzed using the new method to enhance data quality for the present (2009) study. The electrical current, voltage, and apparent resistivity values of the CCR profiles were examined to identify outliers. Data points were removed if: (1) the current was not equal to 4 milliamps (mA), (2) the voltage was less than 200 microvolts (μV), or (3) there was a substantial spike in the apparent resistivity. Additional apparent resistivity values were removed if they were spatially separated from the bulk of the data by substantial distance gaps. A summary of data values removed, as a result of the filtering process, is presented for each profile in table 1. Because of their close proximity, the profiles for sites TH22 and TH22A were filtered as a single data set.

After data removal, a 20-m moving-window mean smooth was calculated laterally across each profile. Finally, the smoothed data were partitioned into 5-m wide intervals along each profile. The mean of the apparent resistivity values in each interval was assigned to the mid-point of the interval to obtain equally spaced apparent resistivity values for 2D inverse modeling.

Two-Dimensional Inverse Modeling

Apparent resistivity is the electrical resistivity computed from the field measurements for an equivalent

Table 1. Summary of data values removed as a result of the filtering process.

[<, less than; >, greater than]

Site identifier (fig. 1)	Initial number of data points	Number of data points removed by indicated filter				
		Current, in data points (percent of initial)	Voltage, in data points (percent of initial)	Apparent resistivity, in data points (percent of initial)	Spatially separated, in data points (percent of initial)	Final number of data points (percent of initial)
TH12	3,203	5 (0.2)	606 (18.9)	2 (<0.1)	55 (1.7)	2,535 (79.1)
TH16A	3,725	720 (19.3)	439 (11.8)	1 (<.1)	10 (.3)	2,555 (68.6)
TH20A	3,325	0 (0)	10 (.3)	0 (0)	0 (0)	3,315 (99.7)
TH21	3,255	0 (0)	0 (0)	2 (<.1)	0 (0)	3,253 (>99.9)
TH22/TH22A	6,375	20 (.3)	1,402 (22.0)	0 (0)	60 (.9)	4,893 (76.8)
TH25	4,180	75 (1.8)	659 (15.8)	4 (<.1)	165 (3.9)	3,277 (78.4)

homogeneous, isotropic subsurface (Loke, 2000). A model comprising multiple rectangular blocks, each assigned a central resistivity value, was developed by an inverse modeling program to help determine a representative distribution of electrical resistivity within the subsurface (Ball and others, 2006). Model-predicted resistivity values were computed from the multi-block model by the inverse modeling program. The predicted apparent resistivity values for the model were then compared to the measured apparent resistivity values and a root-mean-square (RMS) difference was calculated. The inverse modeling program, through numerical optimization, minimized the RMS by altering the assigned resistivity values of the multi-block model. Each optimization step is known as "an iteration." When the RMS did not decrease by more than 3 percent between iterations, the authors deemed that an acceptable solution had been reached. The inverse modeling process is described in detail by Loke (2004).

The filtered CCR data were inversely modeled using EarthImager 2D (version 2.2.6, Build 554) (Advanced Geosciences, Inc., 2008). Specifically, each CCR profile was inversely modeled using the smooth-model inversion method supported by the software. Depending on the site, inverse modeling produced a final model with resistivity values for either 10 or 11 depth levels. The model-inverted data for sites TH12 and TH25 have 10 depths. The model-inverted data for sites TH20A, TH21, TH22, and TH22A have 11 depths. The model-inverted data for site TH16A have 10 depths with a partially populated 11th depth level. For consistency in applying the geostatistical methods and for the cross-comparisons presented in this report, the 11th depth level (8.2 m below land surface) of sites TH16A, TH20A, TH21 TH22, and TH22A was removed. Thus, 10 depths of model-inverted resistivity data were analyzed for all sites.

Estimation of Leakage Potential Using Geostatistical Analysis of Capacitively Coupled Resistivity Profiles

Inversely modeled CCR measurements are directly related to sediment grain size, a critical factor controlling hydrogeologic permeability. Typically, fine-grained sediments contain a higher proportion of pore water and clay than do coarse-grained sediments. Consequently, fine-grained sediments with low permeability are generally less electrically resistive than coarser grained sediments of higher permeability (Ball and others, 2006). For this reason, resistivity values can be used as a surrogate for permeability in estimating a leakage potential. To arrive at an estimate appropriate for use in a surface-water/groundwater interaction model, an interpretive method is needed to characterize the model-inverted 2D resistivity values as a one-dimensional (1D), streamwise representation of the overall hydraulic permeability of the shallow subsurface. Three such characterization methods were applied and evaluated: the (1) mean, (2) minimum-unadjusted, and (3) minimum-adjusted methods. Each method is described in the following sections of the report.

Mean Method

The method used in Ball and others (2006) estimated a 1D leakage potential by computing the mean of the inverse-model resistivities of all depth levels for each analyzed point along the profile. This method characterizes the overall vertical permeability of the underlying geologic materials.

The block size of the inversion model increased in thickness by 10 percent with each depth level. Therefore, successive depth levels form a geometric sequence with a common ratio of 1.1 (Varberg and Purcell, 1992). The resulting vertical data spacing is least at the surface and gradually increases in constant proportion with depth. Because of the non-uniform data spacing—geometrically increasing layer thickness with depth—the use of a simple vertical mean resulted in mean-resistivity values biased towards the surface. The biased characterization of the mean method was considered by Ball and others to be a more accurate representation of leakage potential than a depth-compensated (weighted) mean that would mitigate depth-related bias. Preference for the mean method was based on the assumption that leakage is predominantly controlled by the sediments directly underlying the canal bed and that geologic effect on leakage progressively diminishes with depth (Ball and others, 2006). The mean method accounts for this assumed phenomenon by using an estimate that is biased toward the surface layers.

The vertical mean computations yield values that retain units of ohm-meters. As a final step, however, dimensionless estimates of leakage potential were calculated by dividing all vertical mean values by the greatest vertical mean value among all profiles. This step yields dimensionless estimates bounded by 0 and 1. A lower bound of zero is ensured because inverse-model resistivities are positive. In addition, because the greatest vertical mean value was used to rescale the data, direct comparisons of leakage estimates between profiles were possible.

Minimum-Unadjusted Method

The minimum-unadjusted method of estimating 1D leakage potential uses the minimum of the inverse-model resistivities for each vertical column of model blocks at each distance interval along the profile. The minimum, as opposed to a mean, is deemed appropriate by the authors because hydraulic conductivity is most affected by the least permeable (and hence least electrically resistive) unit in the subsurface (Smith and Wheatcraft, 1993). For example, an area containing an intact confining unit of clay will result in low overall leakage potential for that area regardless of the permeability of the overlying or underlying material. Therefore, confining subsurface units, when present, tend to characterize the 1D representation of the 2D profile. The minimum-unadjusted method is "unadjusted" because no compensation for local geologic heterogeneity is made in the computations.

As with the mean method, a final standardization step is used to obtain dimensionless estimates of leakage potential bounded by 0 and 1. This is achieved by dividing all the minimum resistivity values by the greatest minimum resistivity value computed among all profiles. Because all profiles are identically rescaled, direct comparisons of leakage estimates between profiles are possible.

Minimum-Adjusted Method

Unlike the minimum-unadjusted method, the minimum-adjusted method incorporates local lithologic heterogeneity into estimation of leakage potential. Qualitatively, lithologic heterogeneity is the overall variation of the lithologic properties of an area of interest. For example, a mixed unit of coarse sand, gravel, and clay lenses would be considered "heterogeneous," whereas a uniform unit of coarse-grained sand deposits would be considered "non-heterogeneous" (or homogeneous). However, to achieve the purposes of this study, a means of mathematically quantifying lithologic heterogeneity was required. Because CCR data are strongly related to lithologic properties such as grain size (Ball and others, 2006), geostatistical methods can be applied to the resistivity data to indirectly quantify the similarity or dissimilarity of the underlying lithology.

Local lithologic heterogeneity can have direct bearing on water transmission, and hence canal leakage, through the subsurface material. Locally homogeneous, electrically resistive regions (high resistivity), such as uniform layers of sand (fig. 2A), would tend toward higher bulk hydraulic conductivity, and therefore high permeability. Conversely, locally

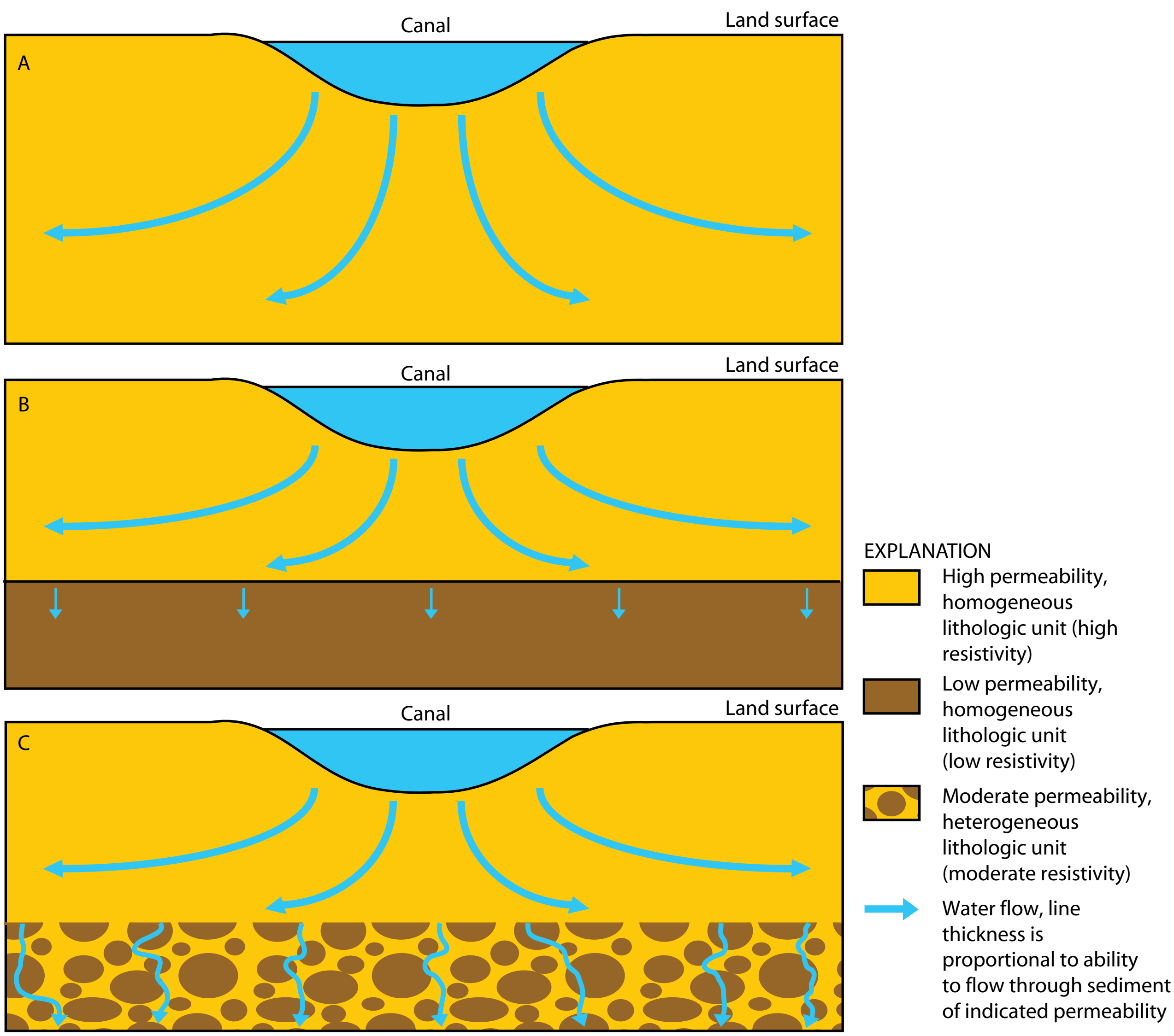


Figure 2. Conceptual model of water transport in (A) homogeneous, high permeability units, (B) homogeneous, low permeability units, and (C) heterogeneous units having low permeability sediment within high permeability sediment.

homogeneous, electrically conductive regions (low resistivity), such as uniform layers of clay (fig. 2B), would tend toward lower bulk hydraulic conductivity (low permeability). However, areas of low electrical resistivity within a locally heterogeneous region (fig. 2C) have a potential for a higher effective hydraulic conductivity than suggested by the mean resistivity value alone. The potential derives from the ability of water to flow through the more permeable areas in the immediate vicinity. Thus, it was deemed appropriate to incorporate local heterogeneity into a method that uses model-inverted electrical resistivity values to estimate leakage potential.

The coefficient of *L*-variation (*L*-CV) was applied to the model-inverted resistivity data to quantify lithologic heterogeneity. *L*-CV is computed as the ratio of the second *L*-moment to the first *L*-moment (arithmetic mean). *L*-moments are defined in Hosking (1990), and Asquith (2007) has summarized the mathematics and theory of *L*-moments in further detail. The *L*-CV is analogous to, but not numerically equal to, the coefficient of variation (CV, the standard deviation of a sample divided by its mean). *L*-CV provides a dimensionless measure of the relative variability of a data sample. *L*-moment statistics, among other advantages, have the benefit of greater robustness and less bias for small sample sizes. These advantages are important in preferring the *L*-CV over the CV or other measures of relative dispersion.

Both the vertical variability (changes with depth) and horizontal variability (changes with longitudinal distance) of the model-inverted resistivity profiles were analyzed to characterize the overall heterogeneity of the study sites. Insights gained from this analysis were used to develop a resistivity-adjustment procedure appropriate for incorporation into a method for estimating leakage potential.

Vertical Heterogeneity

Vertical heterogeneity was analyzed for each of the seven model-inverted resistivity profiles. Vertical heterogeneity, an expression of variability with depth, provides information on how the geophysical properties of the subsurface materials change from shallow to deeper depths. For examination of vertical heterogeneity, the CCR data were partitioned into three depth zones: upper, middle, and lower (fig. 3). The partitioning of the data into zones allows the analysis of the heterogeneity of each zone individually along the profile, as

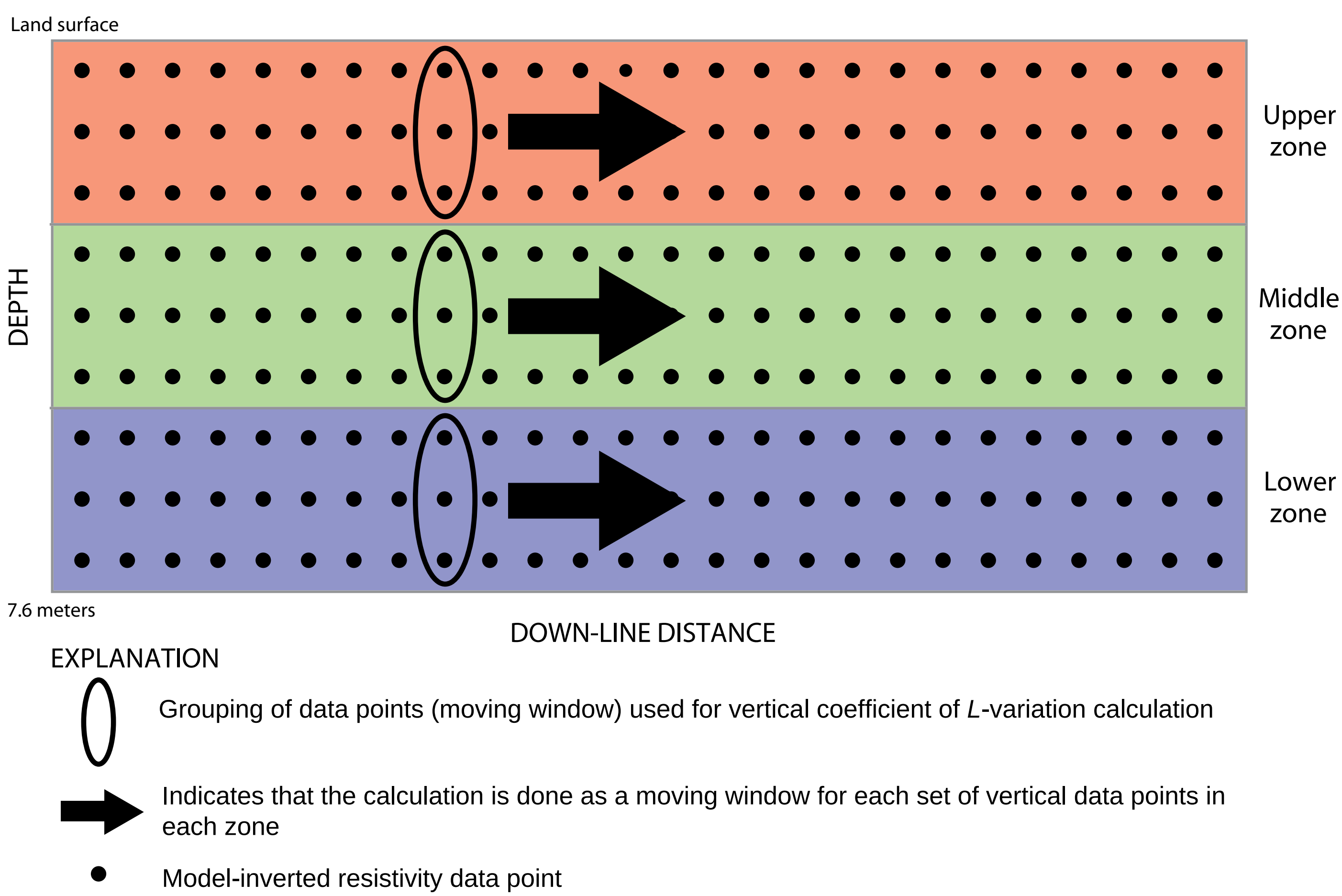


Figure 3. Schematic representation of the vertical heterogeneity analysis method.

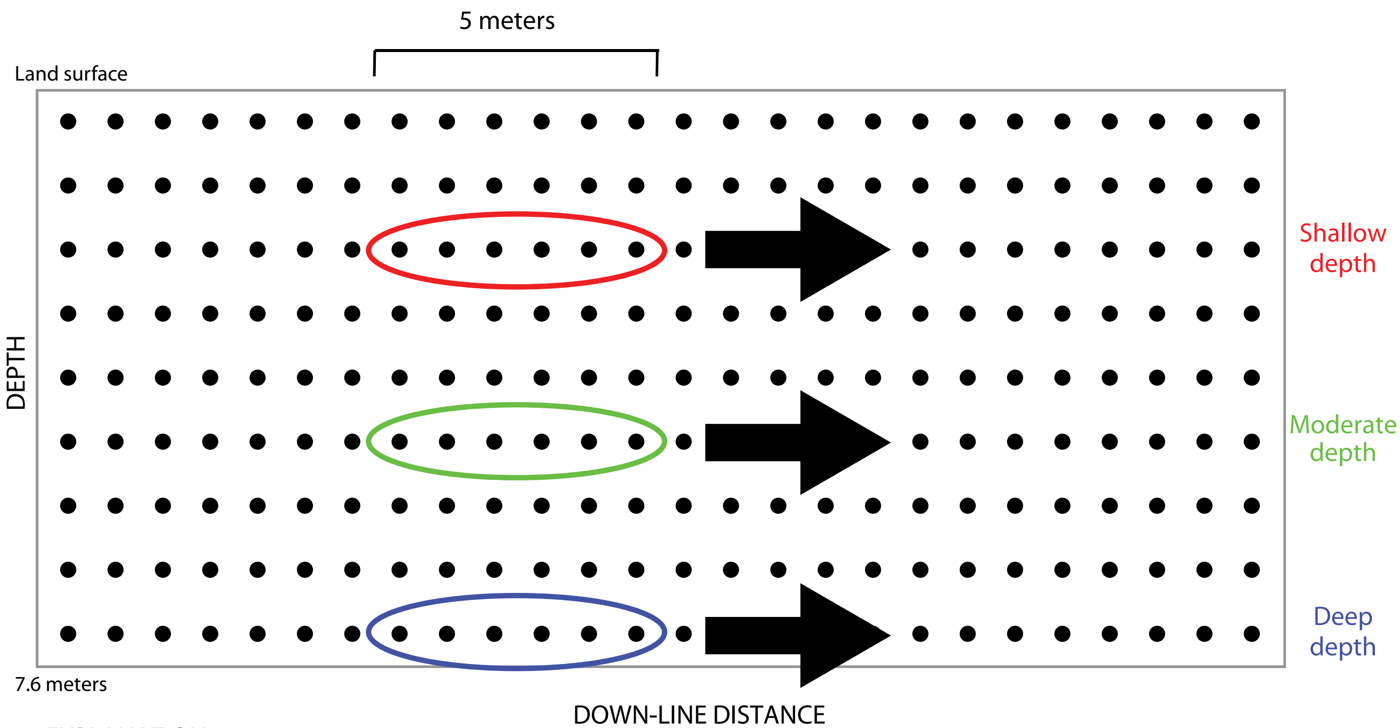
well as graphical (not computational) comparisons of relative heterogeneity among the zones. The inverse modeling output data consist of resistivity values at 10 discrete depths ranging from land surface to 7.6-m below land surface. The shallowest depth (land surface) was excluded from the analysis described here. The remaining nine depths were then partitioned into upper, middle, and lower zones. The *L*-CV for each of the zones at each down-line distance (distance along the data collection path) was then computed. Because each of the three zones contains three discrete depths, each down-line distance corresponded to a sample size of three data values per depth zone.

Horizontal Heterogeneity

An analysis of horizontal heterogeneity was made for each of the seven model-inverted resistivity profiles. Horizontal heterogeneity, an expression of variability with down-line distance, provides information on how the geophysical properties of the subsurface units change laterally along the profile. Horizontal heterogeneity was examined at depths of 0.94, 3.3, and 6.3 m (fig. 4). These depths were chosen to assess representative heterogeneity for shallow, moderate, and deep zones. For each depth, the horizontal collection of data values was summarized for 5-m data groups, or bins, incremented at 1-m intervals longitudinally along the profile. The *L*-CV statistic was computed for each bin, resulting in a measure of the local relative variability of the data values. This process is similar to a moving-window mean, except the *L*-CV statistic is computed instead of the mean. Although the number of data values in each bin varied because of non-uniform measurement intervals and data gaps (6 to 18), the *L*-CV statistic was applied to sample sizes averaging about 11 data values per bin.

Heterogeneity Adjustment

Each of the seven model-inverted resistivity profiles was statistically analyzed to simultaneously assess both the vertical and horizontal local heterogeneity of the subsurface materials. A 5-m by 5-m cell centered at each data point is established creating a collection of neighboring data values above, below,



EXPLANATION

Grouping of data points (moving window) used for horizontal coefficient of *L*-variation calculation

Indicates that the calculation is done as a moving window for each 5-meter group of horizontal data points

Model-inverted resistivity data point

Figure 4. Schematic representation of the horizontal heterogeneity analysis method.

and to the sides of the central point (fig. 5). The *L*-CV was computed for this subset of points as a relative measure of the local variability around the central data point. This procedure was repeated for the entire data set so that each data value has an associated dimensionless measure of local relative variability. Because of the spatially non-uniform interval of the measurements, the number of data points enclosed by the moving cell varied, but the count was not less than 21 for any *L*-CV computation. The median sample size was 65.

Because *L*-CV is a statistical measure of relative dispersion, it was assumed that *L*-CV is scaled proportionally to local lithologic heterogeneity. Consequently, homogeneous areas have smaller *L*-CV values than highly heterogeneous areas. Additionally, it was assumed that high heterogeneity results in either (1) proportionally higher effective hydraulic conductivity if the surrounding region is, on average, more hydraulically conductive (greater average electrical resistivity) than the central point, or (2) proportionally lower effective hydraulic conductivity if the surrounding region is, on average, less hydraulically conductive (less average electrical resistivity) than the central point. For example, a low-resistivity data point within a heterogeneous, high electrically resistive unit would have a proportionally higher effective hydraulic conductivity than the same low-resistivity data point in a comparatively homogeneous unit. Conversely, a high-resistivity data point within a heterogeneous, low electrically resistive unit would have a proportionally lower effective hydraulic conductivity than the same high-resistivity data point in a comparatively homogeneous unit.

Consequently, it is possible to use the *L*-CV values as a means to adjust the model-inverted resistivity values for the anticipated hydrological effects of lithologic heterogeneity. To accommodate both increases and decreases in hydraulic conductivity, the *L*-CV values are linearly transformed (rescaled and translated) to a percent-change scale. Linear transformation preserves the relational characteristics of a data set but changes the upper and lower bounds (Friedberg and others, 1997). For the lowest *L*-CV value in a data set (corresponding to the most homogenous area), the potential for changes of hydraulic conductivity because of heterogeneity is least. Thus, the lower bound of the transformed scale is set to 0, resulting in no change to the resistivity value. An

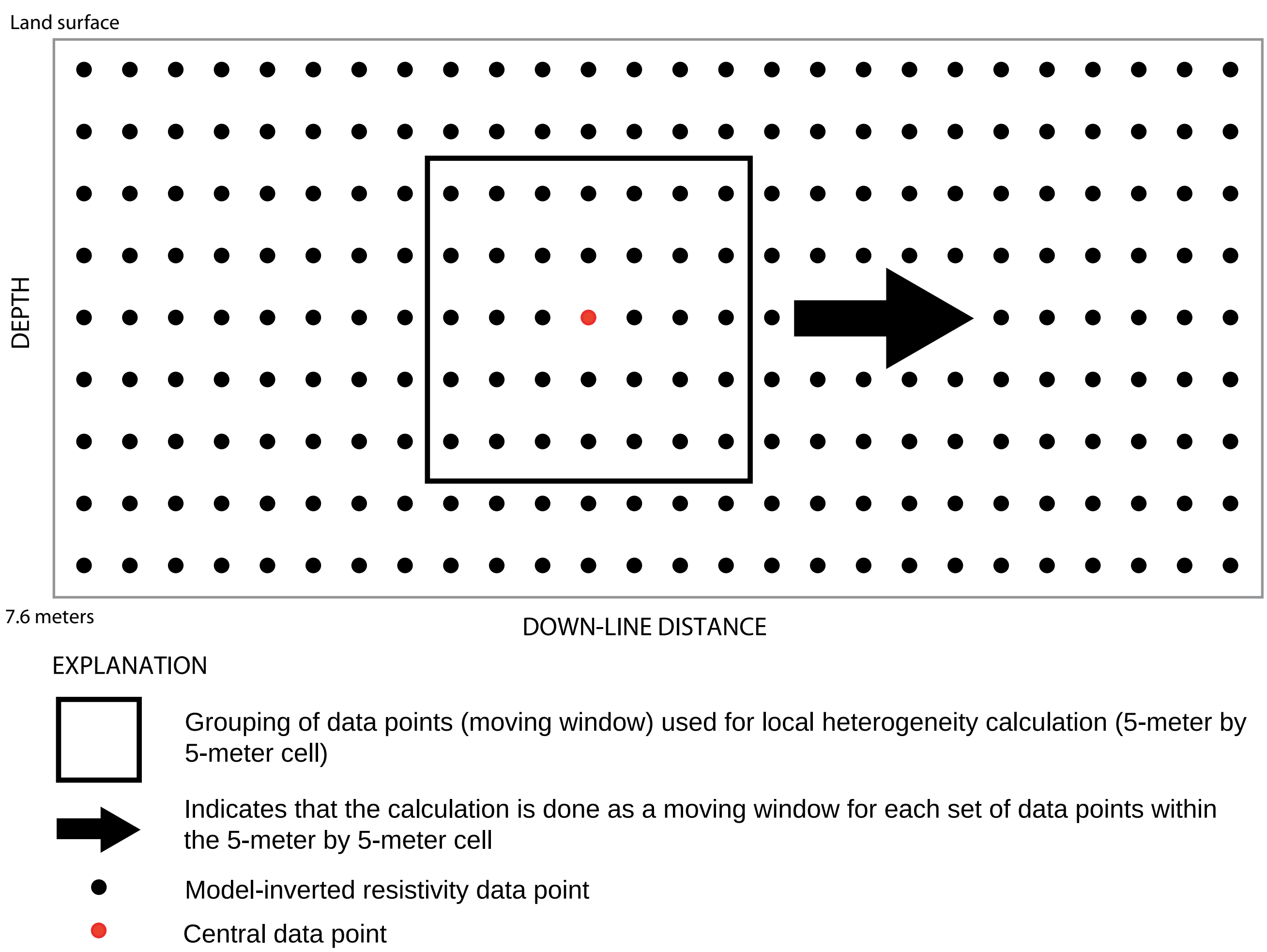


Figure 5. Schematic representation of the local heterogeneity analysis method.

upper bound of 0.5 was chosen by the authors in a site-specific manner, resulting in a maximum adjustment of 50 percent for the most heterogeneous region. Using these lower and upper bounds restricts the potential effect of heterogeneity adjustment. A percent-change increase was applied to central-point resistivity values where the surrounding locality was, on average, higher in resistivity than the central value; a percent-change decrease was applied to central-point resistivity values where the surrounding locality was, on average, lower in resistivity than the central value.

Finally, the minimum-adjusted method assigns the minimum of the heterogeneity adjusted model-inverted resistivity values from the percent-change scale at each down-line distance along the profile. As for the mean method and minimum-unadjusted methods, a final standardization is applied to obtain dimensionless estimates of leakage potential bounded by 0 and 1. This is achieved by dividing all the minimum-adjusted resistivity values by the greatest minimum-adjusted resistivity value computed among all profiles. Because all profiles are rescaled identically, direct comparisons of leakage estimates between profiles are possible.

Estimates of Leakage Potential for Selected Capacitively Coupled Resistivity Profiles

The inversely modeled CCR profiles of the seven study sites are shown in figures 6A through 12A. The figures are presented in order of test-hole names. The horizontal down-line distance axis is referenced to the direction of data collection; the corresponding compass directions are labeled at the top of the figures. The color-coded logarithmic resistivity scale used for sites TH12, TH16A, TH20A, TH22, TH22A, and TH25 (figs. 6A through 8A, 10A through 12A) is similar to the one used in Ball and others (2006). With this scale, low-resistivity features, represented as light to dark blue, are associated with well sorted, very fine sand and silt, such as the siltstone of the Brule Formation. Moderate-resistivity features, represented as green to yellow, are associated with moderately to well sorted, fine-to-medium sand with some occasional coarser sand. High-resistivity features, represented as orange to red, are associated with coarse sand and poorly sorted sediments containing gravel. Because the range of model-inverted resistivities of site TH21 exceeds this scale, a different logarithmic resistivity scale is used for site TH21 (fig. 9A) that spans the full resistivity range to show color variation. All subsurface materials for site TH21 are highly resistive coarse sand and poorly sorted sediments, regardless of color-coding.

The computed minimum, mean, and maximum *L*-CV values for the vertical heterogeneity analysis of the upper, middle, and lower zones at each site are listed in table 2. Results of the vertical heterogeneity analysis for each site are shown in figures 6B through 12B. A 5-m moving average was used to smooth the data prior to plotting. In each plot, the red, green, and blue curves show the vertical heterogeneity of the respective upper, middle, and lower zones with down-line distance. To facilitate comparison between profiles, the axes of the plots were adjusted to a common range.

The computed minimum, mean, and maximum *L*-CV values for the horizontal heterogeneity analysis at each site are listed in table 3. Results of the horizontal heterogeneity analysis for each site are shown in figures 6C through 12C. A 5-m moving average was used to smooth the data prior to plotting. In each plot, the red, green, and blue curves show the horizontal heterogeneity at depths of 0.94, 3.3, and 6.3 m, respectively. To facilitate comparison between profiles, the axes of the plots were adjusted to a common range.

The minimum, mean, and maximum absolute and percent changes in resistivities resulting from the local heterogeneity adjustment for each site are listed in table 4. Graphical comparisons of the mean, minimum-unadjusted, and minimum-adjusted estimates of leakage potential are shown in figures 6D through 12D. A 5-m moving average was used to smooth the data prior to plotting. To allow relative comparisons of the methods, scale standardization for these plots was achieved by dividing all values by the overall maximum value of the three methods.

TH12

INTERPRETATION — Site TH12 has two resistivity units with a moderately resistive unit overlying a less resistive unit (fig. 6A). The total depth for the moderately resistive unit ranges from 2.5 to 5.5 m with the shallowest and deepest areas at about 460 and 110 m down-line distance, respectively. This site was interpreted to have a low-lying confining unit below a unit of moderately permeable material.

ANALYSIS — The vertical heterogeneity analysis for site TH12 (fig. 6B) showed a consistently higher vertical heterogeneity in the middle zone than in either the upper or lower depth zones. In the resistivity profile (fig. 6A), the middle zone appears as transitional between the moderately resistive unit and the less resistive unit, thereby resulting in greater variability (as measured by *L*-CV). There is generally no horizontal heterogeneity at this site for the moderate and deep depths, but for the shallow depth there is minor horizontal heterogeneity at about 100 m down-line distance (fig. 6C).

At this site, the deeper impermeable unit would control the overall effective hydraulic conductivity of the shallow subsurface, and expected leakage potential would be low. Compared to the mean method, both minimum-based methods better account for this effect and accordingly estimate a lower leakage potential (fig. 6D).

TH16A

INTERPRETATION — Site TH16A has two resistivity units with a moderately to highly resistive unit overlying a less

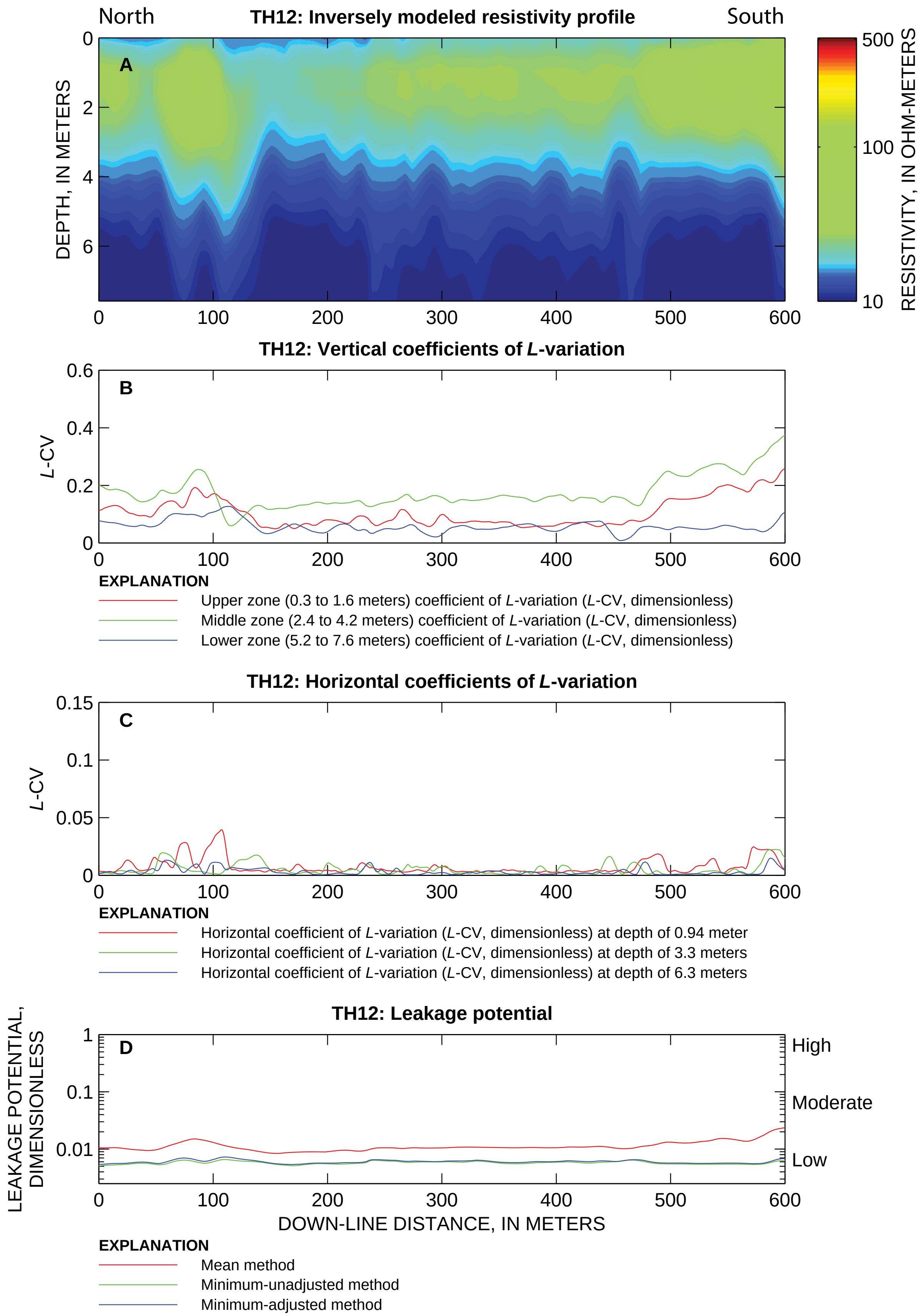


Figure 6. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH12, Interstate Canal, Nebraska.

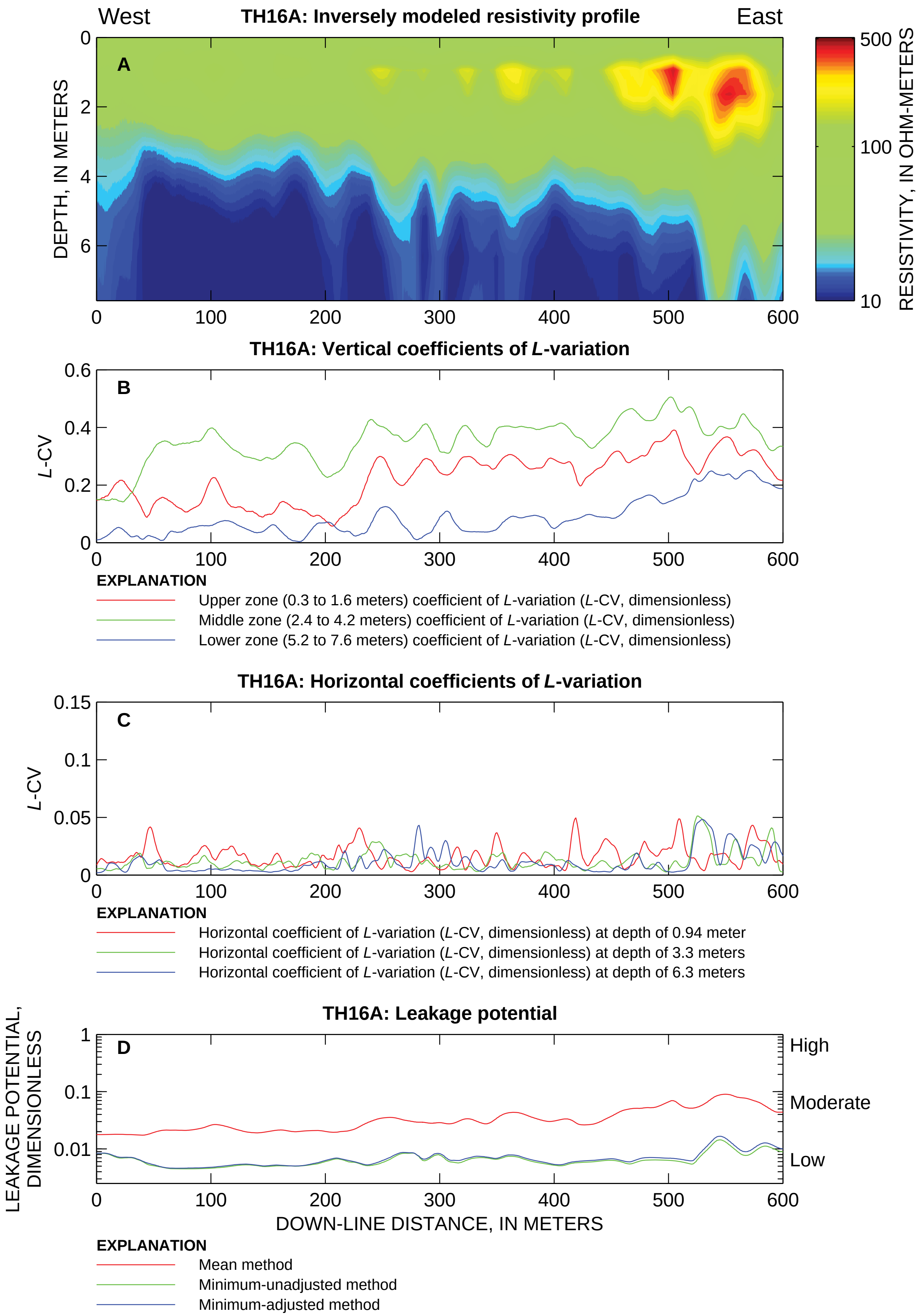


Figure 7. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH16A, Interstate Canal, Nebraska-Wyoming.

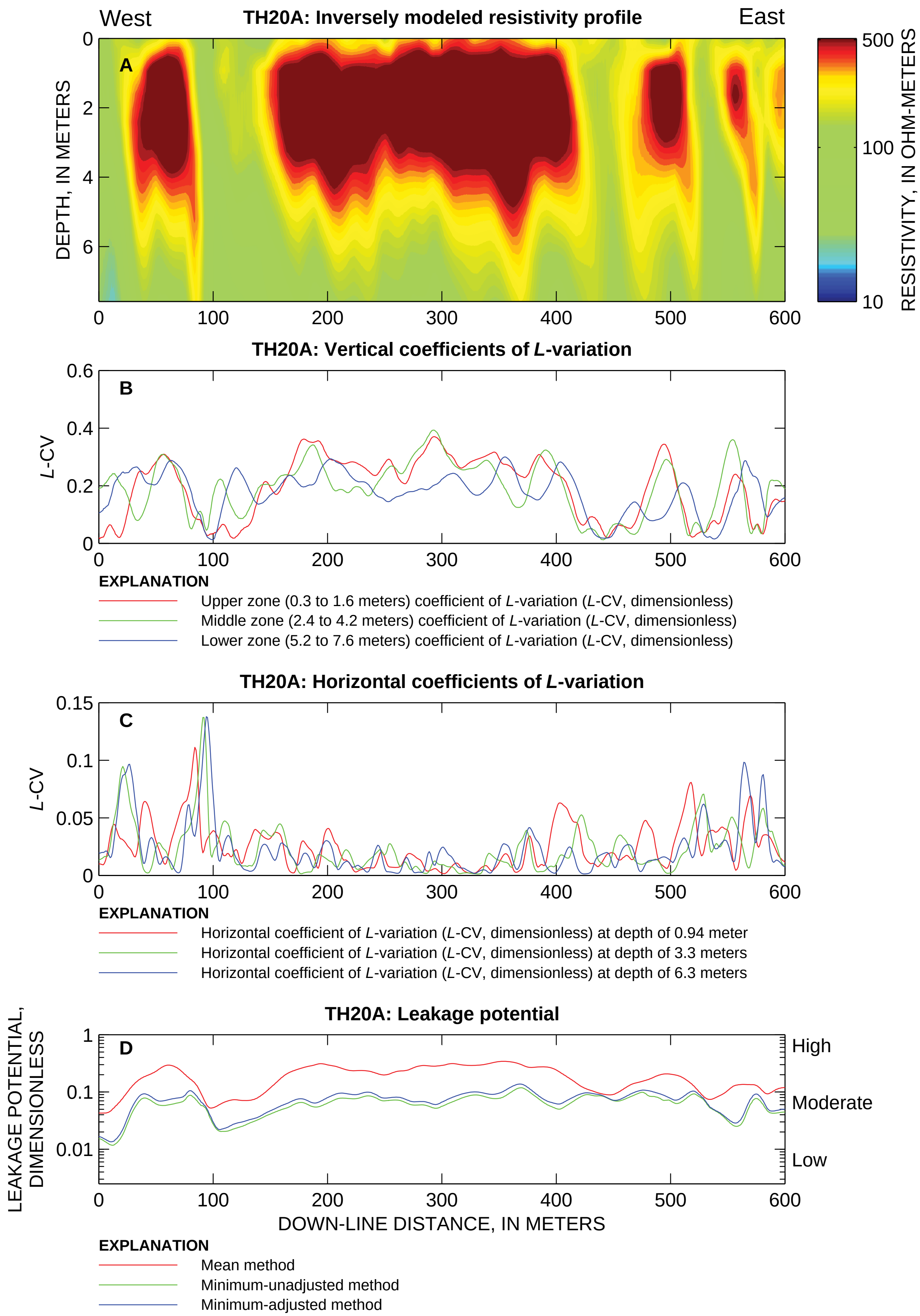


Figure 8. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH20A, Interstate Canal, Nebraska.

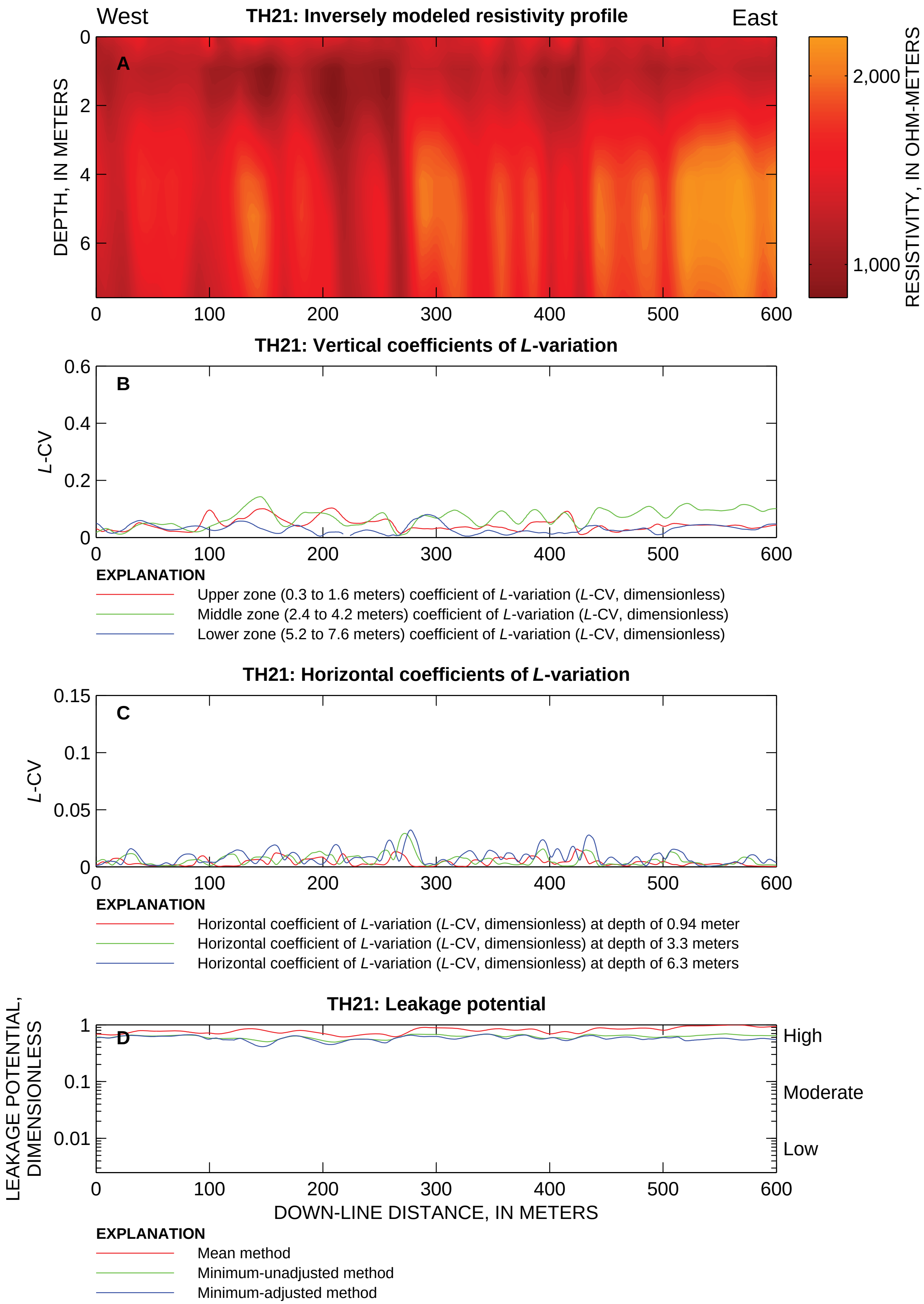


Figure 9. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH21, Tri-State Canal, Nebraska.

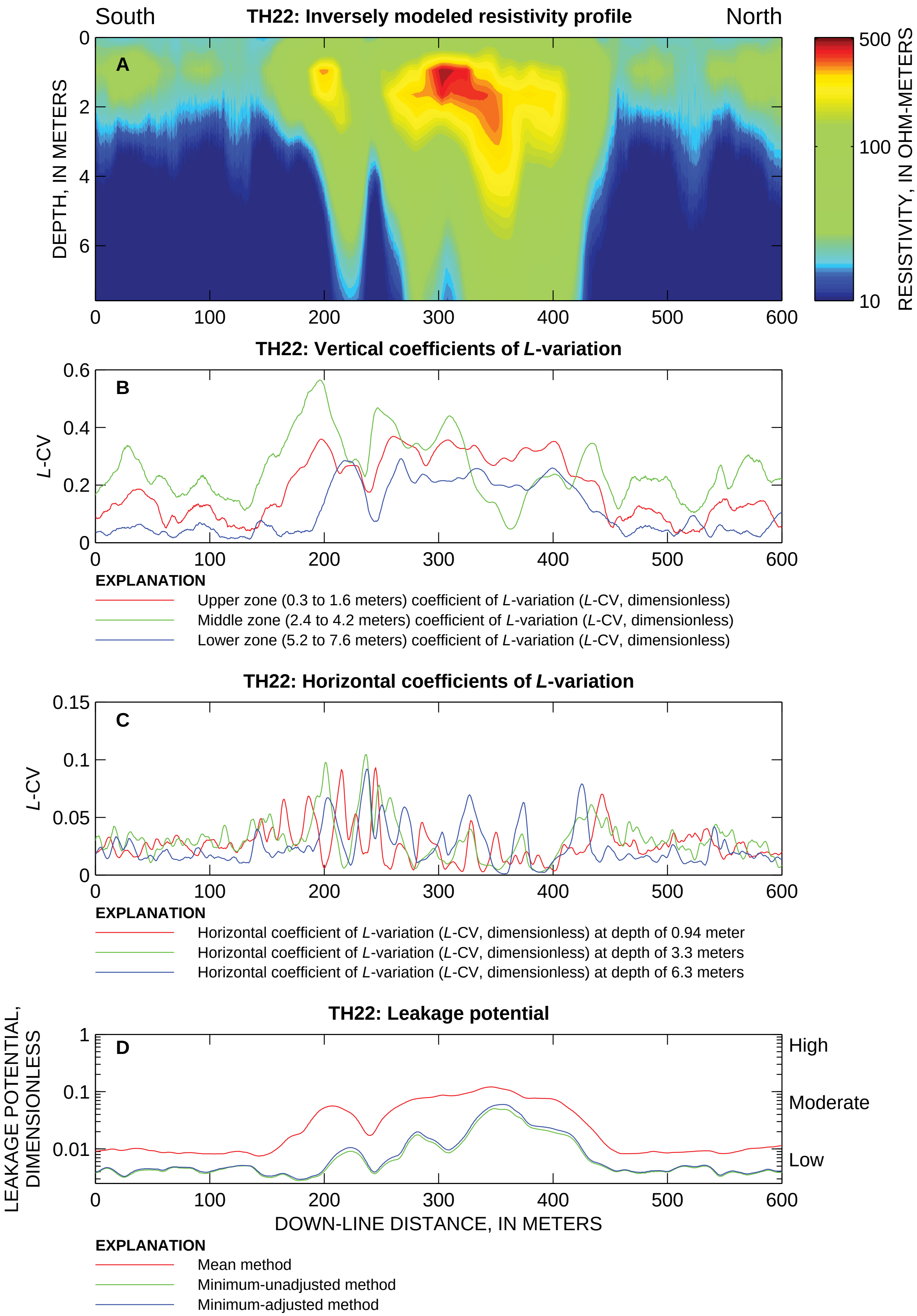


Figure 10. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH22, Interstate Canal, Nebraska.

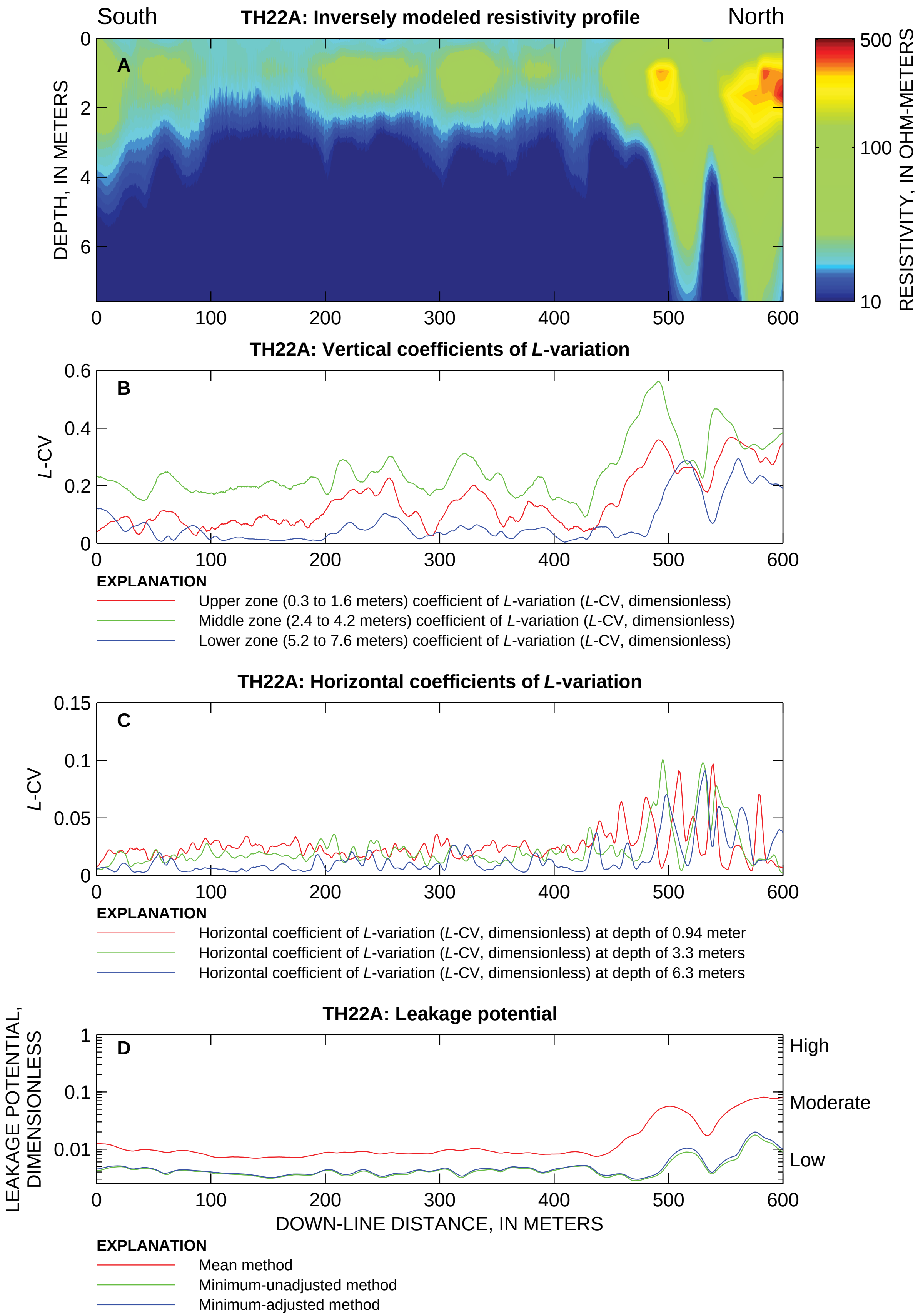


Figure 11. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH22A, Interstate Canal, Nebraska.

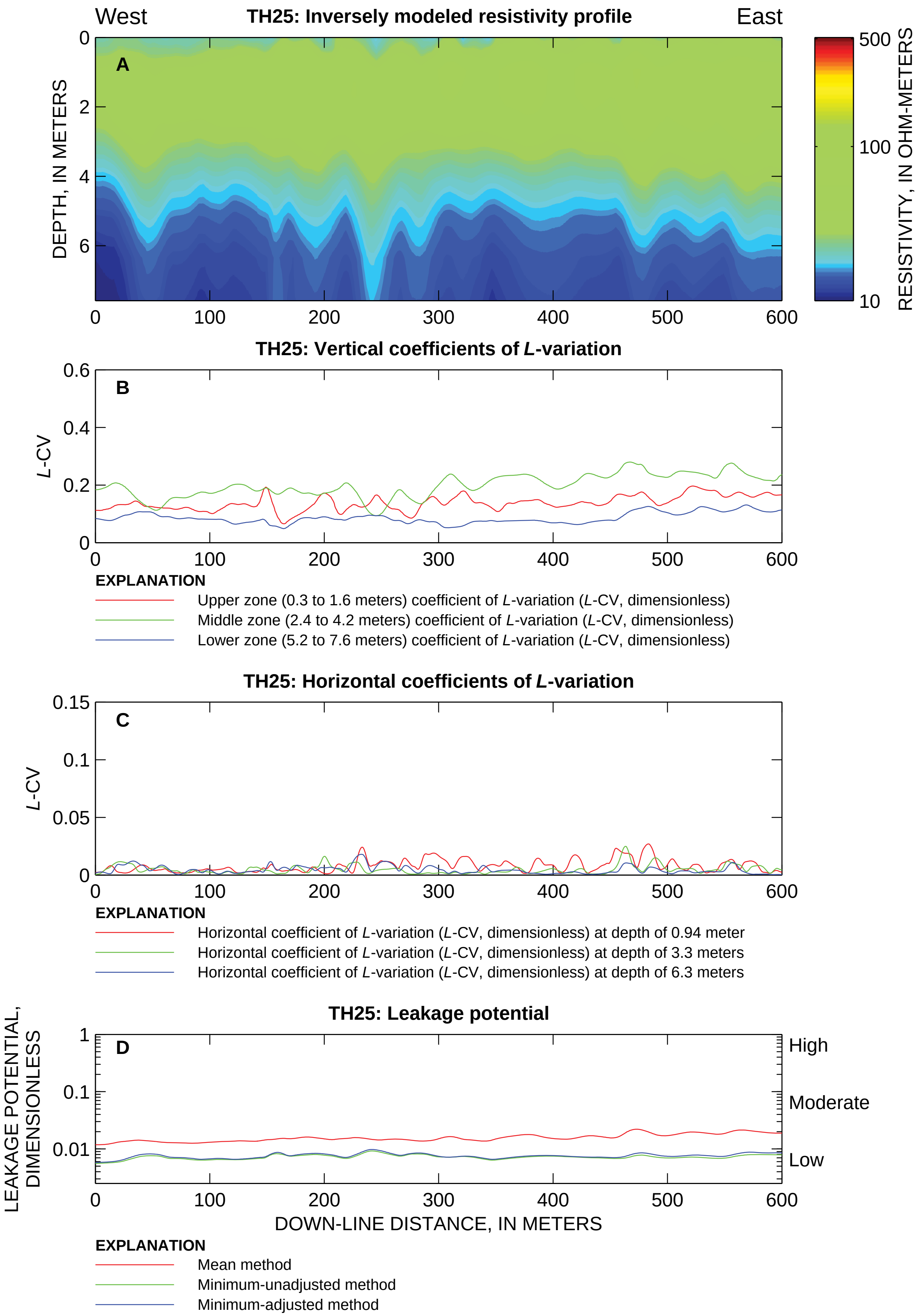


Figure 12. (A) Inverse-modeling results for capacitively coupled resistivity, (B) vertical heterogeneity analysis results, (C) horizontal heterogeneity analysis results, and (D) estimates of leakage potential for site TH25, Interstate Canal, Nebraska.

Table 2. Summary of vertical heterogeneity of upper, middle, and lower zones at selected sites, Interstate and Tri-State Canals, western Nebraska.

[*L*-CV, coefficient of *L*-variation; <, less than]

Site	Zone	Depth range (meters below land surface)	Minimum *L*-CV	Mean *L*-CV	Maximum *L*-CV
TH12	upper	0.3–1.6	0.046	0.10	0.26
	middle	2.4–4.2	.057	.17	.39
	lower	5.2–7.6	.007	.06	.13
TH16A	upper	.3–1.6	.050	.22	.40
	middle	2.4–4.2	.130	.36	.51
	lower	5.2–7.6	<.001	.09	.25
TH20A	upper	.3–1.6	<.001	.20	.38
	middle	2.4–4.2	.002	.19	.40
	lower	5.2–7.6	.004	.18	.31
TH21	upper	.3–1.6	.008	.05	.10
	middle	2.4–4.2	.002	.07	.14
	lower	5.2–7.6	.002	.03	.08
TH22	upper	.3–1.6	.001	.19	.37
	middle	2.4–4.2	.044	.25	.57
	lower	5.2–7.6	<.001	.11	.31
TH22A	upper	.3–1.6	.005	.14	.37
	middle	2.4–4.2	.071	.25	.57
	lower	5.2–7.6	<.001	.07	.31
TH25	upper	.3–1.6	.056	.14	.21
	middle	2.4–4.2	.092	.20	.28
	lower	5.2–7.6	.046	.09	.13

resistive unit (fig. 7A). The moderately to highly resistive unit increases in thickness and resistivity from west to east. This site was interpreted to have a moderately to highly permeable unit overlying a low-lying confining unit.

ANALYSIS — There is a positive trend in vertical variability (fig. 7B) for all zones across the profile. This is an indication that for each zone, the vertical heterogeneity consistently increased from west to east. In the resistivity profile (fig. 7A), the thickness of the moderately to highly resistive unit increases consistently from west to east. The vertical heterogeneity analysis also shows that there is greater vertical heterogeneity within the middle depth zone, which appears in the resistivity profile as transitional between the moderately to highly resistive unit and the less resistive unit. The horizontal heterogeneity at this site was generally low for all depths, but there was a small increase in *L*-CV at depths of 3.3 and 6.3 m from about 525 to 600 m down-line distance (fig. 7C).

Similar to site TH12, the overall effective hydraulic conductivity of the shallow subsurface would be controlled by the deeper impermeable unit. Even though the moderately to highly permeable unit thickens, the confining unit is still present at depth within the resistivity profile, thereby causing the overall leakage potential to be low in both minimum-based methods (fig. 7D). The mean method does not adequately take into account the confining unit located directly below the moderately to highly permeable unit. Consequently, the leakage potential estimated by the mean method was shown to increase from west to east whereas the minimum-based methods estimate leakage potential as relatively constant. There is a slight localized increase in leakage potential for both minimum-based methods near the eastern end of the profile where the moderately to highly permeable unit penetrates the confining unit.

TH20A

INTERPRETATION — Site TH20A has two resistivity units with an intermittent highly resistive unit overlying a

Table 3. Summary of horizontal heterogeneity at selected sites, Interstate and Tri-State Canals, western Nebraska.

[*L*-CV, coefficient of *L*-variation]

Site	Depth (meters below land surface)	Minimum *L*-CV	Mean *L*-CV	Maximum *L*-CV
TH12	0.94	0.0015	0.008	0.045
	3.30	.0004	.005	.024
	6.30	.0002	.003	.016
TH16A	0.94	.0021	.016	.052
	3.30	.0023	.012	.054
	6.30	.0017	.011	.051
TH20A	.94	.0012	.025	.120
	3.30	.0009	.023	.150
	6.30	.0011	.023	.160
TH21	.94	.0002	.004	.017
	3.30	.0002	.006	.032
	6.30	.0005	.009	.035
TH22	.94	.0019	.027	.110
	3.30	.0023	.031	.110
	6.30	.0009	.025	.110
TH22A	.94	.0030	.026	.110
	3.30	.0015	.023	.110
	6.30	.0013	.015	.097
TH25	.94	.0009	.008	.029
	3.30	.0004	.005	.027
	6.30	.0003	.005	.019

moderately resistive unit (fig. 8A). The highly resistive unit is separated by moderately resistive materials into four sections located at 35–95 m, 150–440 m, 460–530 m, and 550–600 m down-line distance. This site was interpreted as being composed of primarily moderately permeable materials with areas of highly permeable sediments near the surface.

ANALYSIS — Site TH20A exhibited relatively small vertical differences in heterogeneity between the three depth zones (fig. 8B). This suggests similar lithologic heterogeneity for all of the zones. There are also three areas of low vertical heterogeneity where the moderately resistive materials separate the sections of the highly resistive unit at about 100, 450, and 540 m down-line distance. Horizontal heterogeneity is least at 150–440 m down-line distance, where a homogenous area of high resistivity is seen (fig. 8C). Areas of moderate to high horizontal heterogeneity correspond to the discontinuity of the near-surface highly resistive layer (fig. 8A). Although no confining unit is apparent, the overall hydraulic conductivity will be controlled by the least permeable materials. Because the moderately permeable sediment underlies the highly permeable sediment, the leakage potential is expected to be moderate. Estimates from the mean method appear to be dominated by the highly resistive sections, causing the estimated overall leakage potential to be moderate to high (fig. 8D). Both minimum-based methods estimated the leakage potential to be moderate.

TH21

INTERPRETATION — Site TH21 has one highly resistive unit for the entire resistivity profile (fig. 9A). Because all resistivity values of the profile exceed the color scale maximum used for all other sites (500 ohm-m), a different color scale is used that spans the full resistivity range. Although the different color scale allows discernable color variation, the color-coding scheme used for this site cannot be used for comparison among other sites. This site was interpreted to be composed primarily of highly permeable sediments.

ANALYSIS — Site TH21 shows little vertical or horizontal heterogeneity (fig. 9B–C). Because subsurface materials

Table 4. Summary of changes in resistivity resulting from local heterogeneity adjustment for selected sites, Interstate and Tri-State Canals, western Nebraska.

[ohm-m, ohm-meters]

Site	Minimum change in resistivity, in ohm-m (percent change)	Mean change in resistivity, in ohm-m (percent change)	Maximum change in resistivity, in ohm-m (percent change)
TH12	-36 (-40.0)	0.29 (1.4)	20 (50.0)
TH16A	-200 (-41.0)	-2.70 (-4.2)	69 (50.0)
TH20A	-490 (-39.0)	-7.60 (-2.2)	240 (50.0)
TH21	-880 (-50.0)	-50.00 (-3.5)	550 (39.0)
TH22	-160 (-38.0)	-2.30 (-3.9)	73 (50.0)
TH22A	-130 (-38.0)	-.94 (-3.0)	60 (50.0)
TH25	-21 (-34.0)	.60 (2.1)	17 (50.0)

at this site are highly permeable, the overall hydraulic conductivity was expected to be high. The leakage potential estimated by all three methods was high (fig. 9D). Although the results of all three methods are similar, both minimum-based methods produced slightly lower estimates than the mean method. This was as expected because the minimum-based methods use the column-minimum resistivity value in the computations, whereas the mean method uses all available resistivity values. The minimum-adjusted method produced slightly lower estimates of leakage potential for some sections of the profile than did the minimum-unadjusted method. This indicates that local lithologic heterogeneity may produce decreased estimates of effective hydraulic conductivity in this situation.

TH22

INTERPRETATION — Site TH22 has two resistivity units with a moderately resistive unit overlying a less resistive unit (fig. 10A). Toward the center of the resistivity profile, there is a moderately to highly resistive feature extending from about 200 to 450 m down-line distance that interrupts the low-resistivity unit where it reaches the bottom of the profile. This site was interpreted to have a shallow alluvial channel incised into a confining unit.

ANALYSIS — Throughout most of the profile, the vertical heterogeneity (fig. 10B) of the middle depth zone was greater than that of the upper and lower zones, except between 335 and 420 m down-line distance, where the middle zone was less heterogeneous than both the upper and lower zones. This indicates that there is greater vertical heterogeneity within the middle zone at this section of the profile. This heterogeneity in the resistivity profile appears as the transition zone between the moderately to highly resistive unit and the less resistive unit (fig. 10A). There was also a general increase in vertical heterogeneity for all depth zones within the section corresponding to the moderately to highly resistive feature. The horizontal heterogeneity analysis (fig. 10C) indicated that higher heterogeneity characterized the margins of the more highly resistive features, but the rest of the profile was relatively homogeneous.

Because there is a moderately permeable unit overlying a confining unit, the overall hydraulic conductivity was expected to be low except where the alluvial channel is located. The alluvial channel fill is mainly composed of moderately permeable materials. Consequently, the leakage potential within this area was moderate. The mean method and the minimum-based methods each estimated that the profile had low leakage potential except where the alluvial channel is located (fig. 10D). Overall, both minimum-based methods estimated lower leakage potential than did the mean method. Neither minimum-based method estimated a moderate leakage potential until the moderately resistive unit penetrated the confining unit to the bottom of the profile.

TH22A

INTERPRETATION — Site TH22A has two resistivity units with a moderately resistive unit overlying a less resistive unit (fig. 11A). This site juxtaposes site TH22 and partially overlaps profile TH22. The same moderately to highly resistive unit that occurred at 180–300 m along profile TH22 also extends from about 490 to 600 m down-line distance in profile TH22A. This site was interpreted to have a moderately permeable unit overlying a confining unit except where the alluvial channel occurs at the northern end of the profile.

ANALYSIS — The vertical heterogeneity analysis (fig. 11B) indicated that the middle depth zone was consistently more heterogeneous than the upper and lower zones. The greater vertical heterogeneity of the middle zone compared with the upper and lower zones is caused by the transition between the moderately resistive unit to the less resistive unit. There was a general increase in vertical heterogeneity (fig. 11B) of all depth zones within the area corresponding to the moderately to highly resistive alluvial channel. The horizontal heterogeneity (fig. 11C) was relatively low throughout the profile except at the margins of the more highly resistive alluvial channel deposits.

Because most of the profile consists of a moderately permeable unit overlying a confining unit, the overall hydraulic conductivity was expected to be low. There is a small area (570–600 m down-line distance) of the profile where the moderately permeable feature penetrates the confining unit. The leakage potential was expected to be moderate at this location. Estimates from all three methods indicated the profile as having low leakage potential except where the alluvial channel is located (fig. 11D). Overall, both minimum-based methods estimated a lower leakage potential than did the mean method.

TH25

INTERPRETATION — Site TH25 has two resistivity units with a moderately resistive unit overlying a less resistive unit (fig. 12A). There was a slight increase in thickness of the moderately resistive unit from west to east. This site was interpreted to have a low-lying confining unit beneath a unit of moderately permeable material.

ANALYSIS — The vertical heterogeneity analysis for site TH25 (fig. 12B) indicated that the middle depth zone had greater vertical variability than either the upper or lower zone. In the resistivity profile (fig. 12A), the middle unit appears as transitional between the moderately resistive unit and the less resistive unit. The minor level of horizontal heterogeneity at this site (fig. 12C) is inconsequential.

The deeper, impermeable unit controls the overall effective hydraulic conductivity of the shallow subsurface and expected leakage potential is low. Compared to the mean method, both minimum-based methods account for this effect and accordingly provided a lower leakage potential estimate than did the mean method (fig. 12D).

Comparative Assessment of Methods

For all sites, the minimum-based methods resulted in lower leakage potential estimates than did the mean method. This was as expected because the minimum-based methods use the column-minimum resistivity values in the inversely modeled resistivity profile. For sites TH12, TH16A, TH22, TH22A, and TH25 (figs. 6, 7, 10, 11, and 12) the minimum-based methods were appropriate because of the well defined underlying confining units. For sites TH20A and TH21 (figs. 8 and 9), where there were no clearly defined confining units, either the minimum-based or the mean methods resulted in similar leakage potential estimates.

For most sites (TH12, TH16A, TH20A, TH22, TH22A, TH25; figs. 6, 7, 8, 10, 11, and 12), the minimum-adjusted method resulted in an overall estimate of greater leakage potential as compared to the minimum-unadjusted method. This indicates that local lithologic heterogeneity may produce greater effective hydraulic conductivity for these sites. The difference was estimated to be proportional to the relative variability (*L*-CV) of resistivity in the immediate surroundings.

For site TH21 (fig. 9), the minimum-adjusted method resulted in a lower overall estimate of leakage potential as compared to the minimum-unadjusted method. This indicates that local lithologic heterogeneity may produce slightly lower estimates of effective hydraulic conductivity for this site. The difference again was estimated as proportional to the relative variability (*L*-CV) of resistivity in the immediate surroundings.

The mean percent difference between the leakage potential estimates computed by the minimum-unadjusted and minimum-adjusted methods for each site is listed in table 5. For these study sites, the minimum-adjusted method has a relatively small effect (4.4–14.2 mean percent difference) on leakage potential estimation when compared to the unadjusted method. The only difference between the methods is the application of an adjustment factor for local-scale spatial heterogeneity in modeled resistivity. As shown in the resistivity profiles (figs. 6A–12A), the minimum resistivities most often occurred in large areas of low heterogeneity (basal confining units). The low heterogeneity of the low-resistivity areas contributed to the overall heterogeneity adjustment of the minimum-adjusted method having a relatively small effect.

Although the minimum-adjusted method has the advantage of incorporating the effects of local lithologic heterogeneity into leakage potential estimation, the method has several inherent limitations. First, an upper bound for the adjustment procedure (the maximum percent change proportionally applied to modeled resistivity based on local heterogeneity) needs to be specified. For the sites presented in this report, a maximum percent change of 50 percent was chosen as a conservative upper bound based on a sensitivity analysis using a broad range of upper bounds. In addition, the quantification of lithologic heterogeneity is limited by the spatial resolution of the modeled resistivity data. Small-scale lithologic detail generally is not resolved by a coarsely gridded (large block size) inversion model. Statistical computation can only characterize variability at the spatial scale of the model, and potential effects of lithologic heterogeneity at smaller scales cannot be included in leakage potential estimates. Potentially indiscernable small-scale features include lithologic fracturing, which (if present) could have a dramatic effect on water transmission. Finally, the spatial scale of local lithologic heterogeneity effects needs to be defined for the inversely modeled data. In this report, the authors chose a spatial local scale of 5 m in consideration of the inverse-model block size. The scale of locality must be large enough in relation to model block size so that statistical computations use sample sizes large enough to yield meaningful results.

Table 5. Summary by site of mean percent difference between leakage potential estimates computed by the minimum-unadjusted and minimum-adjusted methods.

Site	Mean percent difference between minimum-unadjusted and minimum-adjusted method	Site	Mean percent difference between minimum-unadjusted and minimum-adjusted method
TH12	4.4	TH22	7.4
TH16A	6.0	TH22A	5.5
TH20A	14.2	TH25	4.8
TH21	6.5		

Summary

With limited supplies but increasing demands for water availability, groundwater flow models often are developed as a means of understanding surface-water and groundwater systems to aid water-management decisions. To accurately simulate current or future conditions, specific hydraulic variables must be quantified. Lack of existing data within the model area can increase uncertainties in estimating hydrogeologic properties, resulting in inadequate conceptualization of the simulated flow system and potential problems with simulation calibration. Drilling additional test holes can be time-consuming and expensive and only provides information at spatially discrete points. Surface geophysical surveys, along with test-hole information, can provide an integrated framework for determining the hydrogeologic conditions within a defined area.

In 2004, the U.S. Geological Survey, in cooperation with the North Platte Natural Resources District, performed a surface geophysical survey using a continuous resistivity profiling technique to map the near-surface lithology of the Interstate and Tri-State Canals in western Nebraska and eastern Wyoming to provide information needed for a groundwater-flow model and to improve the general understanding of groundwater recharge. Using a capacitively coupled resistivity (CCR) technique, the upper 8 m along 110 km of these canals were mapped. The resulting CCR profiles were evaluated using the mean method to classify areas of low, moderate, and high leakage potential. The mean method used the simple vertical mean of inverse-model resistivity values for depth levels with geometrically increasing layer thickness with depth to estimate overall leakage potential. This method assumes that leakage is affected primarily by the sediment directly underlying the canal bed and that geologic effect on leakage progressively diminishes with depth.

The mean method produced reliable results generally, but an improved analysis method was needed to account for situations where confining units, composed of less permeable material, underlie units with greater permeability. The present (2009) report, prepared by the U.S. Geological Survey in cooperation with the North Platte Natural Resources District, develops the minimum-unadjusted method, which computes a relative leakage potential using geostatistical analysis based on the minimum resistivity value in a vertical column of the resistivity model. The minimum-unadjusted method considers effects of homogeneous confining units in the estimation of overall leakage potential because the least permeable materials are allowed to control the overall effective hydraulic conductivity of the shallow subsurface. The minimum-adjusted method incorporates the effects of local lithologic heterogeneity in estimating overall leakage potential. The minimum-adjusted method adjusts the modeled resistivity values in proportion to their local variability (coefficient of *L*-variation [*L*-CV]) and then computes a relative leakage potential based on the column-minimum-adjusted resistivity value. Selected CCR profiles from Ball and others (2006) were reevaluated, wherein the mean, minimum-unadjusted, and minimum-adjusted methods were applied to compare each method in context of differing geologic situations. Since 2006, a new (2009) filtering method for processing CCR profiles was developed. Accordingly, the originally collected data were reprocessed to ensure data quality.

Seven CCR profiles were selected using test-hole information and CCR results to represent a variety of geologic contexts. For each selected site (identified by the associated test-hole name), a 600-m CCR profile centered at the test-hole location was reanalyzed. Six sites are located on the Interstate Canal: TH12, TH16A, TH20A, TH22, TH22A, and TH25. The seventh site, TH21, is located on the Tri-State Canal.

Low-resistivity features are associated with well sorted, very fine sand and silt, such as the siltstone of the Tertiary-age Brule Formation. Moderately resistive features are associated with moderately to well sorted fine-to-medium sand with occasional coarser sand. Highly resistive features are associated with coarse sand and poorly sorted sediments containing gravel.

Sites TH12, TH16A, and TH25 are typical examples of geologic situations containing a confining unit. At these sites, shallow pockets of moderately to highly resistive (permeable) material overlie comparatively less resistive (impermeable) material. The deeper, impermeable layer predominantly affects the overall hydraulic conductivity of the shallow subsurface, and the expected leakage potential is low. Compared to the mean method, both minimum-based methods account for this effect and accordingly produced a lower estimate of leakage potential for these sites.

There is no confining unit apparent in the CCR profile for site TH20A, yet the overall hydraulic conductivity will be controlled by the least permeable materials. Because highly permeable sediment overlies moderately permeable sediment, the leakage potential is expected to be moderate. Estimates from the mean method appear to be dominated by the highly resistive areas, causing the estimated overall leakage potential to be moderate to high. Both minimum-based methods estimated the leakage potential to be moderate.

The hydraulic conductivity was expected to be high for site TH21 because the CCR profile indicated a single highly resistive unit. All three methods estimated high leakage potential at this site, with both minimum-based methods producing slightly lower estimates than the mean method. This was as expected because both minimum-based methods use the column-minimum resistivity value in their computations. The minimum-adjusted method estimated an overall lower leakage potential for some areas of the profile than did the minimum-unadjusted method. This indicates that local lithologic heterogeneity may produce slightly lower effective hydraulic conductivity.

Sites TH22 and TH22A each had a moderately permeable unit overlying a confining unit into which an alluvial channel had incised. Consequently, the overall hydraulic conductivity was expected to be low except where the alluvial channel is located. Because the alluvial channel is primarily filled with moderately permeable materials, the leakage potential within this area was moderate. The mean method and the minimum-based methods each estimated that the profile had low leakage potential except where the alluvial channel is located. Overall, both minimum-based methods estimated lower leakage potential than did the mean method. Neither minimum-based method estimated moderate leakage potential except where the moderately resistive unit penetrated the confining unit to the bottom of the profile.

For most sites (TH12, TH16A, TH20A, TH22, TH22A, TH25), the minimum-adjusted method resulted in an overall estimate of greater leakage potential as compared to the minimum-unadjusted method. This indicates that local lithologic heterogeneity may produce higher effective hydraulic conductivity for these sites. The difference was estimated to be proportional to the relative variability of resistivity in the immediate surroundings. For site TH21, the minimum-adjusted method resulted in a lower overall estimate of leakage potential as compared to the minimum-unadjusted method. This indicates that local lithologic heterogeneity may produce slightly lower effective hydraulic conductivity for this site. The difference again was estimated to be proportional to the relative variability of resistivity in the immediate surroundings.

In contrast to the mean method, both minimum-based methods allowed the least permeable areas to control the overall vertical permeability of the subsurface. The minimum-adjusted method refines this advantage by including effects of local lithologic heterogeneity on hydraulic conductivity. However, the minimum-adjusted method is also inherently limited by several factors including: (1) an upper bound for the adjustment procedure needs to be specified, (2) the quantification of lithologic heterogeneity is limited by the spatial resolution of modeled resistivity data, and (3) the spatial scale of lithologic heterogeneity effects needs to be defined for the inversely modeled data so statistical computations yield meaningful results.

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