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Water Content Effect on Soil Salinity Prediction: A Geostatistical Study Using Cokriging

Peter J. Vaughan,* Scott M. Lesch, Dennis L. Corwin, and David G. Cone

ABSTRACT

A geostatistical analysis of soil salinity in an agricultural area in the San Joaquin Valley included measurements of electrical conductivity of soil paste extract (EC_e) and water content of soil samples supplemented by surface measurements of apparent electrical conductivity (EM_H). Prediction of soil salinity at unsampled points by cokriging $\log_e(EC_e)$ and EM_H is worthwhile because EM_H measurements are quicker than soil sampling. This work studies how patterns of $\log_e(EC_e)$ predicted by cokriging with EM_H are influenced by variation in gravimetric water content (W). The data are mean EM_H = 1.00 ± 0.13 dS m^{-1} for 2378 locations, mean $\log_e(EC_e)$ = 1.40 ± 0.29 dS m^{-1}, and mean gravimetric W = 0.260 ± 0.003, both averaged for four samples from 0.3-m intervals to 1.2-m depth for 315 locations. The coefficient of determination (R^2) for EM_H vs. $\log_e(EC_e)$ increased with depth from 0.05 to 0.54 whereas the R^2 for EM_H vs. W decreased from 0.48 to 0.28. A gray-scale EM_H map contained nine out of 56 quarter-section boundaries coinciding with step variations in EM_H. The t-statistics for differences in mean W were six of nine significant at 0.001 and nine of nine at 0.05, but mean $\log_e(EC_e)$ had only two of nine at 0.05, implying that W caused EM_H steps. Water-affected EM_H impaired prediction of EC. at depth by cokriging, because near-surface variations in Wmasked EC,. Two subareas were defined, one where management factors, such as irrigation, controlled EM_H, causing steps, and one where near-surface W varied less, making cokriging predictions more reliable.

ASSESSMENT OF SOIL SALINIZATION in irrigated agriculture is important for evaluation of the long term sustainability of agricultural production. Several measurement techniques requiring varying amounts of effort have been developed in support of salinization assessment. Soil sampling and subsequent analysis of samples is time consuming but provides the most accurate and reliable data for estimation of EC, (Rhoades et al., 1989a). The four-electrode Wenner array method provides on-site estimation of electrical conductivity by injecting current directly into the ground and measuring the voltage between two passive electrodes. Direct current methods such as the Wenner array rely on effective electrical contact between the electrodes and the soil. In dry soils, an effective electrical contact can be difficult to establish and an alternative technique utilizing a nonintrusive EM method may be preferable (Rhoades and Corwin, 1981). Both the Wenner array and the EM methods result in an estimation of apparent electrical conductivity at the surface that is likely to be a complicated average of variable electrical conductivity in the subsurface. Given the high degree of nonuniqueness in the problem of inverting the results of a set of surface measurements to obtain a subsurface electrical conductivity distribution, the obvious choice is a simplified model involving a small number of horizontal layers of infinite extent. Under the assumption of a horizontally layered electrical conductivity structure, Rhoades and Corwin (1981) used regression analysis to calibrate EM measurements with independent measurements of electrical conductivity as a function of depth. An independent measurement might be EC, of a soil sample or an in situ measurement of EC, using a salinity probe (Rhoades and van Schilfgaarde, 1976). Rhoades and Corwin (1981) obtained empirical equations relating EC, at various depths to a linear combination of EM measurements of different types taken at a single site, an approach that was later improved on (Corwin and Rhoades, 1982, 1983). Further refinement in the prediction of EC, from EM measurements was accomplished by a more rigorous statistical analysis (Rhoades et al., 1989b).

Calibration of EM measurements for prediction of EC, by regression techniques have considered soil texture, water content, and soil temperature as influential variables (McKenzie et al., 1989; Slavich and Petterson, 1990). A strong correlation between soil water content and EM measurements was obtained for a wide range of soil textures in a field area in southern Ontario (Kachanoski et al., 1988). But an assessment of soil salinity in Pakistan, utilizing EM measurements and a calibration provided by Rhoades et al. (1990), concluded that water content was not necessarily a critical factor (Hendrickx et al., 1992).

Spatial variation of soil salinity was mapped by measuring EC, for samples taken at a relatively small number of sites; then, by regression analysis, $\log(EC_e)$ was predicted on a much denser array of EM measurement sites (Lesch et al., 1992b). The mapped prediction of soil salinity from regression equations contained some discrepancies when compared with a map exclusively drawn from a dense array of EC, measurements. Spatial autocorrelation of the residuals would suggest use of geostatistical techniques. When residuals from multiple linear regression models are spatially uncorrelated, however, multiple linear regression techniques can be implemented more efficiently than cokriging to accomplish the same objective (Lesch et al., 1995b). The observed lack of spatial autocorrelation of the residuals implied that the errors were not due to variability in soil physical properties (Lesch et al., 1992b).

Electrical conduction in soil is caused by ionic conduction in soil water coupled with conduction through the soil solids. The conductivity will be sensitive to variations in the salinity of the soil water as measured by EC, and

P.J. Vaughan, S.M. Lesch, and D.L. Corwin, USDA-ARS, U.S. Salinity Lab., 4500 Glenwood Dr., Riverside, CA 92501; and D.G.Cone, Broadview Water District, P.O. Box 95, Firebaugh, CA 93622. Contribution from the USDA-ARS, U.S. Salinity Lab. Received 23 May 1994. *Corresponding author (vpeter@ucrac1.ucr.edu).

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Abbreviations: EC,, electrical conductivity of soil paste extract; EC,, soil electrical conductivity; EM, electromagnetic induction; W, gravimetric water content; BWD, Broadview Water District; GPS, global positioning system.

W. We examined these two contributions to apparent electrical conductivity measured at the ground surface in a field area of 2350 ha containing four soil texture map units. Also, considering the laboratory data obtained for both variables along with soil maps and information regarding management practices such as irrigation scheduling and cropping, a rationalization of the pattern of apparent electrical conductivity as measured by the EM-38 instrument (Geonics Inc., Mississauga, ON) is presented [1].

In this study, data were analyzed either as a single, complete set covering the entire area or by subdividing the data by quarter section. No attempt was made to subdivide the data by soil unit because the main intent of this study was a discussion of the relative correlation of measured *W* and $\log(EC_e)$ with EM measurements.

MATERIALS AND METHODS

A comprehensive field study of soil salinity was conducted within the BWD in the San Joaquin Valley of California in May and June 1991. The field area studied consisted of 37 quarter sections (65-ha squares). A quarter section is the normal management unit for agriculture in the BWD. Generally, a single crop is grown within a quarter section, but occasionally a quarter section is split, with different crops growing in different parts. Each part, in this case, would be considered a management unit. Quarter sections are bounded by dirt roads or drainage ditches. The term section refers to a surveyed square consisting of four quarter sections. Sections in the field area are numbered according to section numbers appearing on two U.S. Geological Survey, 7.5min quadrangle maps called Broadview Farms and Firebaugh. Two basic soil types occur in this field area (Fig. la), the Lillis series (very fine, montmorillonitic, thermic Entic Chromoxererts) and the Cerini series (fine-loamy, mixed (calcareous), thermic Typic Torrifluvents). These units were mapped and described by the Soil Conservation Service during the period 1990 to 1992 when the remapping of soils in the BWD and surrounding areas occurred.

Various crops are grown in the BWD and cropping of individual quarter sections may change from season to season. In September 1991, the land-use distribution for crops was: 54% cotton (Gossypium *hirsutum* L.), 27 % fallow, 8 % tomato *[Lycopersicon Zycopersicum* (L.) Karsten], 6% seed alfalfa *(Medicago sativa* L.), 4% melon *(Cucumis melo* L.), and 1% oat *(Avena sativa* L.) hay. These five crops grew during the summer growing season, which may start as early as March and runs through September. In most years, winter wheat *(Triticum aestivum* L.) is also grown in a few quarter sections. The summer crops were already growing in the cropped quarter sections when the measurements discussed here were made.

During the summer growing season of 1991, irrigated quarter sections received, on average, 0.35 m (depth) of irrigation water. Amounts of irrigation water varied from 0.04 to 0.55 m. Nine quarter sections were not irrigated. Complete tile drainage systems were installed in at least 26 of the 37 quarter sections. Due to lack of documentation, there is uncertainty regarding the existence and extent of tile drainage in some of the other quarter sections. The density of tile drainage varies from 12 to 134 m ha^{-1}. All tile drainage systems in the BWD are operated by sump pumps.

[1]The use of brand names in this report is for identification purposes only and does not constitute endorsement by the USDA.

The data given above on crops, irrigation, and tile drainage are elements of a body of data collectively referred to here as *management factors*. Other management factors include tillage and soil treatments such as mulching. Management factors are approximately constant within a management unit.

Sampling and Chemical Analyses

Eight locations in each quarter section were designated as sites for taking soil samples. The EM-38 instrument was operated in both horizontal dipole (EM_H) and vertical dipole (EM_V) modes at heights of 0.1 and 0.5 m above the ground surface for a total of four readings per site (Lesch et al., 1992a). For each quarter section, EM readings were taken at the eight soil sampling sites in addition to 56 other sites located roughly on a 100 by 100 m grid (Lesch et al., 1992a). The instrument was operated in the low induction number range for which the voltage in the receiver coil is out of phase and is directly proportional to the apparent electrical conductivity (Keller and Frischknecht, 1966). Under these conditions, the electrical conductivity of a hypothetical infinite half space (apparent conductivity) was digitally recorded directly from the instrument for each of the four readings.

Locations of the EM measurement sites were determined by GPS equipment. As much as possible, the readings were differentially corrected using readings obtained from an additional GPS receiver at a fixed location with known geographic coordinates. Differential correction requires data from four satellites in the GPS system but sometimes fewer than four satellites were visible and operating. In such cases, differential correction was not possible. However, the scatter in the location data was substantially reduced because the fields were furrowed and movement of measuring equipment through the fields occurred along straight lines constrained by the furrows. Measurement locations were repositioned based on simple averaging of the coordinate direction lying perpendicular to the beds.

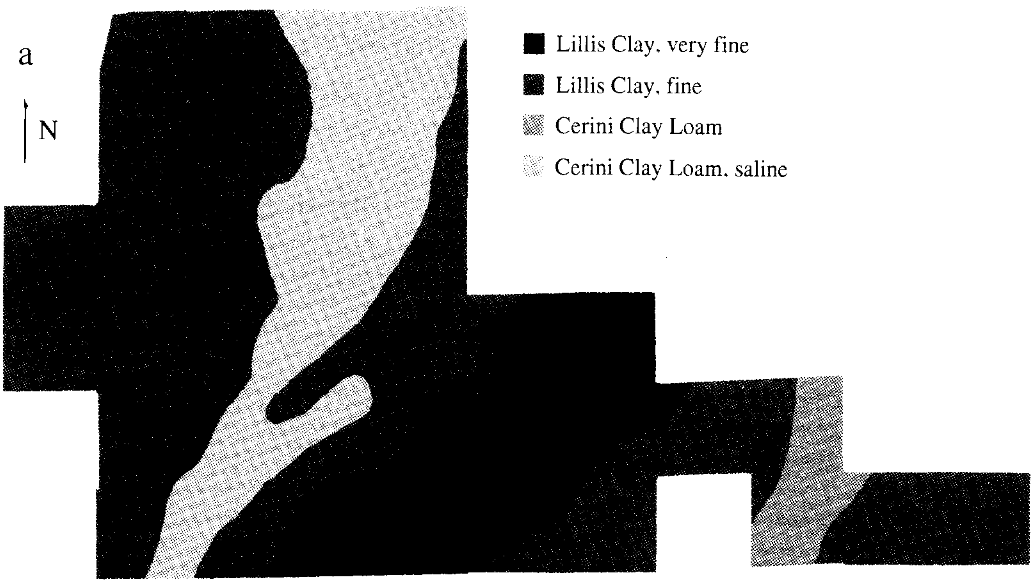
Soil samples were taken in furrows at 0.3-m depth intervals to a maximum depth of 1.2 m with an auger. Each sample, of length 0.3 m, was mixed prior to any measurements. Measurements made on each mixed sample include: (i) EC, of the soil paste extract; (ii) W; and (iii) determination of the saturation percentage (water content of the saturated soil paste). Gravimetric water content was calculated from the mass lost after drying at 105°C for 24 h divided by the dry mass. The depths of samples are given as the midpoint of the depth range for that sample. For example, the soil sample from the top 0.3-m depth range is considered to represent the 0.15-m depth.

Geostatistical Analysis

A geostatistical analysis of the data was performed to attempt to determine soil salinity, as measured by $\log(EC_e)$, at unsampled points by kriging and cokriging. Semivariograms were calculated for $\log(EC_e)$, the apparent electrical conductivity (EM), and W. The semivariance *y(h),* representing spatial autocorrelation of a variable, u, is a function of the spacing, *h,* between pairs of points:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{ij} = h}^{N(h)} (u_i - u_j)^2 \qquad [1]$$

where the sum runs across all pairs *(i,j)* that lie within a specified tolerance of a central value, *h* (Isaaks and Srivastava, 1989). Cross-correlation between variables was calculated using the cross-variogram, γ_{uv}:



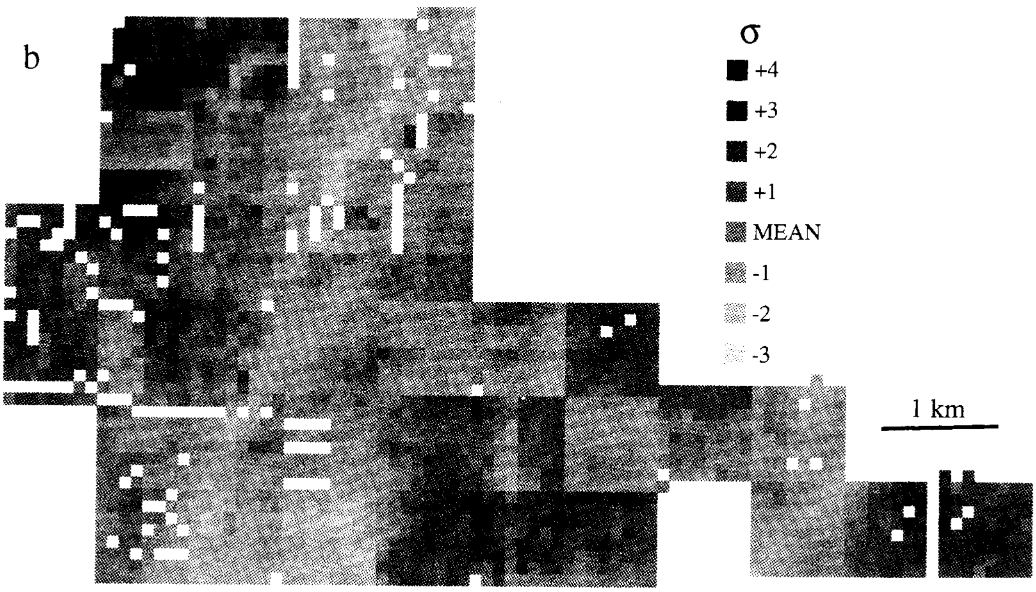


Fig. 1. (a) Soil map of the study area in the Broadview Water District digitized from a preliminary map provided by the Soil Conservation Service. (b) Gray-scale map of apparent electrical conductivity (EM_H) normalized to zero mean and unit variance. Measurements were made on a roughly 100 by 100 m grid. Squares in the grid are shaded based on measured values at enclosed points. Some squares, shown in white, enclosed no point.

$$\gamma_{uv}(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{ij}=h}^{N(h)} (u_i - u_j)(v_i - v_j) \qquad [2]$$

where u and v represent correlated variables. For cross-variograms and semivariograms used for cokriging, the data were normalized to zero mean and unit variance prior to the calculation of y(h). Data were not normalized prior to computation of the semivariogram used for ordinary kriging.

Estimation of the measured variables at unsampled points on a square 100 by 100 m grid was accomplished by ordinary block kriging (Joumel and Huijbregts, 1978). The estimation facilitated representation of the variables in map form by providing a higher resolution coverage. For variables that are cross-correlated an alternative technique is cokriging, where measurements of both variables together form the basis for estimation of one of the variables (Deutsch and Joumel, 1992; Isaaks and Srivastava, 1989; Yates and Warrick, 1987; Vauclin et al., 1983; Joumel and Huijbregts, 1978). The equations defining the cokriging algorithm can be found in any of these references.

Cokriging provides an estimate of a primary random function based on a combined set of samples of the primary function and one or more auxiliary, cross-correlated random function. Cokriging is most useful in situations where one function is sampled more intensively than the other (Yates and Warrick, 1987). In this case, the less-sampled function can be estimated at a point density equivalent to that of the more intensively sampled function. Cokriging requires the computation of semi-variograms and cross-variograms for a pair of variables to prepare models of spatial autocorrelation and cross-correlation structure. Parameters for the semivariogram model may need to be adjusted to maintain a reasonable fit and simultaneously provide a linear model of coregionalization, $|\gamma_{ij}(h)| \leq \sqrt{[\gamma_{ii}(h)\gamma_{jj}(h)]}$ where i and j refer to the primary and auxiliary functions (Isaaks and Srivastava, 1989; Yates and Warrick, 1987). The type of colcriging discussed here, standardized ordinary cokriging, was accomplished utilizing the single non-bias condition that the sum of the weights for both data sets combined was unity (Deutsch and Journel, 1992). Cokriging may be done with multiple auxiliary variables, but the modeling of all required semivariograms and cross-variograms renders such an approach too tedious for most practical considerations (Lesch et al., 1995a).

RESULTS AND DISCUSSION

Figure lb is a map of the field area showing normalized variance of the apparent electrical conductivity measured with the EM-38 in the horizontal dipole mode and located 0.1 m above the ground surface **(EM_H)**. The values of **EM_H** and **EM_V** are highly correlated both in the present data set ($R^2 > 0.93$) and in a study of a quarter section in the adjacent Westlands Water District near Coalinga, CA (Lesch et al., 1995b). Theoretical predictions indicate that **EM_V** samples a lower depth range than **EM_H**. The value of **EM_H** was consistently lower than **EM_V** (average $EM_H/EM_V = 0.62 \pm 0.01$ dS m^{-1}) indicating increasing electrical conductivity with depth, as found by Lesch et al. (1992a) by regression analysis on the same data set. The high value of R^2 for **EM_H** vs. **EM_V** suggests that little will be gained by treating **EM_H** and **EM_V** separately. Thus, we will deal exclusively with **EM_H** data.

The electrical conductivity of soil should be more accurately predicted by a volumetric rather than gravimetric expression. But, conversion to volumetric water content requires knowledge of the soil bulk density. A limited sampling for soil bulk density was conducted in the BWD in 1993 when 98 samples were collected at 0.3-m depth. This limited sampling did not have sufficient coverage of the area to warrant use of the bulk density data to convert gravimetric to volumetric water content.

Figure lb was produced by overlaying a square 100 by 100 m grid on the **EM_H** data points. Each square in the grid was then filled in from a gray scale according to the value at the enclosed data point. Squares enclosing no data point remained white. In the few cases where more than one data point was enclosed, the geographic information system that was used to prepare this map selected one of the data values arbitrarily. Figure la is a soil map of the same area digitized from a larger map provided by the Soil Conservation Service. A north-northeast-trending low value of **EM_H** runs from the north-east comer down toward the southwest comer of the central portion of the field area (Fig. lb). The **EM_H** value is also low in an area near the southeast comer. These two lows occur in the same general areas as the Cerini clay loam soil. In an area of the map between the two low values of **EM_H** just described, there is evidence of quarter-section control of **EM_H**. The map of quarter-section outlines (Fig. 2) can be compared with the **EM_H** map (Fig. lb) to note significant step variations in **EM_H** occurring at some of the boundaries. This localized pattern of step variations in **EM_H** conforming to quarter-section boundaries is most reasonably explained by differences in management practices between adjacent quarter sections. An inference that may be drawn from visual inspection of the raw **EM_H** data is that both soil texture and management practices appear significant in determining **EM_H** in the BWD. Also, the relative importance of soil texture or management factors appears variable across the area.

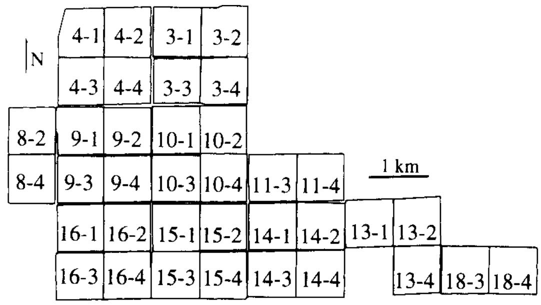


Fig. 2. Quarter-section identification map.

The apparent electrical conductivity measured at the surface **(EM_H)** is likely to be correlated with several physical variables including salinity of the soil water, water content, and properties such as clay content that are determined by soil texture (Lesch et al., 1992b). Mean gravimetric water content was obtained by averaging across the four sampling depths. The EC, value for the same set of samples was log transformed and then averaged. These results were normalized to zero mean and unit variance and plotted with normalized **EM_H** (Fig. 3). There is roughly the same coefficient of determination between each of these physical variables and **EM_H** [$R^2 = 0.48$ for **$\log(EC_e)$** and $R^2 = 0.55$ for W] indicating that both variables influence the pattern of apparent electrical conductivity in the BWD. Correlation between depth-averaged W and **$\log(EC_e)$** is low ($R^2 = 0.1$).

For both W and **$\log(EC_e)$**, the relative contributions of samples from different depths to the **EM_H** measurement was studied by calculating the coefficient of determination for each of the four sampling depths (Fig. 4). The coefficient of determination for **EM_H** vs. log(EC,) increases significantly with increasing depth (R^2 = 0.05-0.54) whereas the correlation of W with **EM_H** decreases with depth (R^2 = 0.48-0.28). For the BWD, measurements of **EM_H** will be most useful for predicting the water content near the surface (O-O.6 m) and the salinity at greater depths (0.6-l .2 m).

Kriging Results

Ordinary kriging of **$\log(EC_e)$** for the samples taken from 1.06-m depth was accomplished by computing and modeling the semivariogram. Then, using the modeling results, a block kriging algorithm computed the interpolation of **$\log(EC_e)$** onto a square grid with a 100-m cell size. An exponential model of the semivariogram with a l-km range provided useful fits for all of the various types of data being modeled. This model is given by

$$y(h) = C_0 + C_c[1 - \exp(-h/a)] \quad [3]$$

where h is the lag distance, C_0 represents the nugget effect, C_c is a structural component, and a is the range.

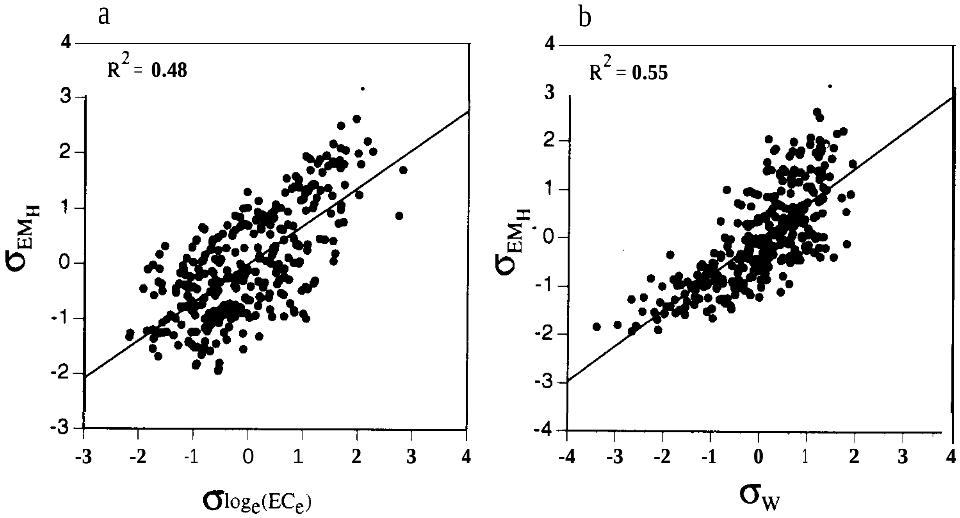


Fig. 3. Scattergrams of normalized apparent electrical conductivity measured at the soil surface (EM_H) vs. normalized log-transformed electrical conductivity of the soil paste extract (EC.) and water content, both averaged across four sampling depths.

The nugget was estimated by the intersection of the fitted exponential model with the semivariance axis at zero lag because very closely spaced data were not available for an independent estimate. The map of the kriged result for $\log(EC_e)$, shown in Fig. 5, has both similarities and differences when compared with the raw EM_H data (Fig. lb). A broad similarity is the correspondence of a low value in EM_H with a low $\log(EC_e)$ in the areas where Cerini clay loam is the soil. Also the highest values of both $\log(EC_e)$ and EM_H occur in the same areas. A difference is the lack of sharp variations in $\log(EC_e)$ at quarter-section boundaries when compared with EM_H. Since this latter effect may simply be due to smoothing caused by a 500-m kriging radius, which is substantially larger than the 100-m spacing for the raw EM_H data, the kriging calculation was applied to the raw EM_H data using a 500-m kriging radius. The resulting map exhibited smoother transitions but a pattern following quarter-section boundaries persisted in the area of sections 1 l-3, 11-4, 14-1, 14-2, 14-3, 14-4, 15-3, and 15-4 (data not shown). Kriged maps of both $\log(EC_e)$ and water content failed to exhibit this pattern. However, based on previous work (Rhoades and Corwin, 198 1; Corwin and Rhoades, 1982, 1983; Lesch et al., 1992b; Lesch et al., 1995b) there is strong evidence for correlation between $\log(EC_e)$ and EM_H. Less work has been done on the correlation between water content and EM_H but there is considerable evidence that a correlation exists because recommendations for salinity survey methods specify that water content should be uniform (Kachanoski et al., 1988; Lesch et al., 1992b). Given these known correlations and the computed coefficients of determination for the BWD data set (Fig. 3), the explanation for differences in the localized patterns of $\log(EC_e)$ compared with EM_H and water content compared with EM_H may lie in the difference in sampling density rather than a lack of correlation. We chose a set of specific subareas within the BWD for detailed examination of the actual data in areas where sharp discontinuities in the mapped values of EM_H occur.

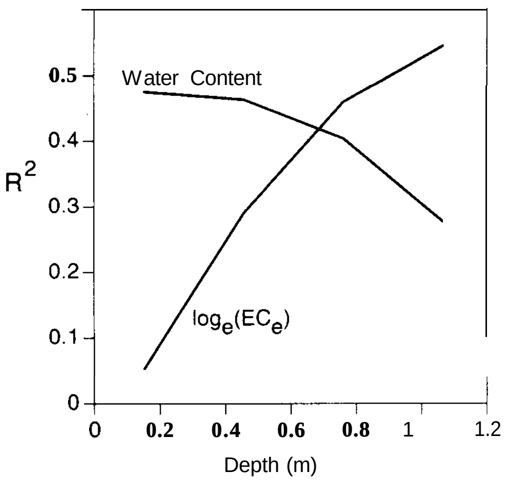


Fig. 4. Coefficient of determination (R^2) for plots of apparent electrical conductivity measured at the soil surface (EM_H) vs. log-transformed electrical conductivity of the soil paste extract (EC_e) and EM_H vs. gravimetric water content (W) is itself plotted against depth. Correlation between EM_H and near-surface $\log(EC_e)$ is near zero but increases with depth, whereas for W the correlation decreases with depth.

Explanations of Mismatch between Surface-Measured and Soil-Paste-Measured Electrical Conductivity

A specific area of mismatch between maps of EM_H and the kriged $\log(EC_e)$ data occurs in quarter section 4-3. An east-west trending boundary in quarter section 4-3 separates a rectangular area of low EM_H in the northern portion from an area of much higher EM_H in the southern portion of 4-3 (Fig. lb). By contrast, $\log(EC_e)$ has a relatively high value forming a north-south trending band along the western half of 4-3 (Fig. 5). Quarter section 4-3 took no irrigation deliveries during the period of 1991 before the field measurements were made. Thus, irrigation management was not a factor causing the east-west trending, split pattern in EM_H.

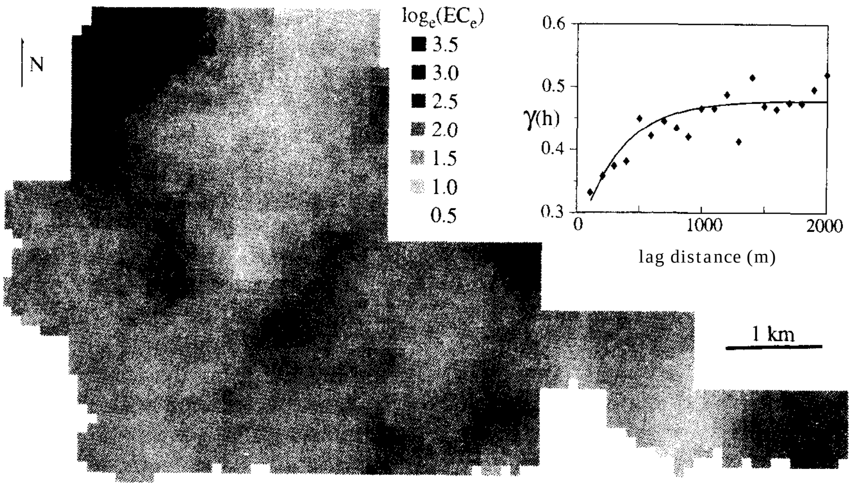


Fig. 5. Gray-scale map of the kriging estimate of log-transformed electrical conductivity of the soil paste extract (EC,) determined from samples taken at 1.06-m depth. Semivariogram was modeled using an exponential with an effective range of 1 km. Lows in the kriged result generally correspond to areas of clay loam-soil texture (Fig. la).

But cropping of the field was split along an east-west trending line, with winter wheat grown in the northern portion while the southern portion remained fallow. The six sampling points in the northern portion of the field were located in the portion where wheat was grown and the other six sampling points were in the fallow area. Within the positional constraint afforded by the soil sampling locations, the location of this east-west trending line is the same as the location of the abrupt change in EM_H between northern and southern areas of the quarter section. Table 1 provides median values of water content at four depths for each portion of quarter section 4-3. In the depth range 0 to 0.75 m, the range in which water content has high variability causing a high sensitivity of EM_H to water content, the median water content in the northern portion was significantly lower than in the southern portion. Thus, variation of water content resulted in a pattern that matches the general pattern of EM_H but variation of $\log(EC_e)$ does not. The winter wheat had matured and was harvested shortly before the field measurements were made on 22 Apr. 1991. Evidently, growth of the wheat depleted the soil water relative to that of the adjacent fallow area, causing both lower values of water content in the soil samples and lower values of EM_H.

Management factors also appear to predominate in the area of quarter section 14-2 and its four nearest neighbors (Fig. lb). No irrigation water was delivered to 14-2 during the period of 1991 prior to the EM_H measurements. Deliveries of irrigation water to all four of the quarter sections that border 14-2 occurred between January and April 199 1. These deliveries are called ***preirrigations,*** meaning that water is applied before a crop is planted. In the depth range of 0 to 0.9 m, the median water content for 14-2 was lower than in any of the bordering quarter sections (Table 2). This low water content may be attributed to the lack of any preirrigation. In general, water content does not correlate particularly well with either the amount of irrigation water applied or the elapsed time between preirrigation and the date of the measurements. While the largest irrigation occurred in quarter section 14-4, which has the highest average water content for all depths, a scatter plot of irrigation amount vs. water content for the four bordering quarter sections gave R^2 = 0.42 (not shown). This suggests that influence by other management factors, as outlined above, may also be affecting water content.

The explanation of irrigation management is even less effective in rationalizing the sharp variations in EM_H between quarter section 11-3 and its neighbors to the east and south. In 1 l-3, the median water content at the 0.3-m depth is 0.185, which is lower than either the corresponding water content of 1 l-4 (0.242) or 14-1 (0.219 for all points). Thus, quarter section 11-3 has lower water content and lower average EM_H, but a substantially larger amount of irrigation water was applied to this quarter section than to either 14- 1 or 1 l-4 (Table 2). Some factor other than simple amount of

Table 1. Median water content for samples from six sites in each subarea.

Subarea	Water content 0.15 m	0.46 m	0.76 m	1.06 m
	kg kg-’			
North	0.198	0.245	0.30s	0.385
South	0.307	0.351	0.344	0.33s

Table 2. Median water content for various quarter-sections.

ID†	Median water content 0.15 m	0.46 m	0.76 m	1.06 m	Irrigation amount‡
	kg kg-’				m
14-2	0.220	0.22s	0.266	0.312	0
13-1	0.316	0.303	0.284	0.281	0.16
14-4	0.298	0.337	0.328	0.298	0.21s
14-l	0.284	0.295	0.282	0.276	0.073
11-4	0.319	0.282	0.283	0.306	0.06s
11-3	0.227	0.260	0.278	0.290	0.128
15-4	0.319	0.271	0.272	0.306	
15-3	0.148	0.154	0.181	0.193	8

† Quarter-section identification number.
‡ Total depth of water applied during S mo prior to sampling.

irrigation water applied caused lower water content in quarter section 1 l-3.

Very low water content occurred at all depths in quarter section 15-3 compared with 15-4 (Table 2). This contrast in water content is correlated with a step increase in EM_H going from 15-3 to 154. Neither quarter section had been preirrigated, implying that the observed variation in water content is also due to some factor other than irrigation. Another step variation in EM_H across a quarter-section boundary occurs between 18-3 and 13-4. The median water content at the 0.15-m depth in 18-3 is 0.229, whereas median water content is 0.192 in 13-4 at the same depth. This variation in water content is particularly difficult to explain by irrigation management since quarter section 134 had been preirrigated whereas 18-3 had not. However, there is a contact between clay loam and clay that lies close to this quarter-section boundary and the occurrence of a step variation in water content may be explained by the difference in soil texture (Fig. la).

Further evidence of the relative significance of water content and $\log(EC_e)$ in explaining the differences in measured EM_H occurring at quarter-section boundaries can be judged by comparing maps of posted data for the two variables at a representative boundary. The posted data were superimposed on a gray-scale map of normalized EM_H, which indicates the step variation in EM_H occurring at the boundary between quarter sections 14-2 and 1 l-4 (Fig. 6a and 6b). All eight measurements of W in the upper quarter section (1 l-4) are higher than the highest measurement in quarter section 14-2 (Fig. 6a). In contrast, there is considerable overlap of the $\log(EC_e)$ data, which varies between 1.63 and 3.08 in 1 l-4 and between 0.66 and 2.53 in 14-2. There is clearly an increase in the mean value of $\log(EC_e)$ going from 14-2 to 11-4, suggesting some correlation between EM_H and $\log(EC_e)$, but the change in W is more definitive and is clearly associated with the quarter-section boundary. Similar results, for this kind of comparison, were obtained at the other nine quarter-section boundaries, indicating that near-surface water content rather than $\log(EC_e)$ is a better predictor of EM_H in areas exhibiting step variations in EM_H at the boundaries. The main evidence that these nine boundaries are associated with step variations in EM_H is drawn from examination of Fig. lb, but to provide some quantification, the mean EM_H values were computed for all quarter sections. Using those means, the nine designated step boundaries

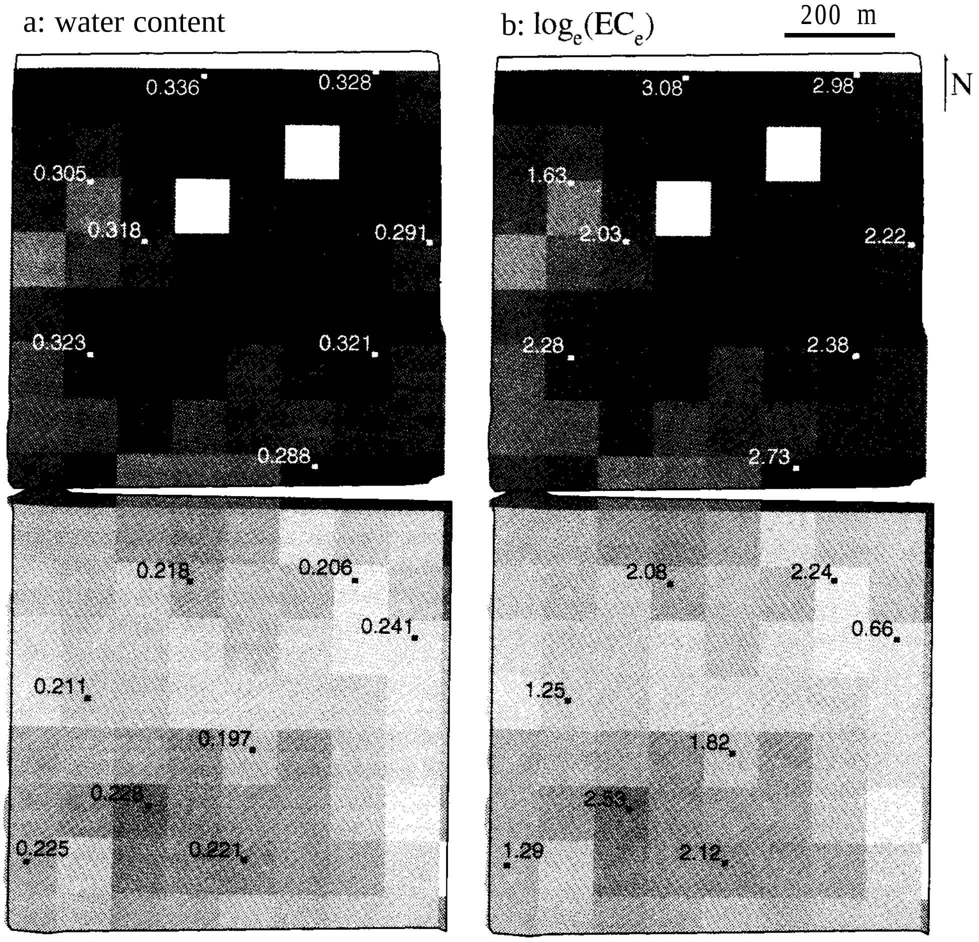


Fig. 6. (a) Gray-scale map of apparent electrical conductivity measured at the soil surface (EM_H) in quarter section 11-4 (top) and 14-2 with superimposed posting of water content at 0.15-m depth for samples taken at eight locations in each. Gray scale was recalculated to maximize contrast; it is uncalibrated. (b) Same gray-scale map with superimposed posting of log-transformed electrical conductivity of the soil paste extract (EC_e) at 1.06-m depth ($dS\ m^{-1}$).

showed a mean, absolute value step of 0.52 ± 0.19 whereas the other 47 boundaries exhibited a mean, absolute value step of 0.18 ± 0.14. The observations of steps in EM_H were statistically analyzed by a series of t-tests conducted for each of the nine boundaries (Table 3). The hypothesis being tested in each case was: Is there a significant difference in the mean of *W* values between the two quarter sections on either side of each boundary having a step variation in EM_H? The same hypothesis was also tested for $\log(EC_e)$ values. In six out of nine cases, the t-statistic for *W* was significant at the 0.001 level. Two of the other cases were significant at a 0.01 level, the last case at a 0.05 level. But, for $\log(EC_e)$ none of the results were significant at a 0.01 level and only two out of nine cases were significant at a 0.05 level. Also, for $\log(EC_e)$, three out of nine cases had negative values because the means for $\log(EC_e)$ were negatively correlated with EM_H.

These results demonstrate that the identified step variations in EM_H are caused by variations in *W* rather than $\log(EC_e)$. The origin of these step variations in water content may be correlated with variations in irrigation amount but this cannot be the explanation of all nine cases. Three of the nine boundaries that were studied (4-2/3-l, 13-4/18-3, and 16-3/16-4) lie close to contacts between clay loam soil and clay (Fig. la). In these three cases the quarter section that is predominantly clay loam had significantly lower water content. Thus, water content in these three cases was probably controlled by soil texture rather than management factors. Another sharp EM_H boundary occurring within a single quarter section (4-3) was also a boundary between higher and lower average values of water content. This latter case cannot be explained by a contact of soil textures and was probably the result of wheat growing in the northern portion while the southern portion was fallow. Of the remaining six quarter-section boundaries, irrigation may explain observed variation in water content in four cases. The other two cases must be due to some other management factor.

Cokriging of Selected Areas to Estimate Soil-Paste-Measured Electrical Conductivity

The argument given above suggests that parts of the BWD are areas in which the management factors involving entire, or portions of, quarter sections are important in determining the measured EM_H. This can be crudely judged by examining the quarter-section boundaries. If there are step changes in EM_H occurring in a consistent manner along the length of a boundary and that boundary does not coincide with a change in soil texture, then management factors such as irrigation, tillage, tile drainage, or cropping may be influencing water content in one or both of the quarter sections on either side of the boundary. For the purpose of comparison, two areas were chosen for further study. One of these is characteristic of a zone judged to be influenced by management factors on the basis of step changes in EM_H occurring at quarter-section boundaries (Section 14). The other section does not appear to be influenced by management factors (Section 3). Section 3 was not irrigated in 1991 prior to taking the EM_H measurements and has a median water content of 0.137, compared with 0.220 for Section 14. For each section, scattergrams of the normalized $\log(EC_e)$ and *W* plotted against normalized EM_H were fitted by linear equations. Section 14 has $R^2 = 0.59$ for water content at 0.15-m depth and $R^2 = 0.44$ for $\log(EC_e)$ at 1.06-m depth The situation is almost the reverse in Section 3, where $R^2 = 0.43$ for water content and $R^2 = 0.54$ for $\log(EC_e)$ at the same depths. There are approximately 32 points in each section, so these numbers are less certain than the R^2 values for the entire area, but the qualitative result, the reversal of relative importance of water content at shallow depths and $\log(EC_e)$ at 1.06 m, is reasonably certain. This comparison of Sections 3 and 14 indicates that the relative importance of *W* and $\log(EC_e)$ in controlling patterns of EM_H is spatially variable as well as varying with depth.

Cokriging is most useful when the auxiliary function is sampled at higher density than the primary function (Yates and Warrick, 1987). This is the case for our data set but, as pointed out above, there are really two primary random functions that may be cokriged with the auxiliary function. The correlation between each of these primary random functions and the auxiliary function is itself spatially variable, such that areas may be delineated in which the auxiliary function will have greater utility in the estimation of one primary variable as opposed to the other. A method is required to distinguish areas in which each type of primary variable can best be estimated. One obvious choice is computation of the coefficient of determination for each variable within some set of area1 subunits. In practical terms, this is somewhat suspect because individual quarter sections generally contain only eight points. Instead, areas lacking obvious, visual evidence of management factors controlling water content were chosen for cokriging to estimate $\log(EC_e)$.

As a first step in the presentation of cokriging results, Fig. 7 is a gray-scale map of the estimation of $\log(EC_e)$ at 1.06-m depth obtained by cokriging $\log(EC_e)$ with EM_H. Two semivariograms for the primary and secondary variables are included in Fig. 7 along with the cross-variogram. These three variograms were approximated by an exponential model (Eq. [3]) including a nugget effect. The model curves do not match the data in each individual variogram particularly well, but instead, represent a compromise required by the constraint of a

Table 3. Comparison of means for EM_H and two variables.

	t statistics	
Boundary†	Water content	$\log_e(EC_e)$
16-3:16-4	3.62**	−0.38 NS
13-1:14-2	7.49***	−0.46 NS
18-3:13-4	2.77*	1.79 NS
14-1:14-2	7.14***	−0.64 NS
14-2:14-1	9.21***	0.45 NS
3-1:4-2	5.34***	0.75 NS
15-3:15-4	13.91***	0.43 NS
11-4:14-2	14.18***	2.37*
11-4:11-3	4.51**	2.79*

*, **, *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively; NS = not significant.
† Boundary between quarter sections in which means were calculated.

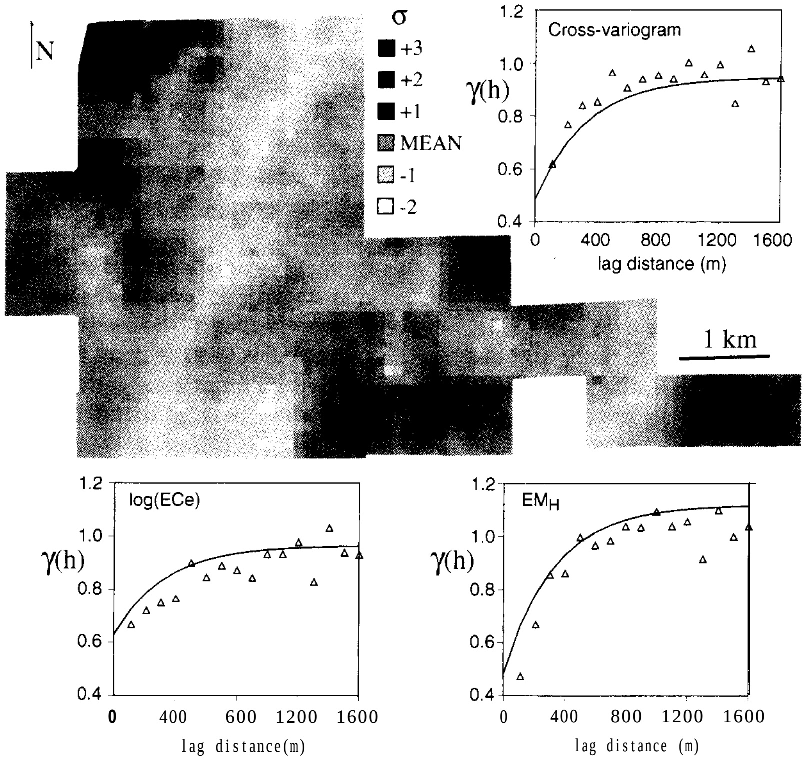


Fig. 7. Gray-scale map of the cokriging estimate of log-transformed electrical conductivity of the soil paste extract (EC_e) at depth using apparent electrical conductivity measured at the soil surface (EM_H) as the auxiliary data. Semivariograms for $\log(EC_e)$ and EM_H were modeled using Eq. [3] hut the evident lack of fit is due to constraints by the linear model of coregionalization.

linear model of coregionalization (Isaaks and Srivastava, 1989). Certain areas of the map in Fig. 7 are characterized by a pattern of step variations at quarter-section boundaries. These patterns are clearly caused by step variations in EM_H because there are no such step variations when $\log(EC_e)$ is kriged by itself (Fig. 5). For example, a ridge of relatively high $\log(EC_e)$ values trends north through quarter sections 14-4, 14-2, and then 1 l-4 (Fig. 5). But in Fig. 7 this same set of quarter sections has high $\log(EC_e)$ in 14-4, low $\log(EC_e)$ in 14-2, and a high value again in 11-4. The low value in the cokriged estimate of $\log(EC_e)$ in 14-2 must be due to low values in EM_H, which were caused by water content variations (compare Fig. lb and 6). Therefore, the operation of cokriging $\log(EC_e)$ with EM_H across the entire study area resulted in a map containing patterns that are artifacts representing water content rather than $\log(EC_e)$ variations. From such a map, one might make the erroneous conclusion that salinity variations in parts of the BWD are the result of management practices.

Visual inspection of the map of EM_H (Fig. lb) combined with information regarding soil texture, irrigation, and cropping resulted in the designation of a contiguous subset of 23 quarter sections in which $\log(EC_e)$ could be estimated by cokriging with EM_H. Within this designated area, the correlation of EM_H with EC, at 1.06-m depth is significantly higher than correlation of EM_H and water content at 0.15 m (R^2 = 0.60 compared with 0.44). Semivariograms for EM_H and $\log(EC_e)$ as well as the cross-variogram were computed for the enclosed sets of data points after normalization to zero mean and unit variance. These semivariograms were modeled using both spherical and exponential models, but the exponential model with a range of 1 km produced the best fits, as verified by cross-validation. Some adjustment of the model parameters was necessary for the three models to conform to a linear model of coregionalization. Cross-validation was then performed to determine whether these adjustments caused large changes in the standard deviation of the point estimation errors. The standard deviation increased by <1 % for the two semivariogram models. A more extensive cross-validation procedure was not warranted in this study because refining the models of semivariograms to accommodate slightly improved cross-validation results is not a recommended procedure (Isaaks and Srivastava, 1989). Furthermore, such refinements are unlikely to significantly improve the resulting estimates. The problem that has been discussed at length regarding spatial variability of water content and its influence on EM_H is likely to be a greater source of error in the cokriged estimates of $\log(EC_e)$.

Block cokriging of 193 $\log(EC_e)$ values for the 1.06-m depth using 100 by 100 m blocks and 1483 EM_H values generated a rectangular grid of estimated values for $\log(EC_e)$. The result provides more detail (Fig. 8) than is available by simply kriging the EC, data (Fig. 5). The map of the cokriged estimates for 23 selected quarter sections (Fig. 8) also does not exhibit artifacts of step variation at quarter-section boundaries (Fig. 7). High $\log(EC_e)$ values occur in quarter section 4-1, and areas of moderately high $\log(EC_e)$ include quarter sections 4-2, 8-2, 8-4, 9-1, 15-2, and the east side of 9-4 (Fig.

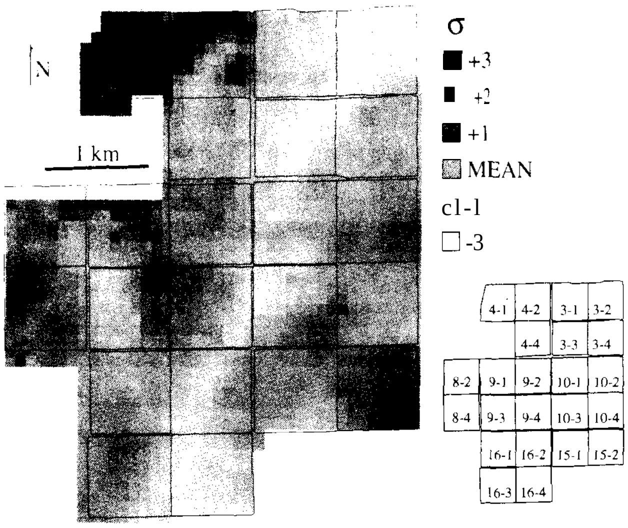


Fig. 8. Gray-scale map of the cokriging estimate of log-transformed electrical conductivity of the soil paste extract (EC,) at 1.06-m depth. The set of quarter sections was chosen based on the perception that management factors related to water content were less significant in determining apparent electrical conductivity measured at the soil surface (EM_H) than for the set not shown. Patterns of EM_H in the quarter sections not shown suggested domination of variability by water content rather than $\log(EC_e)$, see Fig. lb.

7). A linear trend of low $\log(EC_e)$ runs between quarter sections 16-3 and 3-l. This trend follows the Cerini clay loam soil unit, which has lower clay content and higher permeability than the surrounding clays.

CONCLUSION

A fundamental objective of studies of the type described here and elsewhere (Lesch et al., 1992b, 1995a,b; Rhoades and Corwin, 1981; Corwin and Rhoades, 1982, 1983) is the assessment of salinization potential. An estimate of the salinity at depths near the base of the root zone is useful for identifying areas subject to salinization. The EM_H (or EM_V) measurements of apparent electrical conductivity are made quickly and extensive coverage of field areas is feasible.

For the BWD data set, both water content and EC, of the soil water are significant factors influencing the measured values of EM_H, but the influence of water content decreases with depth while the influence of EC, in soil water increases. Water content is controlled by both soil texture and management factors such as irrigation and cropping. In those regions where soil water content near the surface was highly variable due to management factors, these variations tended to mask the variability in EM_H due to depth variations in EC,. An attempt was made to rationalize those variations of EM_H not associated with soil texture contacts by analyzing the potential of particular management factors to explain observed soil water content. Extensive data are available for irrigation and some variability in soil water content appears related to irrigation amounts, but soil texture and irrigation cannot account for all of the observed variability. Thus, prediction of soil water content by a combination of soil texture and management factors was not possible.

An alternative and less ambitious undertaking is the designation of particular areas as unsuitable for cokriging EM_H and $\log(EC_e)$ because of the water content effect. In certain parts of the BWD study area, variations in soil water content occurred in regular patterns with step variations at quarter-section boundaries and, in one instance, a boundary between crops within a single quarter section. This pattern also appeared in the EM_H data. Identification of this pattern in gray-scale maps of EM_H permitted designation of areas where water content was likely to be dominating variability of EM_H. At certain quarter-section boundaries, variation in water content was associated with a variation in soil texture. At other quarter-section boundaries, variations in water content are the result of either irrigation management or some other management factor. Isolation of the areas in which management factors were not significant defined a zone where cokriging of EM_H and the deepest level data for $\log(EC_e)$ resulted in a map with improved resolution of $\log(EC_e)$ compared with the map obtained by kriging of $\log(EC_e)$ alone.

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REFERENCES

Corwin, D.L., and J.D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46: 517-520.

Corwin, D.L., and J.D. Rhoades. 1983. Measurement of inverted electrical conductivity profiles using electromagnetic induction. Soil Sci. Soc. Am. J. 48:288-291.

Hendrickx, J.M.H., B. Baerends, Z.I. Raza, M. Sadig, and M.A. Chaudhry. 1992. Soil salinity assessment by electromagnetic induction in irrigated land. Soil Sci. Soc. Am. J. 56:1933-1941.

Isaaks, E.H., and R.M. Srivastava. 1989. An introduction to applied geostatistics. Oxford Univ. Press, New York.

Deutsch, C.V.,andA.G. Joumel. 1992. GSLIB geostatistical software library and user's guide. Oxford Univ. Press, New York.

Joumel, A.G., and C.J. Huijbregts. 1978. Mining geostatistics. Academic Press, New York.

Kachanoski, R.G., E.G. Gregorich, and I.J. Van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68: 715-722.

Keller, G.V., and F.C. Frischknecht. 1966. Electrical methods in geophysical prospecting. Pergamon Press, Oxford, England.

Lesch. S.M.. J.D. Rhoades. and D.L. Corwin. 1992a. Statistical modeling and prediction methodologies for large scale spatial soil salinity characterization: A case study using calibrated electromagnetic measurements within the Broadview Water District. U.S. Salinity Lab. Tech. Rep. no. 131.

Lesch, SM., J.D. Rhoades, L.J. Lund, and D.L. Corwin. 1992b. Mapping soil salinity using calibrated electromagnetic measurements. Soil Sci. Soc. Am. J. 56:540-548.

Lesch, S.M., D.J. Strauss, and J.D. Rhoades. 1995a. Spatial prediction of soil salinity using electromagnetic induction techniques, 1. Statistical prediction models: A comparison of multiple linear regression and cokriging. Water Resour. Res. 31:373-386.

Lesch, S.M., D.J. Strauss, and J.D. Rhoades. 1995b. Spatial prediction of soil salinity using electromagnetic induction techniques, 2. An efficient spatial sampling algorithm suitable for multiple linear regression model identification and estimation. Water Resour. Res. 31:387-398.

McKenzie, R.C., W. Chomistek, and N.F. Clark. 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. Can. J. Soil Sci. 69:25-32.

Rhoades, J.D., and D.L. Corwin. 1981. Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivitv meter. Soil Sci. Soc. Am. J. 45:255-260.

Rhoades, J.D., N.A. Manteghi, P.J. Shouse, and W.J. Alves. 1989a. Estimating soil salinity from saturated soil-paste electrical conductivitv. Soil Sci. Soc. Am. J. 53:428-433.

Rhoades, J.D., S.M. Lesch, P.J. Shouse, and W.J. Alves. 1989b. New calibrations for determining soil electrical conductivity: Depth relations from electromagnetic measurements. Soil Sci. Soc. Am. J. 53:74-79.

Rhoades, J.D., P.J. Shouse, W.J. Alves, N.A. Manteghi, and S.M. Lesch. 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. Soil Sci. Soc. Am. J. 54:46-54.

Rhoades, J.D., and J. van Schilfgaarde. 1976. An electrical conductivity probe for determining soil salinity. Soil Sci. Soc. Am. J. 40: 647-65 1.

Slavich, P.G., and G.H. Petterson. 1990. Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements. Aust. J. Soil Res. 28:453-463.

Vauclin, M., S.R. Vieira, G. Vachaud, and D.R. Nielsen. 1983. The use of cokriging with limited field soil observations. Soil Sci. Soc. Am. J. 47:175-184.

Yates, S.R., and A.W. Warrick. 1987. Estimating soil water content using cokriging. Soil Sci. Soc. Am. J. 51:23-30.