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An Improved Technique for Determining Soil Electrical Conductivity–Depth Relations from Above-ground Electromagnetic Measurements[1]

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ABSTRACT

An improved method has been developed for determining the distribution of bulk soil electrical conductivity, EC_a, through the soil from electromagnetic measurements taken at the soil surface with the Geonics Limited EM-38 device. Induced electromagnetic conductivity readings taken with the EM-38 device's coil configuration oriented parallel and then perpendicular to the soil surface provided sufficient information, when used with equations derived from geophysical instrumentation data, to produce a soil electrical conductivity–depth profile. The simplicity of this method further enhances the praiticability of the newly developed electromagnetic technique for field measurements of salinity and for saline seep diagnosis.

Additional Index Words: **soil salinity, soil resistivity, electromagnetic conductivity.**

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Recently, Rhoades and Corwin (1981) have shown that bulk soil electrical conductivity, EC_a, of incremental depth intervals within the soil profile can be obtained from above-ground electromagnetic measurements of apparent soil electrical conductivity, EM, using multiple regression coefficients which relate electromagnetic conductivity to EC_a. This initial method required the solution of a complex system of simultaneous equations. The coefficients of these equations were determined by multiple regression analyses of EM readings taken at five incremental heights (0, 0.3, 0.6, 0.9, and 1.2 m) above the soil and of EC_a values measured (using a four-electrode probe) at corresponding depths (0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m) in the soil. It is the purpose of this paper to describe a less complicated method for obtaining EC_a–depth relations of any soil from only two EM measurements taken at the soil surface. In this approach the EM readings are related to EC_a by a series of simple equations derived from instrumentation data provided by the manufacturer of the EM device (EM-38).[3]

THEORY

The design of the EM-38 soil electromagnetic conductivity meter is such that when a conductivity reading is taken at the surface of a homogeneous medium the result reflects a cumulative relative contribution of soil conductivities from the various strata above some depth (Fig. 1). Furthermore, the relative contribution of conductivity from the various depths depends upon the orientation of the transmitter coil (Fig. 2) with respect to the soil surface. Assuming that the EM-38 response curve holds for measurements taken over nonhomogeneous media, it is possible to derive a series of equations which relate EC_a within a soil depth interval to the horizontal and vertical electromagnetic conductivity measurements, i.e., apparent conductivity.

For the 0- to 0.3-m increment of soil, the equations derived from Fig. 1 are:

$$EM_{0,V} = 0.15\ EC_{0\text{–}0.3,V} + 0.85\ EC_{>0.3,V}, \text{ and} \qquad [1]$$

$$EM_{0,H} = 0.435\ EC_{0\text{–}0.3,H} + 0.565\ EC_{>0.3,H}, \qquad [2]$$

where $EM_{0,V}$ and $EM_{0,H}$ are the electromagnetic apparent conductivities measured at the soil surface in the vertical and horizontal positions, respectively; and $EC_{0\text{–}0.3,V}$, $EC_{>0.3,V}$, $EC_{0\text{–}0.3,H}$, and $EC_{>0.3,H}$ are the actual bulk soil electrical conductivities for the 0- to 0.3-m and >0.3-m soil depth intervals, respectively.

Discussions with the manufacturer of the EM-38 revealed that the volume of soil measured within the 0- to 0.3-m increment is very similar for the vertical and horizontal orientations; therefore, it is reasonable to assume that $EC_{0\text{–}0.3,V} = EC_{0\text{–}0.3,H}$. However, in the case of the > 0.3-m increment, the volumes of measurement are quite different (as reflected in Fig. 1); consequently, it is unlikely that $EC_{>0.3,V}$ will equal $EC_{>0.3,H}$. This fact presents a problem because, in order to arrive at a relationship between $EC_{0\text{–}0.3}$ and $EM_{0,V}$ and $EM_{0,H}$ using Eq. [1] and Eq. [2], it is necessary to equate $EC_{>0.3,V}$ and $EC_{>0.3,H}$. This problem was overcome when it was found that $EM_{0,H}$ could be adjusted so that $EC_{>0.3,V}$ calculated from Eq. [1] would equal $EC_{>0.3,H}$ for a large number of sites where $EC_{0\text{–}0.3}$, $EM_{0,V}$, and $EM_{0,H}$ were measured. Adjustment of $EM_{0,H}$ was made as follows:

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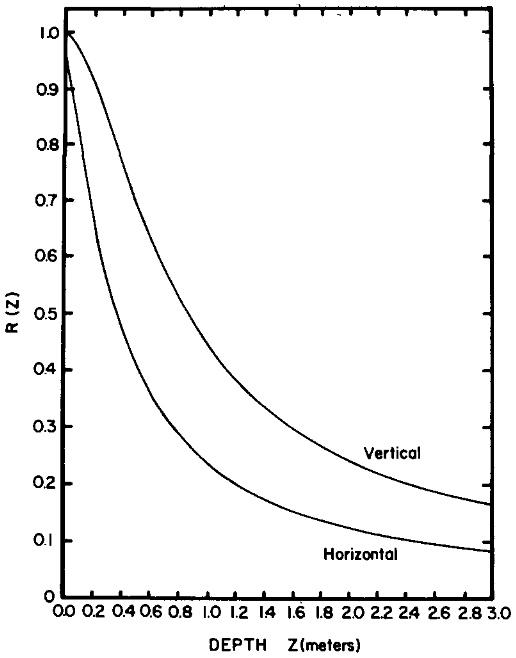

Fig. 1—Cumulative relative contribution of all soil electrical conductivity R(Z) below various depths to the EM-38 reading when the device is held in a horizontal (parallel) and vertical (perpendicular) position.

Values of $EC_{>0.3,V}$ were calculated with Eq. [1] using $EC_{0-0.3}$ as measured with the four-electrode probe, and of $EM_{0,V}$ as measured with the EM-38 device. It was assumed that $EC_{>0.3,V}$ is a better estimate of actual $EC_{>0.3}$ than $EC_{>0.3,H}$ because it contributes 85% of the $EM_{0,V}$ reading, whereas $EC_{>0.3,H}$ only contributes 56.5% of the $EM_{0,H}$ reading. The adjusted $EM_{0,H}$ for the 0- to 0.3-m depth increment was then calculated from Eq. [2] using the measured values of $EC_{0-0.3}$ and the calculated values of $EC_{>0.3,V}$. A plot of measured and adjusted $EM_{0,H}$ values for each depth increment of all 16 sample sites revealed a set of linear relations (Fig. 3). Therefore, it appears that these relations can be used, irrespective of the site of measurement, to adjust measured values of $EM_{0,H}$ for a specified depth increment (0-*h* meters) so that $EC_{>h,V} = EC_{>h,H}$ as demonstrated in Eq. [3] and Eq. [4] for the 0- to 0.3-m increment:

$$EM_{0,V} = 0.15\ EC_{0-0.3} + 0.85\ EC_{>0.3,V}, \text{ and} \quad [3]$$

$$EM_{0,H(\text{adjusted},0-0.3\text{ m})} = 0.435\ EC_{0-0.3} + 0.565\ EC_{>0.3,V}. \quad [4]$$

Equations [3] and [4] can now be reduced by substitution to a single equation:

$$EC_{0-0.3} = 2.982\ EM_{0,H(\text{adjusted},0-0.3\text{ m})} - 1.982\ EM_{0,V}.$$

Thus, the bulk soil electrical conductivity of the 0- to 0.3-m depth of any site can be determined from two electromagnetic measurements made above ground.

Table 1—Equations used to calculate electrical conductivity for soil increments from electromagnetic conductivity measurements.

Depth, m	Equations for electrical conductivity
	Composite depths
0-0.3	$EC_{0-0.3} = 2.982\ EM_{0,H(\text{adjusted},0-0.3\text{m})} - 1.982\ EM_{0,V}$
0-0.6	$EC_{0-0.6} = 2.286\ EM_{0,H(\text{adjusted},0-0.6\text{m})} - 1.286\ EM_{0,V}$
0-0.9	$EC_{0-0.9} = 2.133\ EM_{0,H(\text{adjusted},0-0.9\text{m})} - 1.133\ EM_{0,V}$
0-1.2	$EC_{0-1.2} = 2.054\ EM_{0,H(\text{adjusted},0-1.2\text{m})} - 0.946\ EM_{0,V}$
	Successive depths
0-0.3	$EC_{0-0.3} = 2.982\ EM_{0,H(\text{adjusted},0-0.3\text{m})} - 1.982\ EM_{0,V}$
0.3-0.6	$EC_{0.3-0.6} = 4.571\ EM_{0,H(\text{adjusted},0-0.6\text{m})}$ $- 2.983\ EM_{0,H(\text{adjusted},0-0.3\text{m})}$ $- 0.5889\ EM_{0,V}$
0.6-0.9	$EC_{0.6-0.9} = 6.400\ EM_{0,H(\text{adjusted},0-0.9\text{m})}$ $- 4.571\ EM_{0,H(\text{adjusted},0-0.6\text{m})}$ $- 0.829\ EM_{0,V}$
0.9-1.2	$EC_{0.9-1.2} = 8.216\ EM_{0,H(\text{adjusted},0-1.2\text{m})}$ $- 6.400\ EM_{0,H(\text{adjusted},0-0.9\text{m})}$ $- 0.384\ EM_{0,V}$

Following the same rationale, two sets of equations can be obtained (Table 1) which provide different types of conductivity–depth profile information. One set of equations permits the determination of average EC_a for composited 0.3-m increments (i.e., 0 to 0.3, 0 to 0.6, 0 to 0.9, and 0 to 1.2 m), while the second set permits the calculation of EC_a for successive 0.3-m increments (i.e., 0 to 0.3, 0.3 to 0.6, 0.6 to 0.9, and 0.9 to 1.2 m). Since it is easy to derive electrical conductivities for successive increments from calculated composite increment apparent electrical conductivities (e.g., $EC_{0.3-0.6} = 2\ EC_{0-0.6} - EC_{0-0.3}$), an alternate means of determining soil electrical conductivity–depth relations for successive incremental depths is provided.

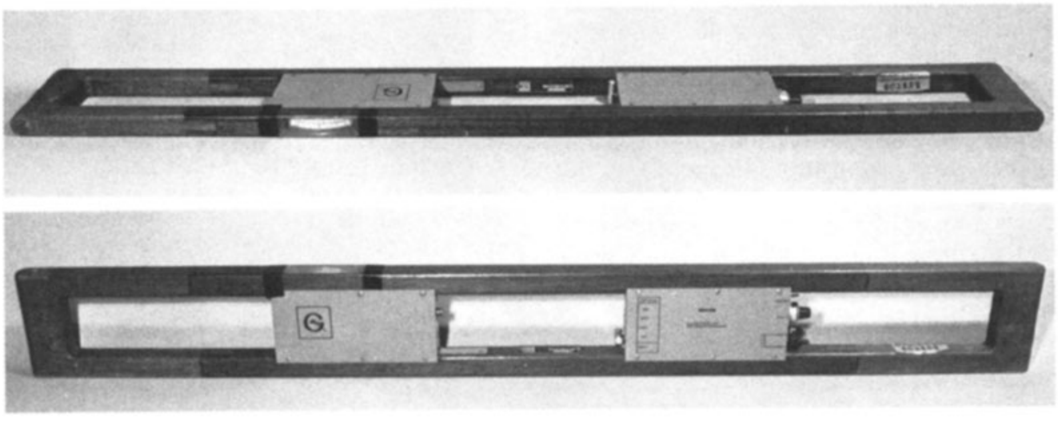

Fig. 2—Geonics EM-38 prototype electromagnetic soil conductivity meter (top) lying in the horizontal position with its coils parallel to the soil surface, and (bottom) lying in the vertical position with its coils perpendicular to the soil surface.

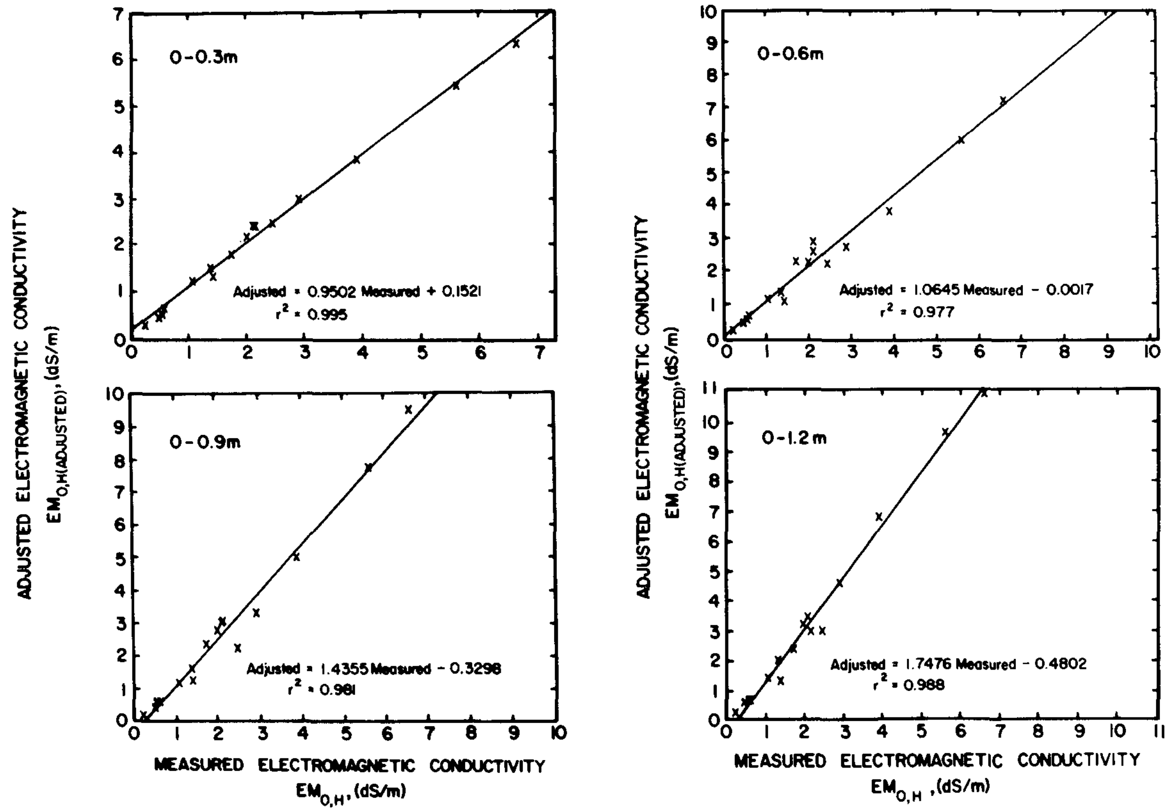

Fig. 3—Relationship between electromagnetic soil conductivity as measured with the EM-38 in the horizontal position at the soil surface, EM$_{0,H(measured)}$ and adjusted electromagnetic soil conductivity, EM$_{0,H(adjusted)}$ for composite depths.

EXPERIMENTAL PROCEDURE

A total of 16 sites were sampled in three different areas of southern California: Lakeview, San Joaquin Valley (Lost Hills, Calif.), and Imperial Valley (Imperial, Calif.). The sites were selected in order to provide a wide range of electrical conductivity–depth relations on different soil types. Electromagnetic conductivity measurements were taken with the EM-38 device positioned in horizontal and vertical positions at the soil surface (Fig. 2). As a precaution, any metal objects that might come within the field of influence of the electromagnetic device were removed. Direct measurements of EC$_a$ were then taken at 0.3-m increments through the soil profile using a four-electrode salinity probe (Rhoades and van Schilfgaarde, 1976).

To evaluate the validity of the equations in Table 1, linear regressions were performed on the electrical conductivity values derived from the electromagnetic conductivity measurements compared with values for corresponding electrical conductivities measured with the four-electrode probe.

RESULTS AND DISCUSSION

Table 2 provides a summary of statistical parameters performed on calculated electrical conductivities obtained from electromagnetic conductivity measurements and their corresponding "ground truth" values as measured with the four-electrode probe. These statistical parameters provide an indication of the agreement between calculated electrical conductivities and ground truth conductivities. Two different calculation methods were compared: the previously used multiple regression coefficient method (Rhoades and Corwin, *1981)* and the newly developed established coefficient method described herein.

A comparison of the two different approaches (Lakeview site only) used in the calculation of conductivity for successive 0.3-m increments reveals that the multiple regression approach has a slightly better one-to-one correspondence since the dispersion of values about the line of regression, as reflected by the standard error of estimate, is less (1.101 vs. 1.773 and 1.858). Nevertheless, the electrical conductivities for successive 0.3-m increments and for successive 0.3-m increments obtained from composite increments as determined from the established coefficient approach are clearly within acceptable limits for survey and diagnostic purposes. Though less accurate, the established coefficient approach only requires two electro-

Table 2—Comparison of linear regression analysis of predicted and measured soil electrical conductivities at three test areas.

Method	Site†	No. of entries	Slope	y intercept	R^2	Standard error
		Multiple regression approach				
0.3-m increments	LV	32	0.990	0.051	0.975	1.101
		Established coefficient approach				
Composite increments	LV,IV,SJV	64	0.940	0.113	0.947	0.625
	LV	32	0.971	0.077	0.971	0.604
	IV	16	0.977	0.015	0.965	0.061
	SJV	16	0.880	0.353	0.871	0.299
Successive 0.3-m increments from composite increments	LV,IV,SJV	64	0.954	0.088	0.928	1.447
	LV	32	0.959	0.092	0.930	1.858
	IV	16	0.610	0.239	0.846	0.619
	SJV	16	0.608	1.451	0.572	1.044
Successive 0.3-m increments	LV,IV,SJV	64	0.937	0.246	0.937	1.341
	LV	32	0.935	0.356	0.935	1.773
	IV	16	0.803	0.172	0.779	0.313
	SJV	16	1.183	0.681	0.681	0.898

† LV = Lakeview, Calif.; IV = Imperial Valley (Imperial, Calif.); and SJV = San Joaquin Valley (Lost Hills, Calif.).

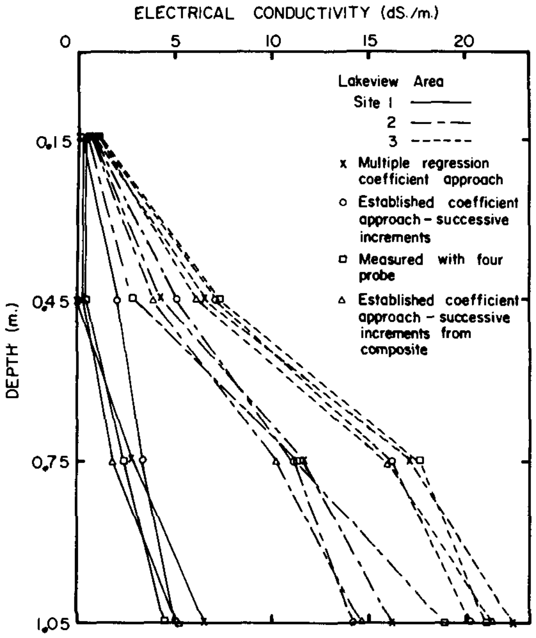

Fig. 4—Graph of representative EC_a-depth profiles for three Lakeview sample sites showing measured and three different calculated profiles for each site.

magnetic measurements as opposed to five for the multiple regression coefficient approach. From these two measurements, electrical conductivities for both successive and composite increments can be determined with less involved computation and a lower computer memory requirement. The fact that the combination of all of the sampling areas does not significantly affect the parameters reflecting correspondence between measured and calculated EC_a indicates that the site specificity seen in the multiple regression approach (Rhoades and Corwin, 1981) is not a restriction in the established coefficient approach. The decreased accuracy of the established coefficient approach and the site specificity of the multiple regression coefficient approach are probably due to magnetic susceptibility differences in the soils at the different sites. In the case of the multiple regression coefficient approach, the magnetic influences are included in the coefficients since this is a statistical approach. This fact could account for its greater accuracy and concomitant lack of general application. The established coefficient approach, on the other hand, does not take into account any magnetic susceptibility influences which probably contribute to its decreased accuracy. Considering the reduction in the number of electromagnetic measurements required, the ease of calculation, and general application, the slight reduction in accuracy of the established coefficient approach seems to be an acceptable tradeoff.

A comparison of the one-to-one correspondence between the calculated and measured EC_a values for 0.3-m composite and successive 0.3-m increments using the established coefficient approach shows that there is a better correspondence for the composite increments (see Table 2). Furthermore, a comparison of all regression and standard error analysis data shows that the calculation of composite 0.3-m increments using the established coefficient approach corresponds most closely to measured electrical conductivities. This is probably due to the fact that in determining EC_a for successive 0.3-m increments, each increment beyond 0.3 m depends upon the accuracy of calculation of the previous increment(s); consequently, error is building as one calculates EC_a deeper in the soil. The equations used to calculate EC_a for composite 0.3-m increments, however, are independent of one another.

Finally, a comparison of calculated and measured correspondence data for successive 0.3-m increments and successive 0.3-m increments obtained from composite increments expectantly indicates that there is little difference between the two, particularly in the case of all sample areas combined.

Figure 4 shows a representative electrical conductivity–depth profile for successive 0.3-m increments obtained using each of the methods of calculating EC_a. This figure demonstrates the practicability of the EM-38 as far as its use as a survey and diagnostic tool is concerned.

SUMMARY

The measurement of bulk soil electrical conductivity using the EM-38 soil electromagnetic conductivity meter has been facilitated by the development of a new calculation approach, referred to as the established coefficient approach. This approach requires fewer electromagnetic readings and is less involved than previous methods. Whereas multiple regression was used in the previous approach to obtain coefficients relating soil electromagnetic conductivity measurements to bulk soil electrical conductivity, the established coefficient approach relies upon coefficients which are derived from inherent EM-38 response curves for homogeneous media. Initial adjustment curves (as shown in Fig. 3) need to be determined, but they appear general in their application; consequently, the established coefficient approach can be programmed on any hand-held calculator allowing 300 to 400 programmable steps. Furthermore, the multiple regression coefficient technique has the limitation of being site-specific in its application, while the established coefficient technique appears to be quite general.

There is some sacrifice of accuracy when using the established coefficient approach to determine successive soil increment electrical conductivities. The loss of accuracy may be related to the influences of varying quantities and types of magnetic materials present in different soil types. It has also been cited as a possible reason for the site specificity noticed in the multiple regression coefficient approach. Future work will be directed toward understanding the effect of magnetic susceptibility upon both approaches to see if compensating for these magnetic materials in soils will improve their accuracy.

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