Evaluation of Electromagnetic Induction as a Reconnaissance Technique to Characterize Unsaturated Flow in an Arid Setting

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Abstract

The use of apparent electrical conductivity (EC_a) measured with electromagnetic (EM) induction was examined as a reconnaissance tool for characterizing unsaturated flow in a semiarid region in the Chihuahuan Desert of Texas. Aboveground conductivity meters (EM31 and EM38) were used to measure EC_a along transects in various geomorphic settings. Eight boreholes were drilled at different locations along the transects, and a downhole conductivity meter (EM39) was used to measure EC_a. Samples were collected for analysis of clay, water, and chloride content to evaluate factors affecting spatial variability in EC_a. Variations in EC_a measured with the aboveground EM31 meter were affected by variations in clay content in a playa/interplaya setting, water content in a fissure, and chloride content adjacent to a drainage system. These factors affecting EC_a were confirmed by comparing EC_a measured with the downhole EM39 meter and clay, water, and chloride content of soil samples from boreholes. The hydrologic significance of parameters controlling EC_a was evaluated. Variations in clay content are not hydrologically significant in this basin. High correlations between EC_a and water content are difficult to interpret because in some areas water content variations simply reflect variations in clay content, as in the playa/interplaya setting, whereas in other areas higher water contents reflect higher water flux, as in the fissure. In some areas water content was below threshold values; therefore, EC_a did not respond to water content or salinity in these areas. Although EM induction alone cannot distinguish causes of EC_a changes, it provides a valuable tool for delineating variations in EC_a that can be used to guide borehole locations and to provide valuable information for interpolating and extrapolating from point estimates provided by borehole data.

Introduction

Noninvasive techniques such as EM induction are becoming increasingly popular because they can be used to rapidly and cost-effectively evaluate spatial variability in apparent electrical conductivity (EC_a) over large areas and provide information on EC_a variations between point measurements provided by boreholes. EC_a in the subsurface varies primarily with clay content, water content, and salinity (McNeill 1992). In an Australian study, the correlation between recharge and EC_a was controlled by clay content; therefore, the EM induction survey primarily mapped clay content at this site (Cook et al. 1992). Comparison of ground measurements of EC_a with recharge estimated according to unsaturated-zone chloride data at 20 sites resulted in an r of 0.7 (Cook et al. 1992). These data suggest that although EM induction cannot estimate recharge directly, it may be useful in reconnaissance and interpolation between borehole measurements. Values of EC_a measured with an EM38 ground conductivity meter in a 1.8 ha field (Ontario, Canada) were highly correlated (r 0.9) with spatial variability in average water content measured with time domain reflectometry probes in the upper 0.5 m of the soil zone (Kachanoski et al. 1988). At other sites, EM induction has been used to map spatial variability in soil salinity related to irrigation in agricultural areas (Rhoades et al. 1990; Lesch et al. 1992, 1995) or as a result of contamination from oil field brines or other sources of environmental contamination (Paine et al. 1997). Because EC_a varies with water content and salinity, evaluations of soil salinity variations are made preferably at field capacity (Rhoades 1992). The aforementioned studies illustrate the primary controls on EC_a in soil: clay content, water content, and salinity. Because of the various controls on EC_a, EM induction may be more suitable for monitoring temporal variations in one parameter such as water content while the other parameters remain fixed, such as soil texture and salinity. Sheets and Hendrickx (1995) demonstrated the use of EM induction for monitoring temporal variations in water content in arid regions once the variations in EM response were calibrated with neutron probe water content data.

The primary objective of this study was to evaluate the potential use of EC_a measured using EM induction tools as a reconnaissance method for characterizing unsaturated flow in an arid setting. To accomplish this objective, the factors affecting EC_a need to be investigated, and the hydrologic significance of these factors needs to be evaluated. This study demonstrates how these factors can be determined. Influences on spatial variability in EC_a measured with surface EM meters (EM31 and EM38) were evaluated by detailed downhole measurements of EC_a with an EM39 conductivity meter and with results of soil sampling for clay, water, and chloride content. After the factors affecting EC_a were estimated, the significance of these factors relative to unsaturated zone hydrology was determined. This study evaluates the potential for the conductivity data

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Table 1

Characteristics of Electromagnetic Induction Conductivity Meters

(including aboveground EM38 and EM31 meters and the downhole EM39 meter used in this study [McNeill 1992]. Exploration depths for the different instruments correspond to approximately 70% of instrument response [McNeill 1992]).

Instrument	Intercoil Spacing (m)	Frequency (Hz)	Exploration Depth (m) Horizontal Dipole Mode	Exploration Depth (m) Vertical Dipole Mode
EM38	1	14,600	0.75	1.5
EM31	3.7	9800	3	6
EM39	0.5	39,200	Radial distance = 0.9 m	

to be used to guide borehole locations and to provide information for interpolating between borehole data.

Theory of Electromagnetic Induction

Electromagnetic induction is a noninvasive technique that measures a depth weighted average of the electrical conductivity termed EC_a. The theoretical basis for EM induction measurements is described in McNeill (1992). The various frequency domain conductivity meters manufactured by Geonics Ltd. (Mississauga, Ontario) differ in the distances between the transmitter and receiver coils, the frequency at which they operate, and their effective exploration depths (Table 1). The exploration depth of the instruments increases with increased intercoil spacing and decreased current frequency and varies with the orientation of coils relative to land surface. The instrument can be operated with transmitter and receiver coils horizontal (vertical dipole [VD] mode) or vertical (horizontal dipole [HD] mode). For a given coil spacing and frequency, the HD mode peak response is from the near surface material, whereas the response for the VD mode is zero at the surface and peaks at greater depth. Under low values of induction number the secondary magnetic field is a linear function of EC_a and the exploration depths are relatively independent of the electrical conductivity of the soil.

Apparent electrical conductivity of the subsurface generally varies with clay content and mineralogy, water content, salinity, porosity, and structure (McNeill 1992). Below threshold water contents, EC_a is controlled by the surface conductance, which is determined primarily by the cation exchange capacity of the clays. Laboratory studies show that threshold water contents range from 0.05 m^3 m^{-3} for sand to 0.12 m^3 m^{-3} for clay (Rhoades et al. 1976). The factors affecting EC_a can be determined by comparing the depth profiles of EC_a with clay content, water content, and pore water conductivity or chloride content.

Site Description

The study area (~ 60 km^2; 31°7′N, 105°16′W), approximately 120 km southeast of El Paso, lies within the Chihuahuan Desert of Texas (Figure 1) in northwest Eagle Flat Basin. Northwest Eagle Flat Basin, a closed topographic depression approximately 500 km^2 in area, is a sediment-filled basin within the Basin and Range physiographic province (Gile et al. 1981). The unsaturated zone ranges from 198 to 230 m in thickness at the proposed site. The regional climate is subtropical arid (Larkin and Bomar 1983). Mean annual precipitation is 317 mm for a 25 year record.

The main geomorphic features are the drainage areas, including Blanca Draw and Grayton Lake playa; interdrainage areas, including basin-fill deposits and eolian sheets; and localized topographic depressions, such as a gully in Blanca Draw and a fissure in the interdrainage area (Figure 1). Blanca Draw, the axial drainage

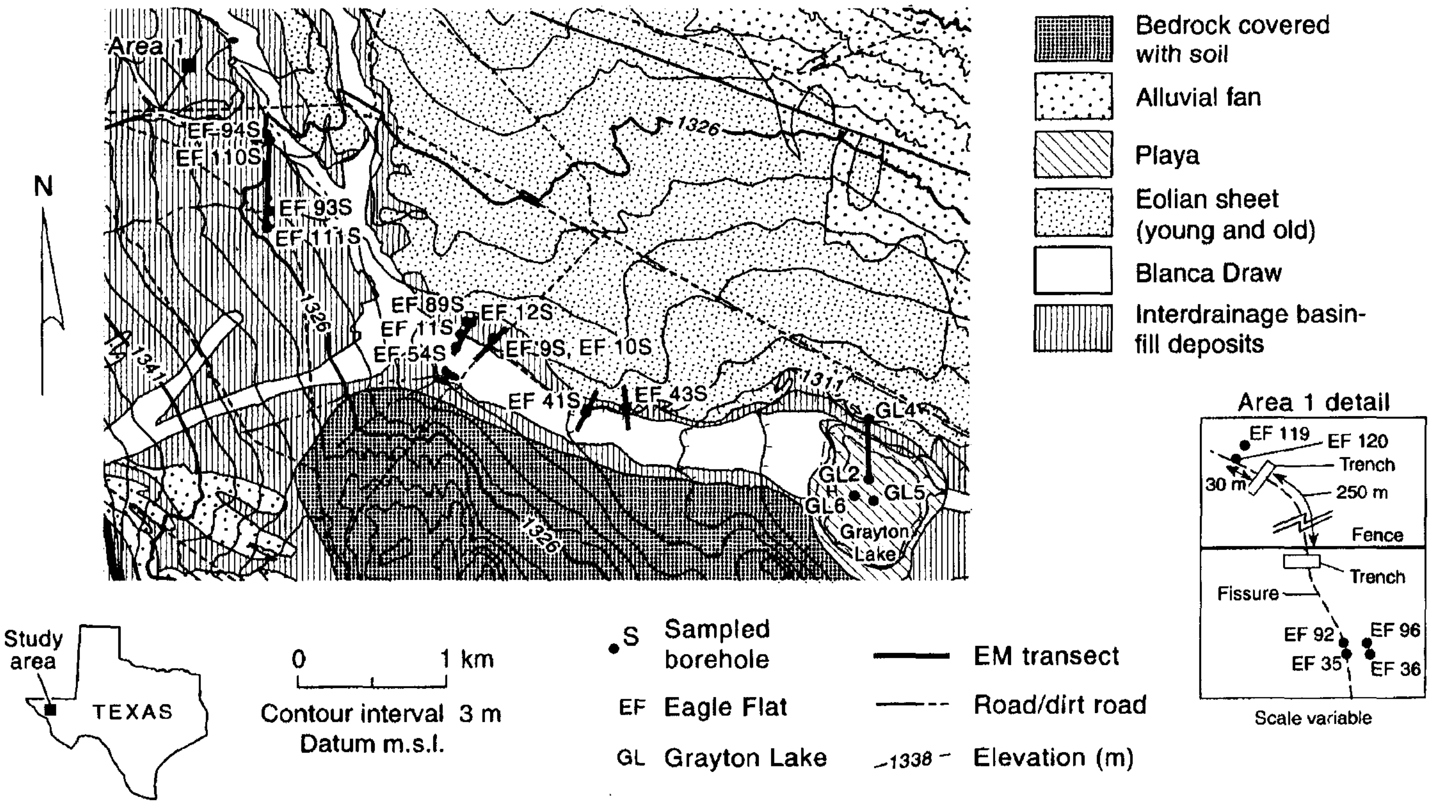

Figure 1. Location of electromagnetic induction transects and sampled boreholes relative to surface geomorphic settings in Eagle Flat Basin.

Table 2

Weighted Means (Equation 2) and Ranges of Water, Chloride, and Clay Contents Calculated from Analyses of Sediment Samples in the Upper 6 m from Sampled Boreholes and EC_a Measured with the EM31 Meter (Vertical Dipole Mode)

Borehole No.	Geomorphic Setting	No. of Samples	Water Content Mean (Range) (g g^{-1})	Chloride Content Mean (Range) (mg Cl kg^{-1} Sediment)	Clay Content Mean (Range) (%)	EC_a (VD) Mean (Range) (mS m^{-1})
EF 94	gully	7	0.16 (0.07–0.21)	13 (5–47)	48 (42–63)	135
EF 110	Blanca Draw	18	0.13 (0.03–0.15)	5 (0–13)	45 (6–54)	30
EF 93	slope	11	0.09 (0.08–0.14)	602 (76–1137)	47 (35–57)	110
EF 111	interdrainage	20	0.10 (0.07–0.13)	318 (8–609)	45 (28–55)	50
EF 92	fissure	20	0.08 (0.05–0.13)	70 (2–280)	32 (9–50)	76–80
EF 96	10 m from fissure	12	0.06 (0.04–0.11)	216 (4–770)	27 (14–57)	61
EF 35	fissure	18	0.12 (0.04–0.20)	<10	24 (4–27)	
EF 36	10 m from fissure	17	0.08 (0.04–0.13)	511 (212–860)	39 (14–52)	
EF 120	fissure	16	0.12 (0.10–0.19)	2.4 (1–23)	32 (25–48)	
EF 119	10 m from fissure	18	0.07 (0.05–0.13)	246 (2–690)	37 (19–52)	
GL2	playa	14	0.15 (0.13–0.17)	59 (5–224)	63 (53–67)	66
GL4	eolian sheet	13	0.05 (0.03–0.11)	89 (1–391)	18 (6–44)	30

system for Eagle Flat Basin, is flanked by moderate slopes. A discontinuous gully in Blanca Draw ponds more frequently than the surrounding draw. The dominant vegetation in the studied area of Blanca Draw is scattered dense mesquite thickets interspersed with grasses and other shrubs. Thickly vegetated grass flats occur in the slope area adjacent to Blanca Draw. Blanca Draw drains into Grayton Lake playa (20 km^2), an ephemeral lake that was flooded between May 1992 and October 1993. When not flooded, it is sparsely vegetated with herbs. The floor of the playa consists of clay containing mud cracks resulting from shrink/swell of the sediment. An earth fissure is found in the interdrainage area. The term fissure refers to the alignment of discontinuous surface collapse structures or gullies; the underlying extensional feature is a fracture that is filled with sediment. The surface expression of the fissure is about 640 m long. Water ponds occasionally in the fissure.

Methods

The EM38 and EM31 ground conductivity meters (Geonics Ltd., Mississauga, Ontario) were used to measure EC_a of the subsurface (McNeill 1992). The characteristics of these instruments are described in Table 1. The EM38 meter senses the upper 0.75 m in the horizontal dipole (HD) mode and 1.5 m in the vertical dipole (VD) mode, whereas the EM31 meter senses the upper 3 m in the HD mode and 6 m in the VD mode. The instruments average the conductivity in the horizontal plane over a distance approximately equal to the length of each probe (~1 m for EM38; ~4 m for EM31). EC_a was measured using surface EM meters along transects perpendicular to the margin of Grayton Lake, to the fissure, and to Blanca Draw. The receiver/transmitter pair was parallel, rather than perpendicular, to the conductive structures such as the fissure to minimize the effect of lateral changes in conductive structures as described in Parasnis (1986). Measurement locations were spaced 10 m apart and all measurements were taken at the ground surface in both the HD and VD orientations.

To evaluate factors affecting EC_a measured with the surface-based conductivity meters, eight boreholes (10 to 27 m deep) were drilled along the transects and soil samples were collected for sediment texture, water content, and chloride content analysis (Figure 1). Textural analyses were conducted by sieving the ≥2 mm fraction, and the percentage of silt and clay was determined by pipette or hydrometer analysis. Gravimetric water content was determined by weighing and oven-drying the samples at 105°C for 24 hours. The volumetric water content was estimated by assuming a bulk density of 1500 kg m^{-3}. The chloride concentration and electrical conductivity of the water were determined on 3:1 dilutions of the sediment (mass of water added = three times mass of oven-dried sediment). Chloride concentrations and electrical conductivities of the original pore water were calculated by correcting for the dilution factor.

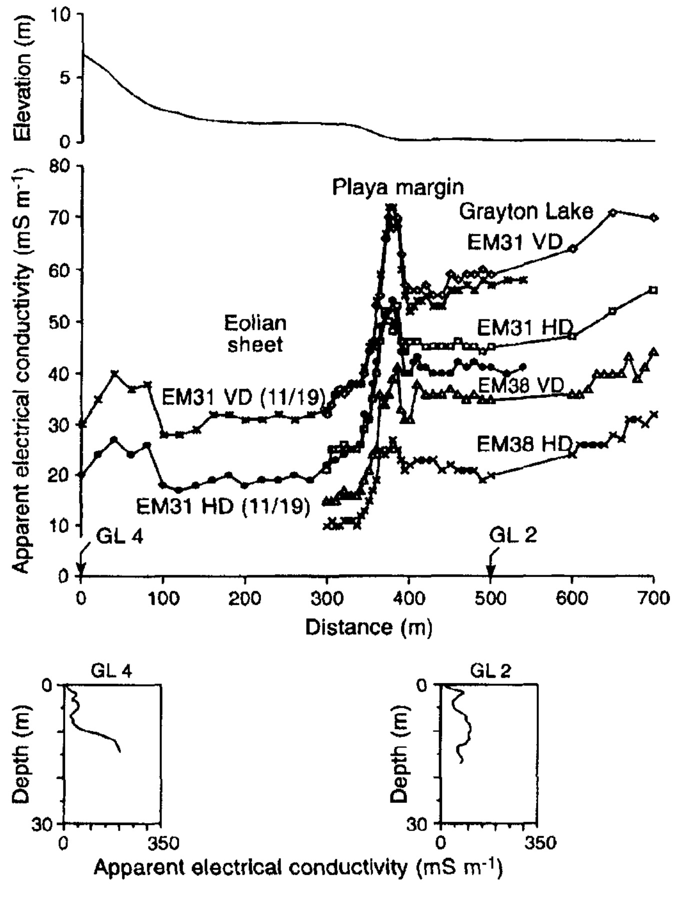

Figure 2. Variations in EC_a along a transect from the sand sheet adjacent to Grayton Lake to Grayton Lake playa measured with EM31 and EM38 ground conductivity meters (VD, HD) and downhole EC_a measured with the EM39 meter in boreholes GL 4 and GL 2. For location of transect, see Figure 1.

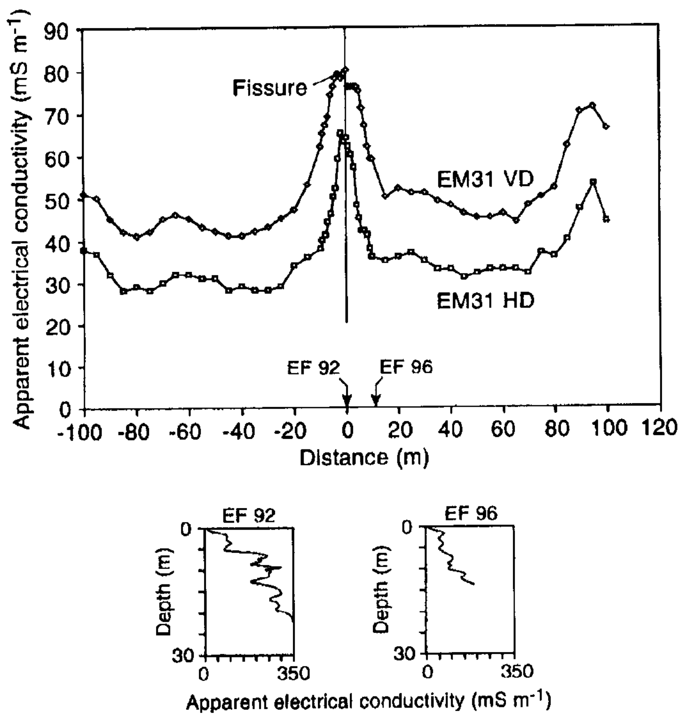

Figure 3. Variations in EC_a along a transect across the fissure measured with EM31 and EM38 ground conductivity meters (VD, HD) and downhole EC_a measured with the EM39 meter in boreholes EF 92 (fissure) and EF 96 (10 m from fissure). For location of transect, see Figure 1.

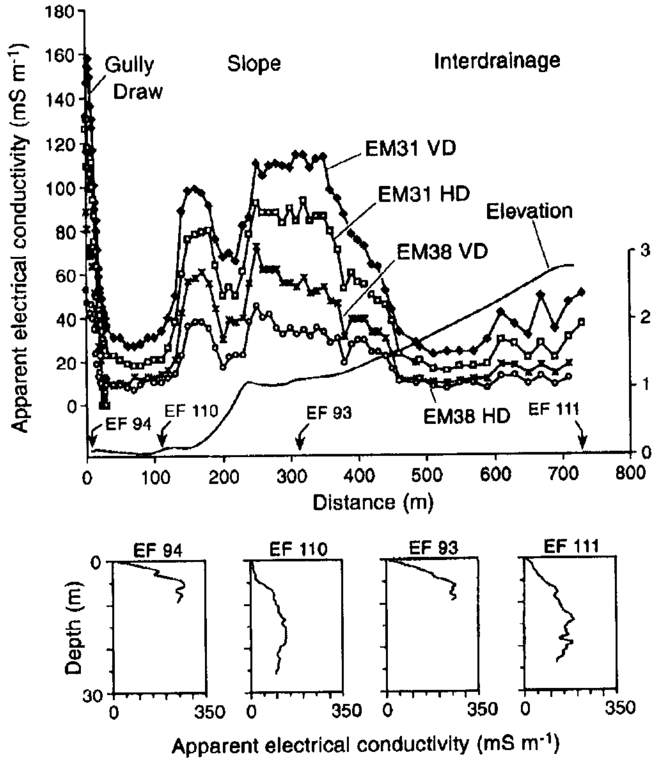

Figure 5. Variations in EC_a along a transect from Blanca Draw to the interdrainage area measured with EM31 and EM38 ground conductivity meters (VD, HD) and downhole EC_a measured with the EM39 meter in boreholes EF 94 (gully), EF 110 (Blanca Draw), EF 93 (slope), and EF 111 (interdrainage).

Downhole EC_a values were logged in eight uncased sampled boreholes (10 to 27 m deep; 0.18 m radius) shortly after the boreholes were drilled (Figure 1). The EM39 has an intercoil spacing of 0.5 m and penetrates 0.9 m into the surrounding sediments (Table 1). Conductivity measurements were taken at 25 mm intervals in the boreholes.

Data Analysis

We evaluated the factors affecting EC_a in two ways: (1) comparing EC_a measured with the aboveground EM31 meter with depth-weighted values of clay, water, and chloride content from borehole samples (Table 2); and (2) comparing EC_a measured with the downhole EM39 meter directly with values of clay, water, and chloride content at the sampled depths (Table 3).

Correlation coefficients were calculated between EC_a measured with the aboveground meter at the borehole locations and the measured values of clay, water, and chloride content of the sediment samples (Table 2). Because the penetration depth of the EM31 meter is greatest (~ 6 m), most comparisons were made with the EM31 data. The EM31 meter measures a depth-weighted average of conductivity:

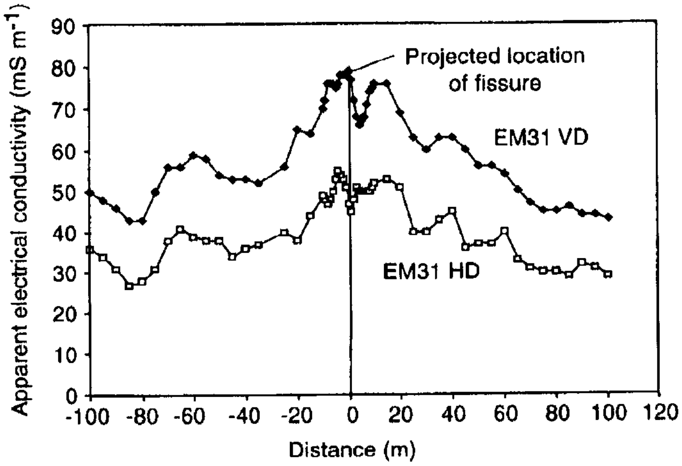

Figure 4. Electromagnetic induction transect measured with the EM31 meter (VD) across the projected line of the fissure, where there is no surface expression of the fissure. For location of transect, see Figure 1.

Table 3

Correlation Coefficients Between EC_a Measured with the EM39 Meter and Clay, Water, and Chloride Content in Soil Sampled from These Boreholes and Between Water Content and Clay Content.

Borehole No.	Geomorphic Setting	EC_a vs. Clay Content	EC_a vs. Water Content	EC_a vs. Chloride Content	Water Content vs. Clay Content
EF 94	gully	0.23	0.33	0.54	0.57
EF 110	Blanca Draw	0.44	0.74	0.76	0.86
EF 93	slope	0.54	0.66	0.18	0.93
EF 111	interdrainage	0.21	0.62	0.35	0.70
EF 92	fissure	0.58	0.75	0.90	0.52
EF 96	10 m from fissure	0.36*	0.58	0.36	0.90
EF 120	fissure	0.53	0.54	0.53	0.86
GL2	playa	0.09	0.61	0.01	0.83
GL4	eolian sheet	0.89	0.92	0.26	0.98

*All r values are significant at $\alpha = 0.05$ except those denoted by an asterisk.

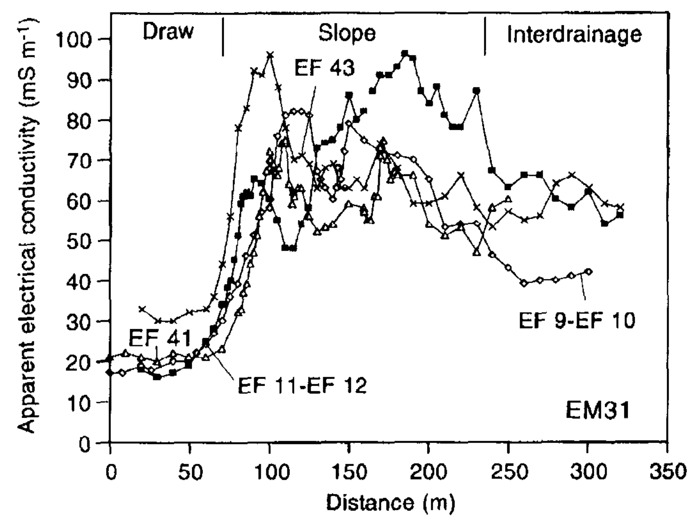

Figure 6. Variations in EC_a along transects at right angles to Blanca Draw measured with an EM31 ground conductivity meter (VD). For location of transects, see Figure 1.

$$EC_a = \int_0^\infty \phi(z)EC(z)dz \qquad (1)$$

where EC(z) is the electrical conductivity of the soil as a function of depth, and $\phi(z)$ is a weighting function that represents the depth-response function of the EM31 meter. At low induction numbers, the weighting function is independent of the conductivity of the soil (Wait 1982; McNeill 1980). The weighting function for the EM31 meter in the VD mode is

$$\phi_v(z) = \frac{4z}{(4z^2 + 1)^{3/2}} \qquad (2)$$

A depth weighted average of the clay, water, and chloride contents was calculated using the aforementioned linear weighting function. The data were used in a relative sense to compare changes in EC_a measured with the EM31 meter with variations in average parameters between boreholes. Borehole logging with the EM39 meter provided information on depth variations in EC_a at high resolution, which were compared with depth variations in clay, water, and chloride content (mg Cl kg^{-1} sediment) directly. Controls on EC_a measured with the EM39 meter were evaluated by plotting EC_a measured with the EM39 meter relative to clay, water, and chloride contents of the sediment samples and calculating correlation coefficients (Table 3).

Results and Discussion

Description of Surface EM Transects

Surface EM transects were conducted in three areas (playa/interplaya, fissure, and drainage/interdrainage) with EM31 and EM38 meters at different times. The following description focuses on the results of the EM31 meter. Values of EC_a measured with the aboveground meters generally ranged from 10 to 120 mS m^{-1} (EM31, VD mode) (Figures 2 through 6). Spatial variability in EC_a is generally related to geomorphic settings. Values of EC_a measured with the EM31 meter were highest in Grayton Lake playa (Figure 2), the fissure (Figure 3), and the gully in Blanca Draw (Figure 5) and decreased away from these settings. Values of EC_a in Grayton Lake and the fissure were as much as two times higher than EC_a values measured in the adjacent sediments (Figures 2 and 3). The original EM transect across the fissure was conducted where there was a gully at the surface. An additional transect was conducted parallel to the first transect where there was no surface expression of the fissure (i.e., no gully) to determine if the effect of the fissure extended away from the surface expression. Results of this transect showed high EC_a values similar to those recorded in the first transect (Figure 4). In the drainage, EC_a decreased sharply from the gully (EM31, VD maximum: 135 to 160 mS m^{-1}) to the surrounding draw (~ 30 mS m^{-1}; Figure 5). The gully is a topographic low and ponds water more frequently than the surrounding drainage area. Values of EC_a increased markedly from the draw, where mesquite trees are found, to the slope (EM31, VD ~ 65 to 110 mS m^{-1}), where grasses occur. High values of EC_a were found in an approximately 200 m section in the slope area parallel to Blanca Draw, and EC_a decreased gradually to lower values typical of the interstream mud deposits (EM31, VD: ~20 to 50 mS m^{-1}). Similar trends in ECa were found in four other transects at right angles to the Blanca Draw, i.e., low EC_a values were found in the draw and sharp increases in EC_a values in the adjacent slope areas (Figure 6).

The transects were conducted at different times of the year to determine whether EC_a changed over time (Figure 7). Values of EC_a did not vary significantly over time in the transect adjacent to

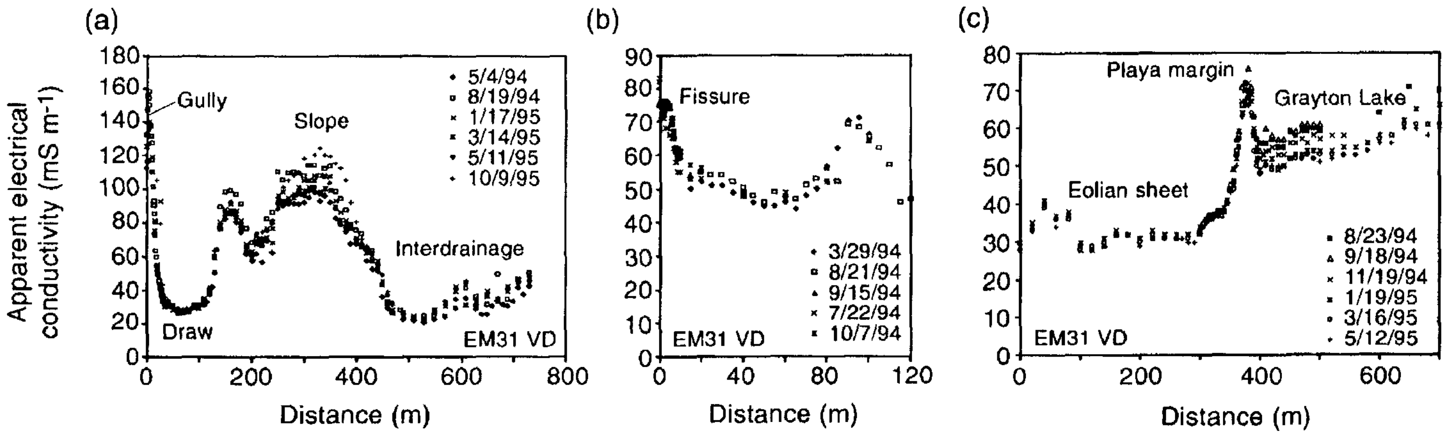

Figure 7. Temporal variations in EC_a measured with the EM31 meter at different times; (a) Grayton Lake playa, (b) the fissure, and (c) Blanca Draw.

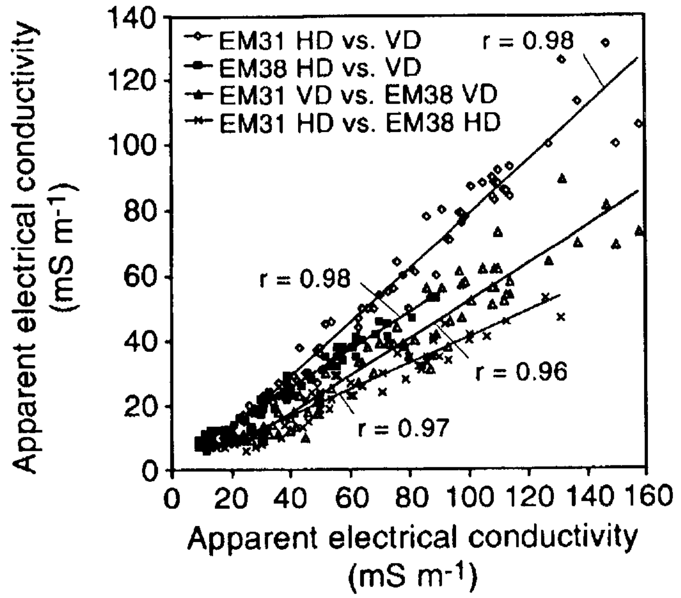

Figure 8. Relationship between EC_a measured with the EM31 and EM38 aboveground conductivity meters.

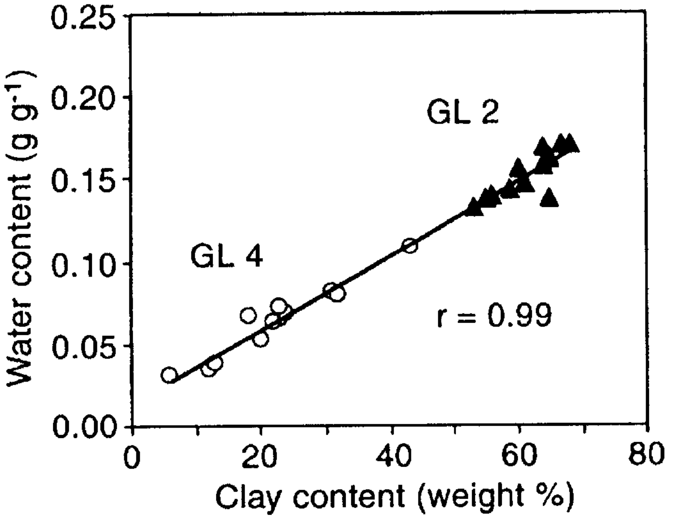

Figure 10. Relationship between water content and clay content in the upper 6 m of profiles in (GL 2) and adjacent to (GL 4) Grayton Lake.

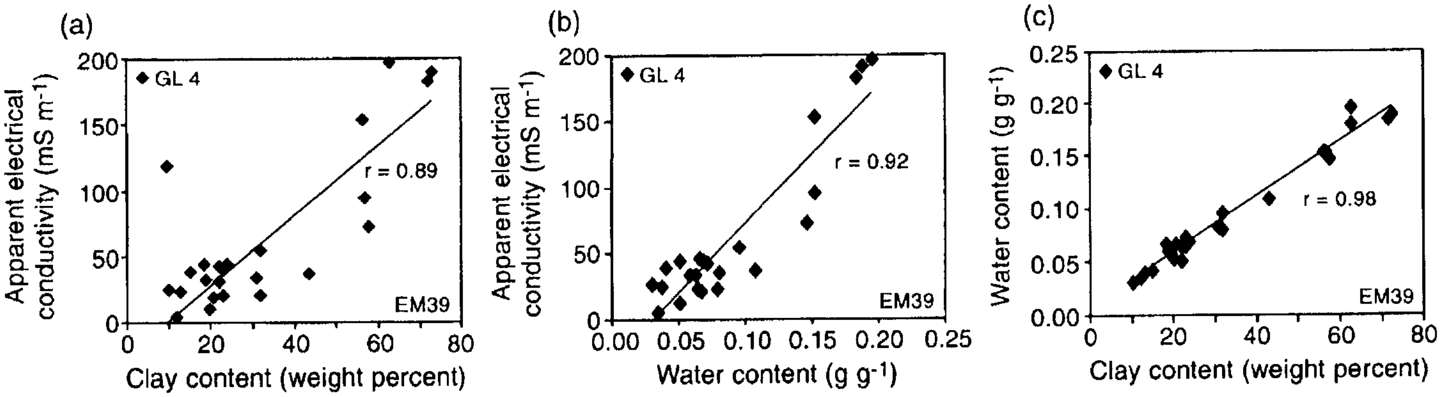

Figure 9. Relationship between EC_a measured with the downhole EM39 meter and (a) clay content, (b) water content, and (c) relationship between water content and clay content in samples from GL 4 adjacent to Grayton Lake.

Blanca Draw, although some large rainfall events occurred during the 1.5 years between the first and last transects (Figure 7a). Slight variations were measured in the slope and interdrainage area. The lack of large variations in EC_a in this transect is consistent with hydrologic data which suggests negligible water fluxes in the slope and interdrainage areas (Scanlon et al. 1999b). Temporal variations in EC_a in and adjacent to the fissure were negligible over long periods of time (Figure 7b). The largest temporal variations in EC_a were measured in Grayton Lake and suggest that it may be possible to use EM induction to evaluate temporal variations in water content in this setting (Figure 7c). In all transects the spatial trends in EC_a were maintained over time.

Trends in EC_a measured with the EM38 meter were similar to those recorded with the EM31 meter. The depths sensed by these meters are greater for the EM31 than for the EM38 and, for a given instrument, are greater in the VD mode than in the HD mode (Table 1). All transects show an increase in EC_a with depth (Figures 2 through 6). Values of EC_a measured with the EM meters in the horizontal and vertical dipole mode were highly correlated (Blanca Draw transect; EM31, r 0.98; EM38, r 0.98), and conductivities measured with the EM31 and EM38 meters were also highly correlated (HD, r 0.97; VD, r 0.96) (Figure 8). These data suggest that the EM38 and the EM31 meters can be used interchangeably. Because the range in EC_a values was greatest for the EM31 meter in the vertical dipole orientation, the EM31 meter provided the most sensitive indicator of spatial variations in EC_a at these sites. The increased range associated with the EM31 meter can be explained by the increase in EC_a with depth.

Factors Affecting Apparent Electrical Conductivity

Factors affecting EC_a, including clay, water, and chloride content, were investigated at three field sites: playa/interplaya, fissure, and drainage/interdrainage. Clay content was found to be the primary control on variations in EC_a in the playa/interplaya setting (Figure 2). The reduction in EC_a values measured with the EM31 meter in VD mode from the playa to the interplaya setting is attributed to a 71% decrease in weighted average clay content (Equation 2) and a 67% decrease in weighted average water content (GL 2 and GL 4; Table 2). In the profile adjacent to Grayton Lake (GL 4), the sediments change from sand sheet in the upper ~ 10 m to clay typical of playa sediments deeper in the profile (Scanlon et al. 1999a). Therefore, the depth variation in EC_a measured with the downhole EM39 meter in the profile adjacent to Grayton Lake is similar to the lateral variation in EC_a measured with

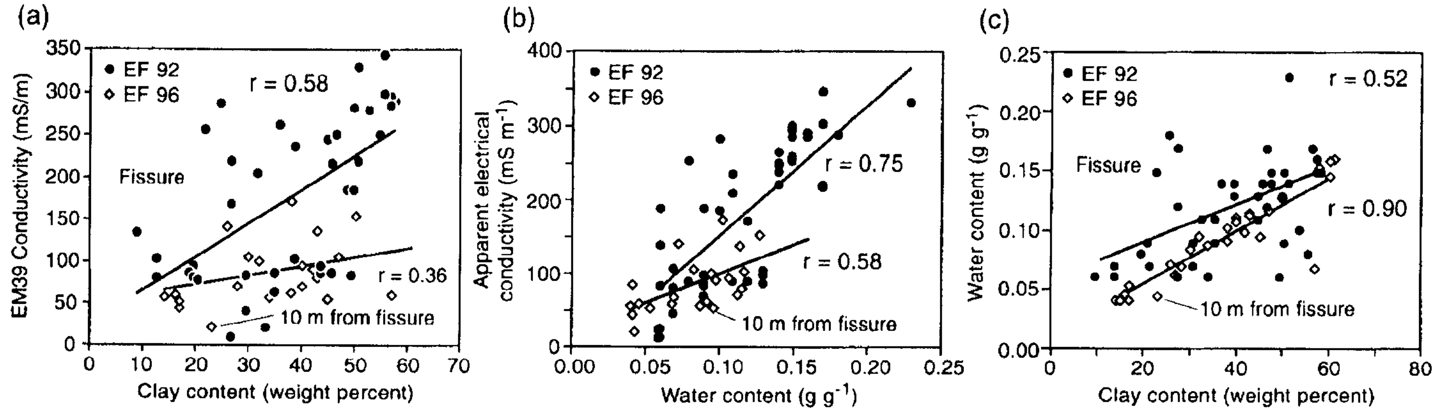

Figure 11. Relationship between EC_a measured with an EM39 meter and (a) clay content and (b) water content and relationship between water content and clay content for profiles in (EF 92) and 10 m away from (EF 96) the fissure.

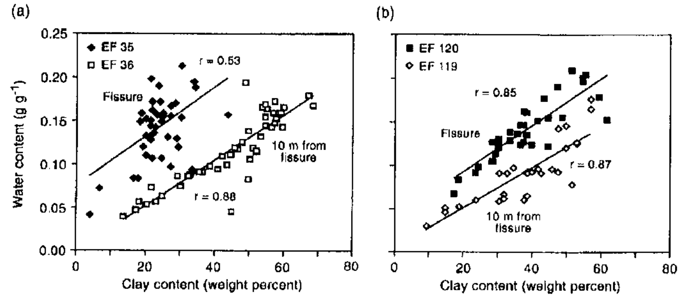

Figure 12. Relationship between water content and clay content in profiles in (EF 35, EF 120) and adjacent to (EF 36, EF 119) the fissure.

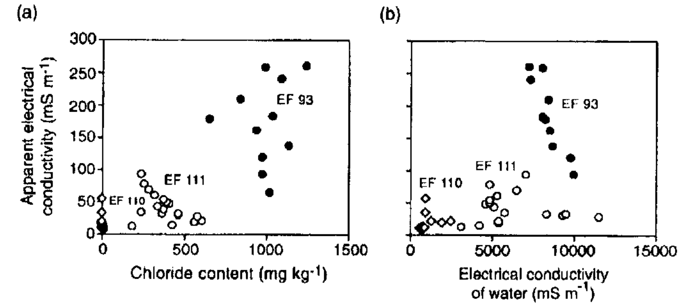

Figure 13. Relationship between EC_a measured with the EM39 downhole meter and (a) chloride content and (b) electrical conductivity of pore water (EC_w) in samples from EF 110 (draw), EF 93 (slope), and EF 111 (interdrainage).

the aboveground EM31 meter from interplaya to playa setting. Both the EM31 and EM39 instruments show similar response; low EC_a in the sand and high EC_a in the clay (Figure 2). The high correlation coefficient between water and clay contents in the samples from the profile adjacent to Grayton Lake (GL 4, r 0.98, Figure 9c; Table 3) indicates that the high correlation coefficient between EC_a and water content in this profile can be explained fully by variations in storage capacity associated with differing clay contents. The variation in clay and water contents within the GL 4 profile is similar to the lateral variation in clay and water content in the shallow sections (6 m) of the profiles in and adjacent to Grayton Lake (Figure 10). The correlation coefficient between water and clay content in samples from the upper 6 m of the profiles in and adjacent to Grayton Lake is also high (r 0.99; Figure 10) and confirms that variations in water content can be explained by differences in clay content.

Slightly higher weighted average clay contents (16%, upper 6 m) and higher water contents (25%) beneath the fissure (EF 92) relative to the profile adjacent to the fissure (EF 96) can explain the higher EC_a values measured with the aboveground EM31 meter in the fissure (Table 2; Figure 3). These increases in clay and water content are sufficient to offset the effect of a 68% reduction in weighted average chloride content (upper 6 m zone) in the fissure (EF 92) relative to the profile adjacent to the fissure (EF 96). Comparison of EC_a measured with the downhole EM39 meter with clay and water content for profiles in and adjacent to the fissure shows that higher clay and water contents contribute to the higher EC_a values beneath the fissure (Figure 11; Table 3). Several transects were conducted across the fissure, and in all cases EC_a was higher in the fissure than away from the fissure. Two other pairs of profiles were drilled in and adjacent to the fissure. Comparison of these profiles indicates that the weighted average clay contents beneath the fissure (EF 35, 24%; EF 120, 32%) are less than those adjacent to the fissure (EF 36, 39%; EF 119, 37%; Table 2). In addition, equations relating water and clay contents in all pairs of profiles indicate that similar clay contents have higher water contents beneath the fissure than adjacent to the fissure, and the intercepts of the equations are significantly different at α 0.05 probability level (Figures 11c, 12a, and 12b). Therefore, high EC_a values in the fissure are controlled by increased water content that reflects higher water flux in the fissure, and not simply variations in clay content.

Chloride content is the primary control on the high EC_a values measured with the EM31 meter in the slope area adjacent to Blanca Draw (EF 93; Figure 13). The high EC_a values measured in the slope (EF 93, 110 mS m^{-1}) relative to those in the adjacent draw (EF 110, 30 mS m^{-1}) and adjacent interdrainage area (EF 111, 50 mS m^{-1}) are attributed to the high chloride content in the slope area (EF 93, 602 mg kg^{-1}) relative to the draw (EF 110, 5 mg kg^{-1}) and the interdrainage area (EF 111, 318 mg kg^{-1}; Table 2). Weighted average clay content is similar in all three profiles (45 to 47%). The increase in chloride content from the draw to the slope is sufficient to offset the effect of the 31% reduction in weighted average water content from the draw to the slope. Weighted average water contents are similar in the slope and interdrainage areas (0.09 to 0.10 g g^{-1}). The 55% reduction in EC_a measured with the EM31 meter from the slope to the interdrainage area is similar to the

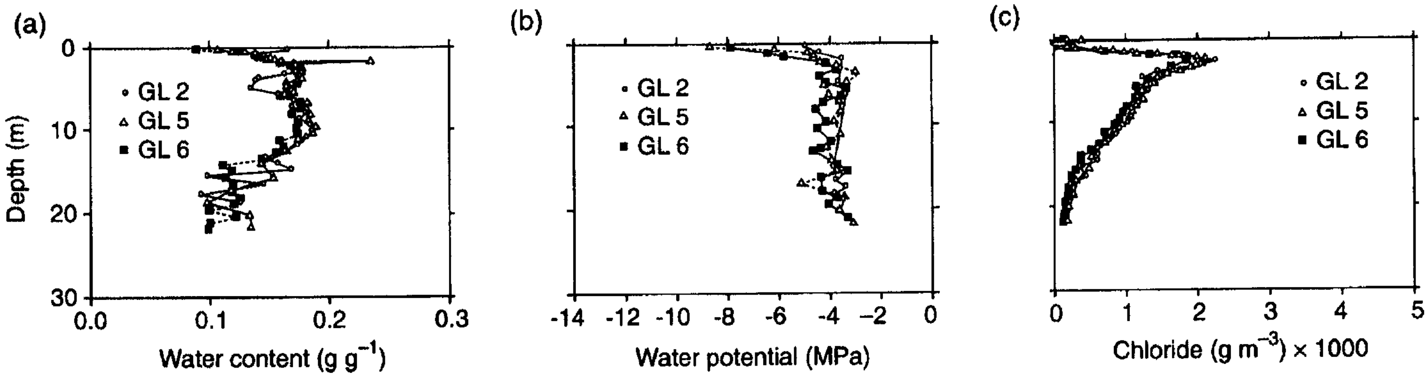

Figure 14. Uniformity in clay, water, and chloride content in borehole profiles (GL 2, 5, and 6) in Grayton Lake. For location of boreholes, see Figure 1.

47% reduction in mean chloride content. A plot of EC_a measured with the downhole EM39 meter versus chloride content and electrical conductivity of water (EC_w) for profiles in the draw, slope, and interdrainage area confirms that high chloride contents (corresponding to high EC_w) in the slope area control the high EC_a in this area (Figure 13).

Potential Use of Electromagnetic Induction for Unsaturated Zone Characterization Studies

Electromagnetic induction cannot be used on its own to characterize the unsaturated zone in areas where more than one parameter, such as clay, water, or chloride content, controls spatial variability in measured EC_a. In these areas, EM induction surveys have to be supplemented with borehole sampling to determine controls on EC_a. This study demonstrated that downhole EM39 logs are useful for direct comparison with sample analyses for clay, water, and chloride content to further evaluate controls on EC_a.

The use of surface EM induction for interpolation and extrapolation from point data provided by borehole samples was also shown in this study. The EM surveys showed that the zone of high chloride adjacent to the draw is not localized but is ~ 200 m wide and extends parallel to the draw for long distances. The similarity in EC_a transects where the fissure is exposed at the surface and in areas where the fissure is projected to occur but where there is no surface expression delineates the usefulness of EM induction for extrapolating borehole data and mapping the fissure. The uniformity of EC_a values across Grayton Lake suggested similar hydrologic conditions across the playa that were later confirmed with additional borehole data (Figure 14). Therefore, the combination of EM induction surveys and borehole data greatly enhances our ability to characterize spatial variability of various parameters.

Once the controls on EC_a have been established in an area it is important to evaluate the hydrologic significance of the controlling parameters. In the Eagle Flat Basin, primary controls on EC_a ranged from clay content in the playa/interplaya setting, water content in the fissure, and chloride content adjacent to Blanca Draw. Areas where EC_a is controlled by clay content may be hydrologically significant if clay content controls infiltration and recharge as found in an Australian study (Cook et al. 1992). In the Eagle Flat Basin, however, previous studies indicate that variations in clay content do not play a significant role in controlling infiltration (Scanlon et al. 1999a). Correlations between EC_a and water content are difficult to interpret; in many cases they simply reflect variations in clay content because clay and water contents are codependent, such as in the playa/interplaya setting. It is difficult to establish how much of the relationship between EC_a and water content reflects higher water flux unrelated to clay content variations in an area. Plots of water content versus clay content in and adjacent to the fissure showed that similar clay contents had higher water contents in the fissure; therefore, in this area the EM induction survey is mapping higher water flux, which is hydrologically significant. Differences in chloride content are extremely valuable in delineating water flux in unsaturated systems because chloride is readily leached in zones of high water flux and accumulates in areas of low water flux. Areas of high water flux are generally characterized by high water content, which results in high EC_a and low chloride content, which results in low EC_a. Therefore, the effects of water content and chloride content will compete with each other to control EC_a. In the fissured sediments, the effect of higher water content dominated over the effect of low chloride in controlling high EC_a. Chloride is a much more accurate indicator of high water flux in the fissure than water content because of the complexities of clay/water content codependence. The insensitivity of EC_a measured by the EM to chloride content could result from the water contents in sediments adjacent to the fissure that are below threshold water contents.

The limitations of EM induction in characterizing unsaturated systems in arid regions should also be recognized. In areas of below-threshold water contents, values of EC_a mapped with EM induction will be insensitive to variations in chloride content that could indicate zones of high water flux in the past. Because chloride takes a long time (thousands of years) to accumulate in the unsaturated zone, zones of low water content and low chloride content may indicate past zones of higher water flux (Scanlon et al. 1999a). Therefore, uniform values of EC_a may not indicate hydrologically similar conditions if water contents are less than threshold water contents.

Conclusions

This study demonstrates the usefulness of EM induction for characterizing unsaturated flow in an arid setting. Primary controls on EC_a measured with EM induction meters include clay content in the playa/interplaya setting, water content in the fissure, and chloride content adjacent to Blanca Draw. Because of the variety of controls on EC_a in this study, EM induction has to be supplemented with borehole data to establish what is controlling spatial variability in EC_a. Spatial variability in EC_a provided valuable guidance for borehole location and allowed us to interpolate and extrapolate from the borehole data. The extension of high water flux associated with the fissure could be mapped in areas where there was no surface expression of the fissure. High chloride zones parallel to the draw could be delineated over large areas. The uniformity of hydrologic conditions in the playa suggested by uniform values of EC_a was confirmed by additional borehole sampling. The hydrologic significance of the factors controlling EC_a is variable. Spatial variability in clay content is not an important factor controlling infiltration at the Eagle Flat Basin. Effects of clay and water content on EC_a are difficult to interpret because of the codependence of these two parameters in many areas. Zones of high water flux are generally delineated by high water content and low chloride content which have opposite effects on EC_a. In this study, the effect of high water content dominated over the effect of low chloride on mapped EC_a in the fissured sediments. EM induction is insensitive to variations in chloride content in areas where water contents are below threshold values.

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