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OBSERVATIONS OF SPATIAL VARIABILITY OF SOIL-WATER PRESSURE IN A FIELD SOIL

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We observed field variability of soil-water pressure along a 290-m transect through a field near Socorro, New Mexico. Pressures were measured by 94 individual tensiometers permanently installed at 3-m intervals along the transect at a 0.3-m depth. To monitor the tensiometers, we used a single, digital-readout, pressure transducer that could be rapidly connected by inserting a hypodermic needle through the rubber stopper seal at the top of the tensiometer unit. With this monitoring system a series of pressure measurements for the entire transect could be completed in 30 min. The transect was monitored several times during a 2-wk period following a 13-mm rainfall.

The observations show a gradual increase of soil water tension over time and a high degree of spatial variability; the tension ranged from 0.15 to 0.7 bars at a given time. Covariance analyses of the pressure data show that the variations are spatially correlated over distances of at least 6 m. The variance of pressure is observed to increase with mean tension; this trend agrees with predictions from stochastic theory.

Soil scientists and hydrologists have long recognized the natural variability of soil hydrologic properties. In the past few decades, numerous field data of physical and chemical soil properties, such as conductivity, particle size, bulk density, moisture content, porosity index, pH, and EC, were collected to characterize their spatial variability in large areas. Summaries of these works are given by Coelho (1974), Bakr (1976), Gajem (1980), and Warrick and Nielsen (1980). In general, it has been reported that saturated hydraulic conductivity is log-normally distributed with a large degree of variability. The bulk density and the sand and clay particle-size have a frequency distribution close to normal. Warrick et al. (1977) reported that a parameter, β, of a hydraulic conductivity-moisture content model has a log-normal frequency distribution.

Recent field studies showed that variation of soil hydrologic properties is not spatially independent. Bakr (1976) reported that, the variation of permeability of the Mt. Simon Sandstone aquifer in Illinois in the vertical profile is correlated for a distance of about 1 m. Smith (1978) found that the correlation scale of saturated hydraulic conductivity of the Quadra Sand unit, Vancouver, B.C., is anisotropic. Sisson and Wierenga (1981) also reported the presence of correlation structure in steady-state infiltration rates. Vieira et al. (1982), using a semivariogram technique, concluded that the steady infiltration rate is correlated over approximately 40 m. The presence of correlation structure in other soil hydrologic properties, such as the water entry value, saturated water content, residual water content, and pore-size distribution parameter, was also reported by Russo and Bresler (1981). The field study by Byers and Stephens (1983) demonstrated that both hydraulic conductivity and d_{10} parameters in a fluvial sand deposit exhibit greater variability in the vertical than in the horizontal direction. It also indicated the similarity between the correlation scales and stratigraphy in the field.

However, field variability of soil-water pressure has not been extensively explored in the past decades. Furthermore, a recent stochastic analysis of effects of field heterogeneity on unsaturated flow (Yeh et al. 1985*b,c*) revealed that the variation of soil-water pressure increases with mean moisture content. This paper provides field observations of spatial variation of soil-water pressure to support our theory and hypothesis that soil-water pressure spatial variances could increase significantly as soil becomes less saturated. Furthermore, this study demonstrates the application of a recently de-

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veloped hand-held transducer system for monitoring soil-water pressure variation in a large area.

MATERIALS AND METHODS

Site description

This field study was carried out at the Herkenhoff farm, which is located about 20 km north of the city of Socorro in central New Mexico. The site was chosen because it was relatively flat, was irrigated frequently, and was cultivated with relatively uniformly distributed alfalfa. The soil at the study site where the transect (AA′ in Fig. 1) was located is classified as Glendale clay loam and Agua loam by the Soil Conservation Service. According to the soil permeability map (Fig. 1, Duffy et al. 1981), the soil permeability ranges from 0.33 to 1.52 and from 3.30 to 5.08 cm per h for Glendale clay loam and Agua loam, respectively.

Monitoring device

To characterize the spatial variation of soil-water pressure, a large number of simultaneous observations in a large area are necessary. Conventional soil-water-pressure-monitoring devices, such as mercury-water manometer-type tensiometers, are inconvenient to install and use. Moreover, because of their slow response, they may observe the temporal variation of the pressure in addition to the spatial variation, if a large number of measurements are to be taken. Thus, a recent technique for a "simultaneous" measurement of soil-water pressure in a large area was used to minimize the temporal variation.

The principle of the monitoring device (Soil Measurement Systems, 1906 South Espina, Las

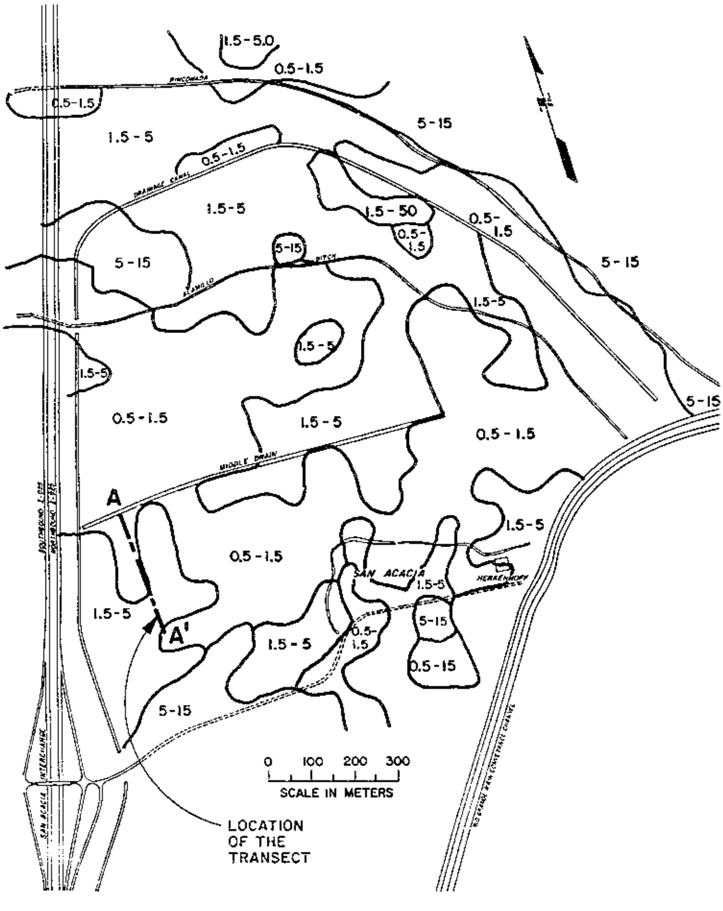

FIG. 1. Map showing the location of the transect, AA′, and soil permeability distributions in cm/h (*after Duffy et al. 1981*).

Cruces, New Mexico) is based on the design by Marthaler et al. (1983). It consists of a tensiometer, a transducer, and a digital-readout device. The tensiometer is made of a porous ceramic cup glued to a 30.5-cm-long PVC pipe of 2.2-cm o.d. and a 6.4-cm length of clear Plexiglas of 1.3-cm i.d. connected to the other end of the PVC pipe. The tensiometer is filled with water to about 2.5 cm below the top. A serum rubber stopper, allowing insertion of hypodermic needles, then seals the top of the tensiometer unit. The transducer and pressure indicator used for the present study are the Druck products, DPCR10/F, and DOI201, respectively. Both units are powered by a rechargeable battery. The transducer is screwed on a brass housing on which a hypodermic needle of 0.48-mm o.d. is mounted. The housing is designed in such a way that a minimal clearance (about 0.05 cm^3 in volume) between the bottom of the housing and the top of the diaphgram in the transducer is obtained.

A volume of 3.2 cm^3 air is retained in the tensiometer to offset the change in pressure due to the insertion of the hypodermic needle. To test if this amount of air is adequate to buffer the disturbance in this field study, a simple analysis based on the ideal gas law was employed. If soil-water pressure to be measured is 0.5 bars (absolute pressure), and the volume of air in the transducer unit is 0.05 cm^3, the analysis shows that the new equilibrium soil-water pressure after the insertion is 0.504 bars. The insertion of the needle thus results in a change of soil-water pressure of the magnitude of 4 cm of water in pressure. Similarly, at 0.95 bars of soil-water pressure, the pressure measured is 0.9507 bars. Therefore, the changes of pressure in these cases are relatively small, as far as our field investigation is concerned (see also Marthaler et al. 1983). The same conclusions were obtained in both field and laboratory tests. Thus, it was concluded that the present design of the tensiometer unit is adequate to monitor the spatial variability of soil-water pressure.

Procedures

All the assembled tensiometers were tested for leaks before field installation. The test was carried out by submerging each tensiometer in water and applying positive pressure, up to 1.5 bars, to the unit. If any leak occurred at this pressure range, the tensiometer was considered defective. All the intact tensiometers then were filled with water up to 2.54 cm below the top and sealed with rubber septum stoppers. This left a volume of air of 3.2 cm^3 in the tensiometer to buffer the disturbance due to insertion of the hypodermic needle.

Holes 2.22 cm in diameter and 30.5 cm deep were prepared along the transect by a coring tool. To ensure a tight contact between the ceramic wall and surrounding soil, a slurry made of water and cored soil was poured into the hole before the tensiometer unit was installed.

Prior to the measurement, the transducer and readout device were calibrated with air-mercury and water-mercury manometers to compensate for the fluctuation of atmospheric pressure and temperature effects. However, in most cases, the calibration was not necessary because variation in these two factors is relatively insignificant.

Leaks in the rubber stopper may occur after it has been punctured several times. This type of leakage is evident when a significant drop of water level in the tensiometer is observed after measurements. To prevent air leaking through the rubber stopper, silicon rubber was applied to the punctured rubber stopper after each insertion.

RESULTS AND DISCUSSION

We installed 94 tensiometers along the transect at intervals of 3 m and at a depth of 0.3 m in the alfalfa field during a no-crop and no-irrigation period. Measurements began a week after installation, a period that allowed the slurry to dry out and allowed the tensiometer to equilibrate with the surrounding soil. Four space series were obtained in 2 wk. The first measurements were carried out on 2 December 1981, 2 d after a rain of 13 mm. The time span required to complete each series was about 30 min. Most of the measurements were conducted at 1500 h; the four space series are shown in Figs. 2a, 2b, 2c, and 2d. These data are the vacuum pressure values registered on the pressure indicator. They are neither corrected for the hydrostatic pressure in the tensiometer nor adjusted according to calibrations. From Fig. 2 it is evident that the spatial variation of soil-water pressure is significant, and that the variation is associated with strong trends. The pressure readings at the first 150 m tend to be much higher than the rest of the pressure readings. Due to the presence of the trend, the series were separated into two

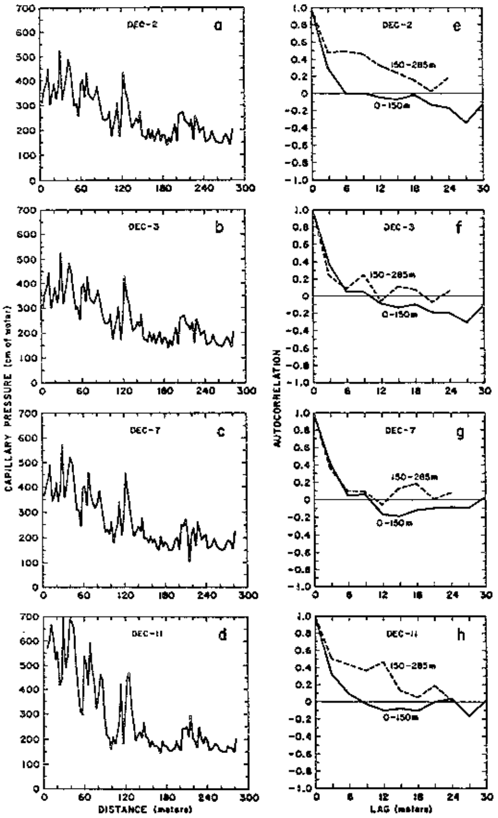

FIG. 2. Space series observed on 2, 3, 7, and 11 December 1981 and corresponding correlograms.

sections for estimation of their statistical properties. The first section consists of data from the first 50 measurements. The second section contains the rest. Estimated standard deviations and means of these series are given in Table 1. Note that the variance of the soil-water pressure head increases with its mean. In other words, the drier the soil is, the larger the variance of pressure head. This mean-dependent behavior demonstrates the nonstationary nature of the soil-water pressure. To illustrate that the variability of the pressure is correlated in space, an autocorrelation analysis was also carried out. Because of the presence of the strong trends in the first section of each space series, before carrying out the autocorrelation analysis, the data were detrended by using a linear regression model. Ten lags were used in estimating the autocorrelation functions for the first section of the series. No trends were removed from the second section of the data, and eight lags were used because of the length of the data set. The estimated autocorrelation functions of the two sections of each space series are illustrated in Figs. 2e, 2f, 2g, and 2h.

Statistical analyses of soil-water pressure data collected by Fritton (1981) in a corn field in Pennsylvania also revealed similar findings in soil-water spatial variation. However, no detailed description of the field site was available. The standard deviations and means from Fritton's field data are presented in Table 1, along with those obtained from this field study. A variogram showing the correlation structure of the soil-water data is illustrated in Fig. 3. Table 1 shows that the variation of soil-water pressure in the corn field is also a function of the mean soil-water pressure.

The results of the field study seem to agree with the result derived from the stochastic analysis of unsaturated flow through heterogeneous soil by Yeh et al. (1985*b*,*c*). They reported that variance of the soil-water pressure, σ_ψ^2 can be expressed as

$$\sigma_\psi^2 = (\sigma_f^2 + \sigma_\alpha^2 \bar{\Psi}^2)\, \lambda_1^2\, G(\rho, \alpha\lambda_1, \theta) \qquad (1)$$

where σ_f^2 and σ_α^2 are the variances of saturated hydraulic conductivity, and α is a parameter that is the decay constant of unsaturated hydraulic conductivity. $\bar{\Psi}$ is the mean soil-water pressure; $\bar{\alpha}$ is the mean α parameter. The aspect ratio, ρ, is the ratio of horizontal correlation scale, λ, to vertical correlation scale, λ_1. θ is the orientation

TABLE 1

Means and standard deviations of soil-water pressures in two fields

Location	Mean	Standard deviation cm of water
Socorro, N.M.	162	22
	185	33
	186	35
	187	36
	325	80
	334	137
	336	95
	402	170
A cornfield in Pennsylvania	1200[a]	470
	2000[a]	1000
	4400[a]	2800
	8980[a]	7140

[a] Estimated from the data collected by Fritton (1980).

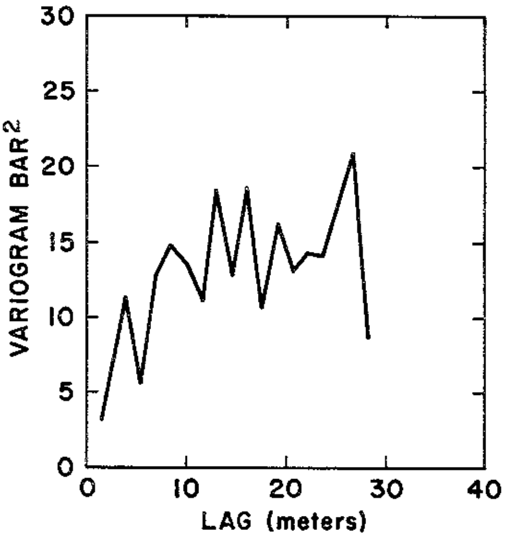

FIG. 3. Variogram calculated from Fritton's field data.

angle of the stratification. G is a complicated mathematical function that depends upon ρ, $\bar{\alpha}\lambda_1$ and θ (see Yeh et al. 1985*b*). Note that σ_f^2, σ_α^2, λ_1, λ, and $\bar{\alpha}$ are constant for a field of interest, and $\bar{\psi}$ will vary as the soil moisture condition changes. It can vary from zero to thousands of centimeters of water. Thus, Eq. (1) shows that the major contribution to the soil-water pressure variance is the product of the mean soil-water pressure square and the variance of the parameter. Because the mean soil-water pressure in the first sections of the space series is high, its variance is large accordingly. The soil in the second section is moister, however, and the mean soil-water pressure is low. Thus, from Eq. (1) its variance is small.

It should be emphasized that there were no visible crops and no irrigation water was applied, except the 13-mm rainfall, during the observation period. It is also evident from the persistent variability of soil-water pressure in each series observed at different dates, that the variability of observed soil-water pressure due to instrumental error is minimal. Note that the standard deviations of the measured pressures are ranging from 22 to 170 cm of water, which are much greater than errors in the transducer (Trotter 1984). Thus, the observed spatial variability of soil-water pressure can be attributed to the variability of soil hydrologic properties, such as saturated hydraulic conductivity and pore-size distribution parameters. The variations in these parameters may be due to variation in soil texture and the presence of cracks and biopores. Although the soil permeability map (Fig. 1) shows that the variation in soil permeability along the transect may range from 0.33 to 1.6 cm/h, the variation of the α parameter, which is the major cause of the variation in soil-water pressure as indicated in Eq. (1), was not available. Note that the soil permeability map was constructed by relating soil permeability to soil texture (Duffy et al. 1981). We conjecture that high mean soil-water pressures may result from the presence of sandy soil in the first part of the transect. These may also be due to a lower water table in the section, which is adjacent to an irrigation drainage ditch. However, no soil samples were taken to verify the hypothesis or to estimate the parameters needed to quantitatively assess the predictability of the stochastic model, Eq. (1). Nevertheless, the result of the field observations of soil-water pressure variability agrees with Fritton's field data and also supports the theoretical results.

CONCLUSIONS

From the results of this field experiment, we conclude that

1. The handheld transducer system used in the study is a useful tool for monitoring the spatial variation of soil-water pressure in a large area. It also can be used in other practical applications. The response of the device is fast, and the accuracy is as good as any other conventional device.
2. There is a large spatial variation in soil-water pressure. The variation is spatially correlated and dependent upon its mean value. This finding agrees with other field observations of soil-water pressure spatial variability. Furthermore, it supports the hypothesis obtained from a stochastic analysis that the variation of soil-water pressure is mean-dependent.

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