Estimating Soil Matric Potential in Owens Valley, California

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Prepared in cooperation
with Inyo County and the
Los Angeles Department
of Water and Power

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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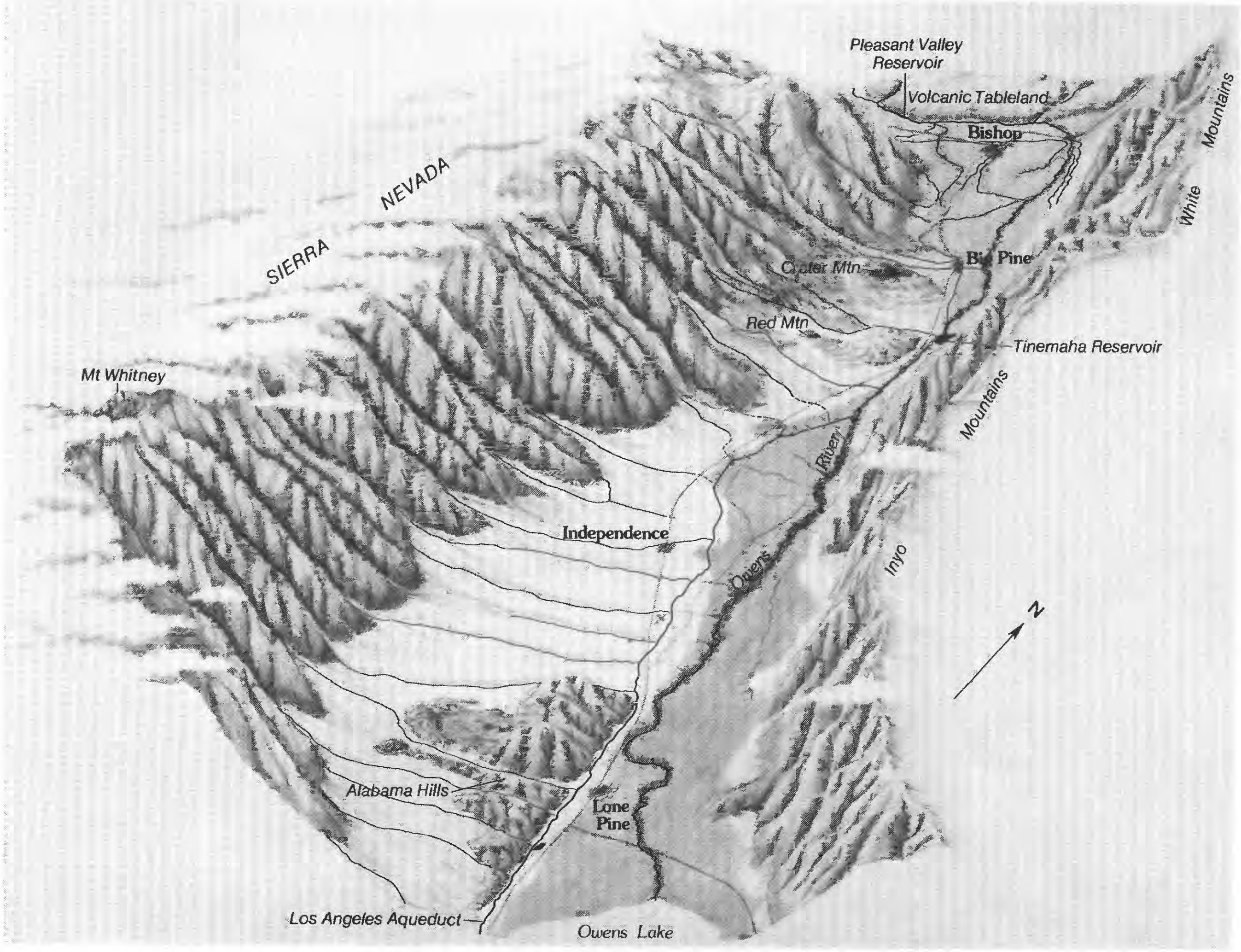
ESTIMATING SOIL MATRIC POTENTIAL IN OWENS VALLEY, CALIFORNIA



Vertically exaggerated perspective and oblique view of Owens Valley, California, showing the dramatic change in topographic relief between the valley and surrounding mountains.

Chapter C

Estimating Soil Matric Potential in Owens Valley, California

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Prepared in cooperation with
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HYDROLOGY AND SOIL–WATER–PLANT RELATIONS IN OWENS VALLEY, CALIFORNIA

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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Conversion Factors

For readers who prefer to use inch-pound units rather than metric (International System) units used in this report, the following conversion factors may be used.

Multiply metric unit	By	To obtain inch-pound unit
cm (centimeter)	0.3937	inch
g (gram)	0.03527	ounce, avoirdupois
	0.002205	pound, avoirdupois
g/cm^3 (gram per cubic centimeter)	62.43	pound per cubic foot
km (kilometer)	0.6214	mile
kPa (kilopascal)	0.1450	pound per square inch
m (meter)	3.281	foot
m^2 (square meter)	10.76	square foot
m^2/g (square meter per gram)	304.93	square foot per ounce
mm (millimeter)	0.03937	inch

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F=1.8(°C)+32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Estimating Soil Matric Potential in Owens Valley, California

By Stephen K. Sorenson, Reuben F. Miller, Michael R. Welch,
David P. Groeneveld,[1] *and* Farrell A. Branson

Abstract

Much of the floor of Owens Valley, California, is covered with alkaline scrub and alkaline meadow plant communities, whose existence is dependent partly on precipitation and partly on water infiltrated into the rooting zone from the shallow water table. The extent to which these plant communities are capable of adapting to and surviving fluctuations in the water table depends on physiological adaptations of the plants and on the water content, matric potential characteristics of the soils. Two methods were used to estimate soil matric potential in test sites in Owens Valley. The first, the filter-paper method, uses water content of filter papers equilibrated to water content of soil samples taken with a hand auger. The previously published calibration relations used to estimate soil matric potential from the water content of the filter papers were modified on the basis of current laboratory data.

The other method of estimating soil matric potential was a modeling approach based on data from this and previous investigations. These data indicate that the base-10 logarithm of soil matric potential is a linear function of gravimetric soil water content for a particular soil. The slope and intercepts of this function vary with the texture and saturation capacity of the soil. Estimates of soil water characteristic curves were made at two sites by averaging the gravimetric soil water content and soil matric potential values from multiple samples at 0.1-m depth intervals derived by using the hand auger and filter-paper method and entering these values in the soil water model. The characteristic curves then were used to estimate soil matric potential from estimates of volumetric soil water content derived from neutron-probe readings.

Evaluation of the modeling technique at two study sites indicated that estimates of soil matric potential within 0.5 pF units of the soil matric potential value derived by using the filter-paper method could be obtained 90 to 95 percent of the time in soils where water content was less than field capacity. The greatest errors occurred at depths where there was a distinct transition between soils of different textures.

INTRODUCTION

In the early 1900's, planners for the rapidly growing city of Los Angeles saw Owens Valley as a long-term, plentiful supply of water. The city purchased most of the land in Owens Valley, and in 1913 an aqueduct was completed that diverted surface water from Owens Valley to Los Angeles. In addition, a series of wells were constructed to supply ground water to the aqueduct during periods of low surface-water runoff. Subsequent extensions of the original aqueduct and construction of a second aqueduct, completed in 1970, have increased the quantity of water diverted. Diversion of surface and ground water from Owens Valley has caused numerous conflicts over the years between the city of Los Angeles and the residents of Inyo County (Smith, 1978). A central focus of these conflicts is the effect of surface- or ground-water diversions on the native vegetation on the valley floor. Lowering of water tables due to pumping or to diversion of surface water that recharges ground water would decrease productivity of existing vegetation and cause a decrease in vegetation cover in plant communities that require the shallow water table (Los Angeles Department of Water and Power, 1979).

In 1982 the U.S. Geological Survey, in cooperation with Inyo County and the Los Angeles Department of Water and Power, began a series of comprehensive studies to define the ground-water system in Owens Valley and to determine what effect ground-water withdrawals might have on native vegetation. These studies, termed the Owens Valley ground-water and plant-survivability studies, are discussed more fully by Hollett (1987). The results of the studies, as well as a comprehensive summary, are presented in a U.S. Geological Survey Water-Supply Paper series as the interpretive products of the studies become available. The series consists of eight chapters as follows:

A. A summary of the hydrologic system and soil–water–plant relations in Owens Valley, California, 1982-87, with an evaluation of management alternatives.

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[1] Inyo County Water Department, Bishop, California.

B. Geology and water resources of Owens Valley, California.
C. Estimating soil matric potential in Owens Valley, California (this report).
D. Osmotic potential and projected drought tolerances of four phreatophytic shrub species in Owens Valley, California.
E. Estimates of evapotranspiration in alkaline scrub and meadow communities of Owens Valley, California, using the Bowen-ratio, eddy-correlation, and Penman-combination methods.
F. Influence of changes in soil water and depth to ground water on transpiration and canopy of alkaline scrub communities in Owens Valley, California.
G. Vegetation and soil water responses to changes in precipitation and depth to ground water in Owens Valley, California.
H. Numerical evaluation of the hydrologic system and selected water-management alternatives in Owens Valley, California.

Purpose and Scope

This report describes the methods used to estimate soil ψ_m (matric potential) in Owens Valley soils. The study consists of four major components: (1) recalibration of the wide-range filter-paper method (McQueen and Miller, 1968), (2) development of a soil water characteristics model based on data derived from the filter-paper method, (3) calibration and evaluation of the model based on data from Owens Valley, and (4) application of the soil water characteristics model to estimate soil matric potential from estimates of volumetric soil water content (θ_v) derived using a neutron probe.

Background information needed to understand the terminology and techniques used in this study is presented.

Description of the Study Area

Owens Valley is between the Sierra Nevada and the White and Inyo Mountains (fig. 1). The relatively flat valley floor is about 190 km long and ranges in altitude from about 1,100 to 1,250 m. Mountains along the east and west sides of the valley rise 900 to 3,050 m from the valley floor. Owens Valley lies in the rain shadow area east of the Sierra Nevada and receives an average of 127 mm annual precipitation. Despite little precipitation, ground water is plentiful in the valley. Runoff from the Sierra Nevada snowpack percolates through the unconsolidated alluvial deposits along the valley margins, supplying most of the recharge to the ground-water system. The water table across much of the valley floor ranges from land surface to about 4 m below land surface. Ground water is within the reach of roots of phreatophytic shrubs and grasses that compose much of the valley-floor plant communities (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1986).

Plant Communities

Most of the natural vegetation on the floor of Owens Valley is an alkaline scrub or alkaline meadow community. These communities are composed primarily of the following species:

Alkaline scrub:
    Atriplex torreyi (Nevada saltbush)
    Chrysothamnus nauseosus (rubber rabbitbrush)
    Sarcobatus vermiculatus (greasewood)
    Atriplex confertifolia (shadscale)
    Sporobolus airoides (alkali sacaton)
    Distichlis spicata (saltgrass)
Alkaline meadow:
    Distichlis spicata (saltgrass)
    Sporobolus airoides (alkali sacaton)
    Juncus balticus (baltic rush)
    Chrysothamnus nauseosus (rubber rabbitbrush)

These plant communities use water transmitted into the rooting zone from the shallow water table to supplement infiltration of rainwater to the soil.

Predominant brush and grass species in the study area extract water preferentially from the near-surface area, where root densities are the greatest and nutrients are most available (Groeneveld and others, 1986). Additional water is available to the plants from the region of soil wetted by capillarity from the water table; however, this source is used secondarily to the water available in the near-surface area. In this sense, these plants do not perfectly fit the classic definition of phreatophytes that extract water from directly above the water table (Meinzer, 1923).

THEORY AND BASIC DEFINITIONS

Understanding of the principles and techniques evaluated in this report requires a clear definition of several basic terms and concepts commonly used in the literature of soil physics. This part of the text is provided for the purpose of defining these terms.

Soil ψ_m is the negative pressure potential in soil resulting from the affinity of water to the whole matrix of the soil, including its pores and particle surfaces together. Soil ψ_m is generally expressed in terms of energy per unit weight or hydraulic head, and because it is measured with respect to atmospheric pressure, it is always negative. A saturated soil at atmospheric pressure has a soil ψ_m of 0.0 kPa. A soil ψ_m of -20 kPa is greater than a soil ψ_m of -100 kPa. Soil ψ_m is usually referred to in units of pF in this report. Schofield (1935) defined pF units as the base 10 log of negative soil ψ_m, in centimeters of water. This

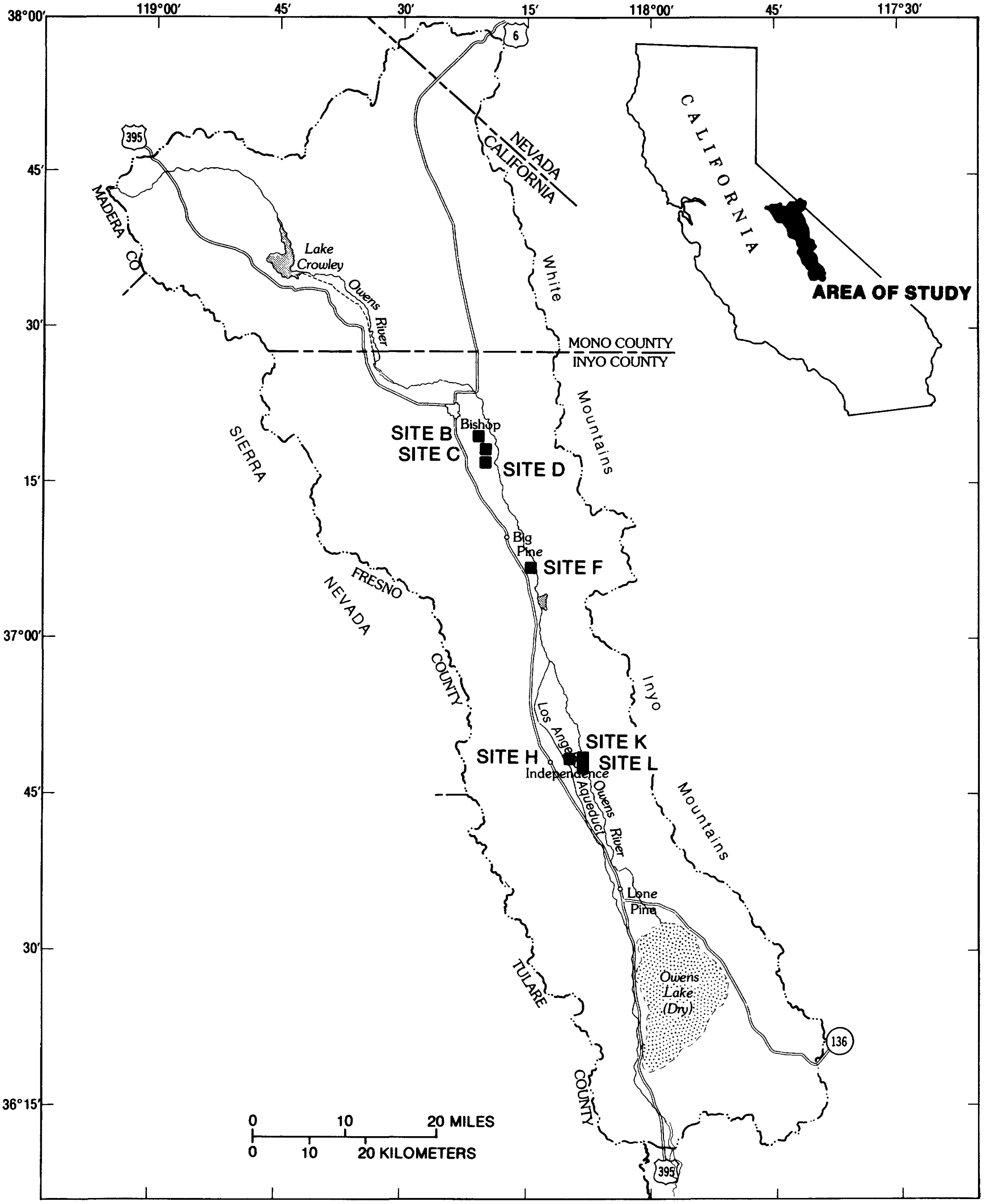


Figure 1. Location of study area and sampling sites.

logarithmic scale is used in this report, because the soil water model and calibration curves used for the filter-paper method use logarithmic correlation between water content and soil ψ_m. Soil ψ_m can be converted to kilopascal units by determining the base 10 antilog of the soil ψ_m and multiplying it by -0.098.

Soil ψ_m is one component of total water potential (ψ_w) defined as follows (Baver and others, 1972):

$$\psi_w=\psi_m+\psi_g+\psi_p+\psi_\pi+\psi_\Omega, \quad (1)$$

where

ψ_w is total water potential,
ψ_m is soil matric potential,
ψ_g is gravitational potential,
ψ_p is pressure potential,
ψ_π is osmotic potential, and
ψ_Ω is overburden potential.

Soil ψ_m is derived from two components, capillary and adsorptive. Capillary forces result from surface tension of water and its contact angle with particles (Hillel, 1982). Adsorptive forces result from the hydrogen bonding of polar water molecules with the oxygen atoms on soil particle surfaces. Water is adsorbed onto particle surfaces in layers. The first few molecular layers are held very strongly to particle surfaces by the adsorptive forces. Each succeeding layer is less strongly held. The relative importance of the two types of forces that make up soil ψ_m depends on the amount of particle surface area, soil structure (how the soil particles are packed, which determines the amount of void space), and the soil water content (Hillel, 1982). The capillary effect tends to predominate in sandy soils, which may have surface areas of less than 1 m^2/g of soil. The adsorptive forces predominate in finer textured soils with high percentages of clay, which may have surface areas as high as several hundred square meters per gram. In these soils, there is little void space that is not occupied by adsorbed water, and thus soil structure is usually insignificant in determining soil ψ_m. Regardless of the type of soil, when soil ψ_m is less than about -30 kPa, enough water has been removed from the soil so that adsorptive forces predominate to the extent that capillary force virtually can be ignored.

A characteristic curve is the relation describing the quantity of water retained by a soil at any equilibrium soil ψ_m. A driving force, such as gravity, applied to a saturated soil causes water to drain, starting with the largest pores. As the force increases, water will drain from smaller and smaller pores, and water adsorbed on particle surfaces also will begin to drain. The quantity of water retained by a soil in the higher potential range of between 0 and -30 kPa depends primarily on the pore-size distribution and is thus strongly affected by soil structure. Water retained at lower potentials is due increasingly to adsorption and is thus controlled primarily by particle surface area and less by soil structure (Hillel, 1982).

EXPERIMENTAL PROCEDURES

Design of Water-Table Drawdown Sites

To test the effect of shallow water-table drawdown on plants, four controlled-drawdown sites were established in 1984 to systematically draw down water levels in a local area. Two types of test sites were established, each designed to investigate different aspects of water-deficit stress caused by controlled dewatering (fig. 2). One type, designated a fast-drawdown site, was designed to rapidly lower the ground-water level 8 to 10 m, by pumping from a small cluster of wells. This pumping was to result in a cone of water-table depression. Vegetation sampling transects (length, 38 m) were at increasing distances away from the wells. Monitoring wells were drilled adjacent to all sampling transects to measure ground-water levels. Two fast-drawdown sites were established: site D about 8 km southeast of Bishop, and site K about 5 km east of Independence. The second type of site, designated a slow-drawdown site, was designed to lower water tables in annual increments of about 2 m. A constant water table was maintained under the test sites by pumping six wells surrounding the site. Two slow-drawdown sites were established: site B about 5 km southeast of Bishop, and site H about 4 km east of Independence.

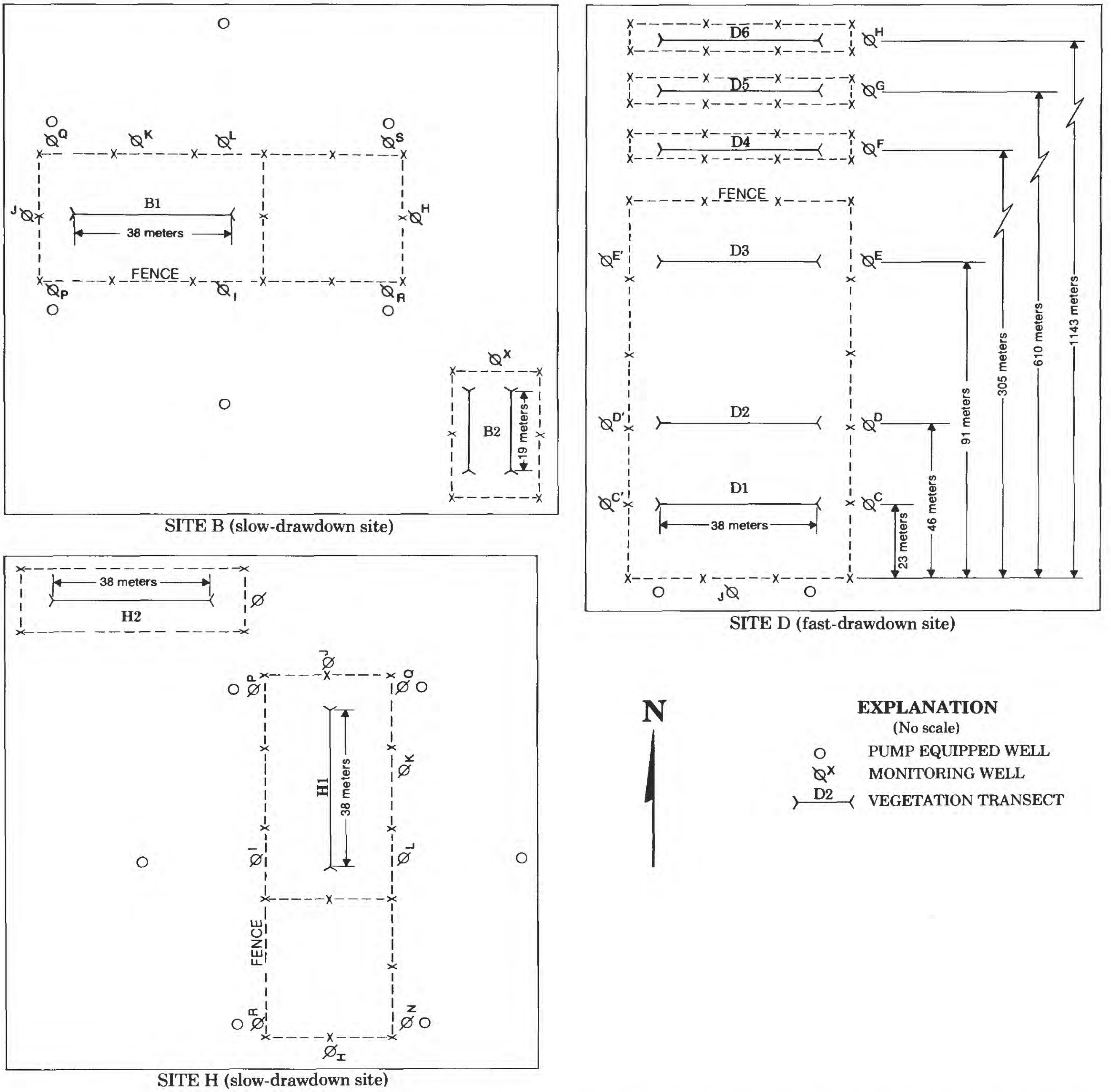
Filter-Paper Method

Most perennial plants in the shallow ground-water areas of Owens Valley are considered phreatophytic. However, they also have xerophytic characteristics in that they are capable of using water held in the shallow soil zone out of hydrologic contact with the water table to a minimum of $-2{,}000$ to $-3{,}000$ kPa. Because of the large variation of soil water characteristics in which these plants operate, the relation between soil ψ_m and plant response must be determined using a method of measuring or estimating soil ψ_m that covers a large variation of soil water content (θ). Many methods of determining soil ψ_m have been described (Hillel, 1982). Two common methods are tensiometers and thermocouple psychrometers.

Tensiometers consist of a porous ceramic cup connected with a manometer or suction gage through a tube filled with water. Because of the limitation of bulk water to sustain tension less than about -85 kPa, this method is usable only when soil ψ_m are greater than about -85 kPa. Tensiometers also require considerable maintenance in the field and are subject to significant error due to temperature gradients between the ceramic cup and manometer.

The thermocouple psychrometer is used to measure a large variation of soil ψ_m less than -200 kPa. The technique, although usable for a large variation of soil conditions, requires expensive instrumentation and is subject to considerable errors due to ambient temperature changes. Producing a profile of soil ψ_m measurements with this method would require placement of ceramic cups at each depth interval desired. The cost and logistical considerations made the technique impractical for this study.

The wide-range filter-paper method, although seldom used, offers several significant advantages over other methods of soil ψ_m measurement. The filter-paper method determines soil ψ_m by allowing a piece of filter paper to come to moisture equilibrium in direct contact with a soil sample collected with a soil auger. The water content of this filter paper is used to determine soil ψ_m from predetermined calibration relations. This method was used in this study because it provides reasonable accuracy for the large variation of soil conditions in Owens Valley, requires minimal equipment, and the soil samples collected for the analysis yield byproducts, such as soil water content and bulk density, that are useful in interpreting soil water and plant relations.



SITE B (slow-drawdown site)

SITE D (fast-drawdown site)

SITE H (slow-drawdown site)

Figure 2. Location of pump-equipped and monitoring wells for the water-table drawdown sites. Site K, not shown, is similar to site D. Letters identify individual wells.

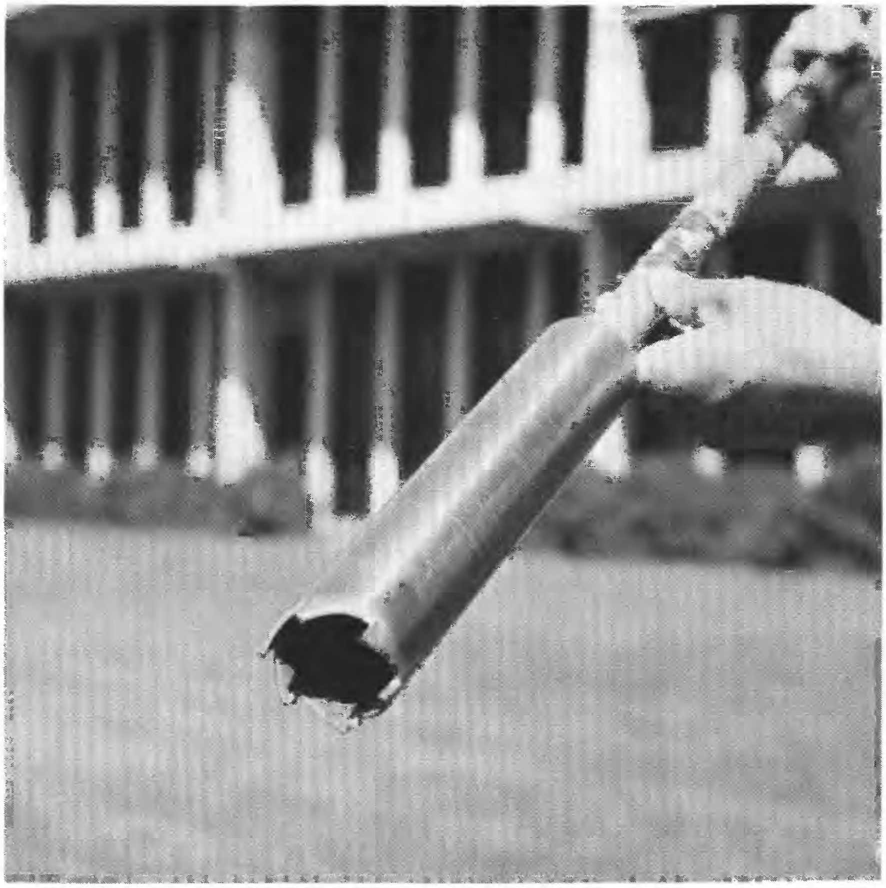


Figure 3. Auger barrel and driver rod used for soil core sampling.

Field Procedure

To analyze soils using the filter-paper method, soil samples were collected from the surface to near the water table using a 50.8-mm-diameter hand auger (fig. 3). The cutting teeth on this auger barrel were tipped with carbide points to facilitate hand augering. (They also are very durable, wear slowly, and do not bend as untipped stainless steel would.) The cutting teeth produce a uniform hole with less tendency to slough than holes made with untipped augers. When hand augering is done carefully using this auger, samples of known volume are obtained and dry bulk densities can be estimated. Care was taken to discard any soil identified as coming from higher in the augered hole. This material was usually identifiable by its differing color and texture.

Successive 0.1-m samples were collected and placed into airtight plastic bags in direct contact with a 55-mm disk of Schleicher and Schuell No. 589 white ribbon filter paper (filter papers are pretreated with 3 percent pentachlorophenol dissolved in methanol to prevent microbial digestion). The plastic bag containing the sample was sealed inside a metal can with electrical tape to prevent loss of water.

Laboratory Procedure

The soil samples were incubated at 20 °C plus or minus 0.1 °C for at least 1 week to allow equilibration between soil and filter paper. Wet soil and filter paper were weighed, oven dried, and weighed again. Gravimetric water content of the soil and the filter paper were calculated from these weights. Soil ψ_m was calculated from the water content of the filter paper in contact with soil, using modifications of regression equations presented by McQueen and Miller (1968).

Neutron Probe

Description of Use of Neutron Probe

The use of a neutron probe to estimate θ is a common technique that allows rapid evaluation of soil water conditions at exactly the same locations over a period of time. This technique was used in Owens Valley to supplement gravimetric methods requiring the use of hand augers and to make it possible to obtain θ data in the coarse-textured soils that were difficult or impossible to hand auger at low θ. This method is particularly well suited to long-term data collection at fixed points and therefore is useful in monitoring soil water conditions in conjunction with studies of plant responses to soil water.

A series 3300 neutron probe, manufactured by Troxler Electronics, was used in this study. This probe uses a 10-millicurie americium-beryllium source to generate "fast" neutrons. These neutrons are scattered away from the source into the surrounding soil. When fast neutrons collide with small nuclei such as those of hydrogen atoms, they are thermalized into slow neutrons that are backscattered to the probe. A detector in the probe measures the backscatter of neutrons, accumulating a count over a standard measurement period. Because virtually all the hydrogen in the soil-water-air system is in the water, the number of slow, backscattered neutrons is directly related to the water content of the soil. The technique requires installation of a permanent access tube to the depth desired for the measurements. The tubes used for the project were aluminum irrigation piping of 50.8-mm outer diameter. The inner diameter of 48.3 mm produced a snug fit around the probe.

Although the counts obtained by the neutron probe indicate the relative amount of water present in the soil, a number of factors may affect the results obtained. One factor is the size of the effective measurement sphere of the probe itself. Drier soils contain fewer hydrogen atoms, which provide neutron thermalization and backscatter resulting in a large sphere of measurement. The sphere of measurement is proportionately smaller in wetter soils because of the attenuating effect of the surrounding water. Where boundaries occur within a profile between wet and dry soil, the neutron probe will indicate an "averaged" θ that is not representative of either soil layer (McHenry, 1962; Lawless and others, 1963).

In addition to the interlayer effect induced by θ boundaries in the soil, the predictive ability of the neutron probe for θ also is affected by the soil texture (Gornat and Goldberg, 1972), soil bulk density (Greacen and Schrale, 1976), iron content (Burn, 1966), and salinity (Benz and others, 1965). Of these factors, soil salinity plays the most significant role in the accuracy of soil water measurement in Owens Valley.

Calibration of Neutron Probe

Neutron-probe calibration was accomplished in two steps. First, a master calibration curve describing the relation between volumetric soil water content (θ_v) and neutron counts was developed using samples collected from seven sites: B, C, D, F, H, K, and L (fig. 1). This curve was used in all areas of the valley and in all soil types. Further site- and depth-specific calibration curves were developed at certain locations where greater precision was needed for estimating θ_v than could be achieved using the master calibration curve. The θ was determined gravimetrically from uniform volume soil cores (Gardner, 1965) that were obtained within the same hole as the neutron access tube or were collected within 0.5 m of the tube. Counts were obtained with the gage during the same field visit and were plotted against θ_v.

Data obtained by the neutron probe are usually expressed as count ratios, which are calculated by dividing the experimental counts by a standard count obtained with the probe positioned within a shield built into the instrument. The shield consists of a hydrogen-rich material such as plastic or nylon that also serves to protect the operator from exposure to neutron radiation during transport of the probe. A calibration curve produced using count ratios has versatility because it permits interchangeable use of gages of similar manufacture; however, differences as much as 4 percent were found in standard counts obtained in the field compared to counts obtained at room temperature. These errors are likely due to thermal expansion of the shield. Simple counts, as opposed to count ratios, were used for the calibration in this project because only one instrument was used. Numerous other researchers (Holmes and Jenkinson, 1959; Luebs and others, 1968; Olgaard and Haahr, 1968; Gornat and Goldberg, 1972; and Cannell and Asbell, 1974) also have applied neutron-probe data without using count ratios.

Volumetric soil water content from all sites were plotted against the neutron-probe counts on a single graph. The resulting plot approximated a straight line. This plot was used to identify outliers that did not fit this relation. These outliers fell into two categories: (1) derived from the effect of soil layering and (2) derived from near-surface samples where the sphere of measurement of the probe had been truncated tangentially by the surface. Neutron escape near the surface of the soil causes a decrease in the backscatter and, therefore, proportionately fewer counts (Van Bavel and others, 1954; Lawless and others, 1963; Luebs and others, 1968). In order to avoid problems associated with neutron escape from the soil surface, including difficulty of interpretation and the need for operator radiation safety, the neutron probe was not positioned for measurements at depths shallower than 0.2 m. The outliers were removed from the data set, and linear regression was used to calculate a line that represented a master calibration curve for the Owens Valley with a correlation coefficient of about 0.9. The equation for this calibration curve is $\theta_v = (0.053 \times \text{counts}) - 5.75$. Similar master calibration curves have been used in other studies to characterize multiple soils in a given geographic area with a high degree of accuracy (Rawls and Asmussen, 1973; Cannell and Asbell, 1974).

During the spring of 1985, after the master calibration curve had been established using previously collected data, neutron-probe access tubes were placed at the water-table drawdown sites in the same holes created by the hand auger in connection with sample collection for ψ_m. Additional auger profiles were collected at the drawdown sites within 1 m of the access tube in March and October 1986 and at transect H1 in March 1987. Neutron counts were obtained within 24 hours of each of these auger profiles. These additional data served two purposes: (1) to obtain paired soil ψ_m and θ_g values for determination of soil water characteristic curves using the modeling approach described later in this report, and (2) to provide additional bulk density and neutron-probe data with which to test the master calibration curve. The counts acquired during this sampling were used to calculate θ_v for each sampling period with the master calibration curve and to compare these values with the θ_v data obtained by gravimetric means from the soil cores. These comparisons indicated that the master calibration curve, although useful on a valleywide basis, provided consistently lower estimates of θ_v than was determined by gravimetric techniques at certain depths at the two transects used for this study. If the soil water model was to be useful, more accurate estimates of θ_v would be required from the neutron probe than were available with the master calibration curve at some depths.

In general, estimates of θ_v in sandier soils deviated from the master calibration curve more than estimates from finer silty soils. In order to produce more accurate neutron-probe calibration, θ_v and simultaneous neutron-count data were plotted for each access tube in groupings of 0.1-m depth intervals that had similar soil-texture characteristics. Regression equations representing new calibration lines were calculated and used to replace the master calibration curve at that depth. The master calibration curve was used where it produced close estimates of θ_v.

Results of the neutron-probe calibration for transects B1 and H1 are shown in figure 4. Gravimetrically determined data points on this graph are unweighted running means of the depth indicated and the depths immediately above and below. Running means were used because the overlapping spheres of influence using the neutron probe created an averaging effect along the soil profile that was roughly equivalent to the running means calculated from gravimetric measurements at discrete depths. The largest errors occurred in the first 0.5 to 0.7 m. This is likely due to larger concentrations of salt in the upper soil horizon.

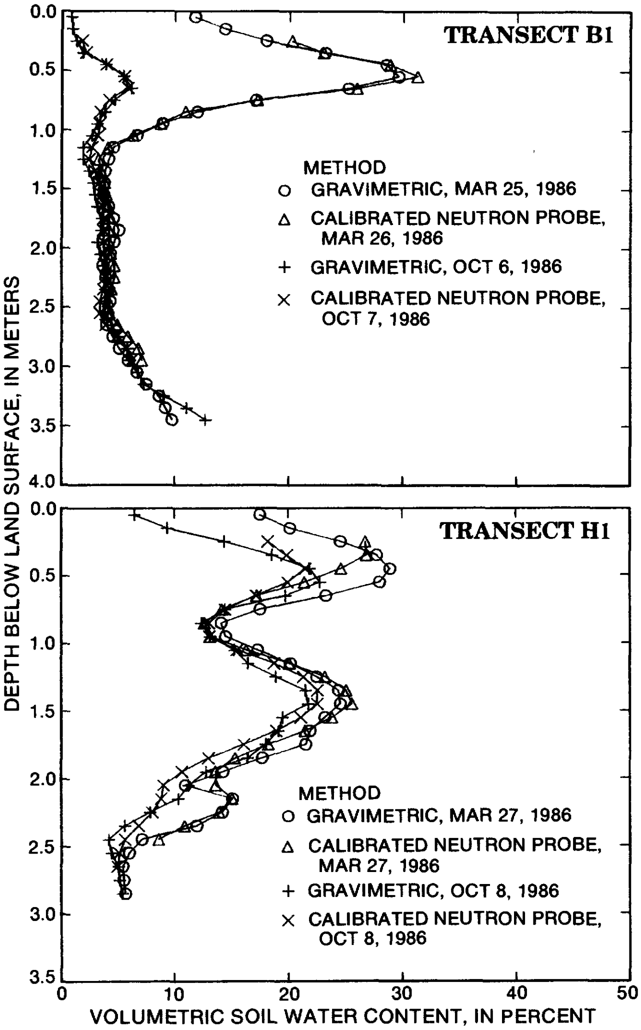


Figure 4. Comparison of volumetric soil water content at transects B1 and H1 determined by using the gravimetric and calibrated neutron-probe methods.

RECALIBRATION OF THE FILTER-PAPER METHOD

The first use in the United States of filter papers as a sensor of soil ψ_m was reported by Gardner (1937). Gardner's method was further developed independently by Fawcett and Collis-George (1967) in Australia and McQueen and Miller (1968) in the United States. Fawcett and Collis-George and McQueen and Miller used virtually the same methods of calibrating the filter paper but used different brands of filter papers. The different papers likely account for the slight differences in their published calibration curves. Further refinement of the method was published by Hamblin (1981). In Hamblin's study, the Whatmans No. 42 filter papers, as previously used by Fawcett and Collis-George, were used to confirm their earlier calibration relations with other batches of filter papers. McQueen and Miller's calibration of the filter-paper method was used extensively in studies of rangeland hydrology in the Western United States since 1968 (Miller and others, 1969, 1982; Shown and others, 1969, 1981; Branson and others, 1970, 1976; McQueen and Miller, 1972; Miller and McQueen, 1972, 1978; U.S. Department of the Interior, 1975, 1976; Branson and Shown, 1975; Branson and Miller, 1981; Hadley and others, 1981).

Reevaluation of the McQueen and Miller (1968) calibration relations using laboratory data acquired since 1968 by Al-Khafaf (1972) has resulted in modified calibration relations that better describe the relations of θ and soil ψ_m of the filter papers. The modified calibration relations and the data points used to establish them, along with calibration relation lines of McQueen and Miller (1968), are shown in figure 5.

Two calibration equations are used with the filter-paper method. These correspond to the variation of soil ψ_m greater than and less than 2.3 pF, which is approximately field capacity. The equation used to define soil ψ_m from the water content of filter papers, when water content is less than 0.585 gram of water per gram of paper, is

$$\psi_m = 5.75 - 5.94 W_p \qquad (2)$$

where

ψ_m is the soil matric potential, in pF, and

W_p is water content of the filter paper, in grams of water per gram of paper.

The coefficient of determination (r^2) of this regression equation is 0.964, based on 72 pairs of data.

The equation used to compute soil ψ_m when water content is more than 0.585 gram of water per gram of paper is

$$\psi_m = 2.62 - 0.68 W_p. \qquad (3)$$

The r^2 value of this regression equation is 0.989, based on 72 pairs of data.

The calibration line represented by equation 2, which covers the higher pF range (drier), was modified based on data obtained by Al-Khafaf (1972). Some of the calibration data used by McQueen and Miller (1968) were obtained from filter papers incubated in the same chamber with soil samples but not in direct contact with it. Al-Khafaf's data resulting from this method differed from data obtained when filter papers were incubated in direct contact with soils equilibrated to the same soil ψ_m. McQueen and Miller (1968) pointed out that the filter papers in contact with the soil measure ψ_m, and those incubated out of contact with soil measure matric and osmotic potential, because vapor exchange is the only mechanism involved in water movement at low θ. Because the methods used for this study indicate that the filter papers are to be incubated in direct contact with soil, only the McQueen and Miller (1968) and Al-Khafaf (1972) data that were obtained in this manner were used in the modified calibration relations.

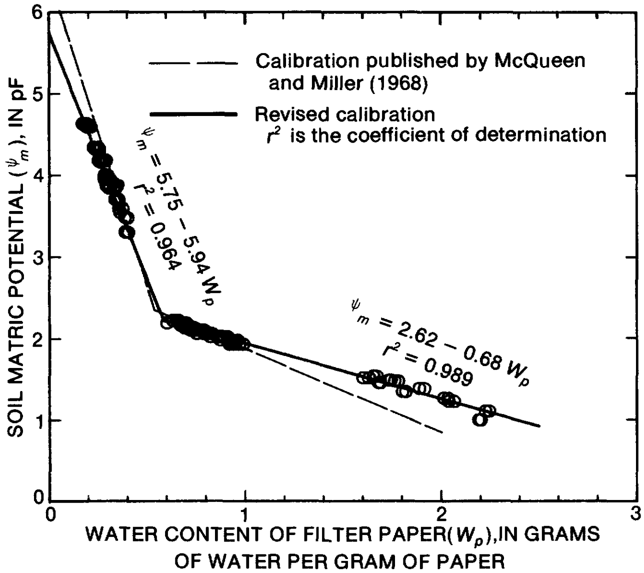


Figure 5. Calibration equations used to determine soil matric potential from filter-paper water content.

The lower part of McQueen and Miller's calibration line (fig. 5) covering the lower soil ψ_m (wetter) was based on data obtained from soils at various heights above a natural water table. Because these samples were, of necessity, disturbed during the soil collection process and through subsequent handling, the relations of θ and soil ψ_m probably were altered from what they were under undisturbed conditions. Al-Khafaf (1972) obtained data from laboratory soil columns in equilibrium with an artificial water table. Because filter papers could be equilibrated with these soils without disturbance, they more closely represented the soil ψ_m calculated by height above the water table. As a result, these data then were used to obtain the lower parts of the modified calibration relation (equation 3). The upper part of the wetter calibration curve is derived from data obtained by McQueen and Miller (1968) at distances of greater than 0.5 m from the natural water table, and from Al-Khafaf's (1972) laboratory data. In this range of soil ψ_m, the two sets of data correlated well.

SOIL WATER CHARACTERISTICS MODEL

Studies of western rangeland hydrology by Branson, Miller, and their associates (McQueen and Miller, 1968, 1972; Miller and others, 1969, 1982; Shown and others, 1969, 1981; Branson and others, 1970, 1976; Miller and McQueen, 1972, 1978; Branson and Shown, 1975; Branson and Miller, 1981) during the last 20 years have yielded data on θ and soil ψ_m relations in a large variety of soils and soil water conditions. These soil ψ_m and θ data were collected by hand auger and were analyzed by using the filter-paper method. Another type of information gathered from many of these soil samples was the soil saturation capacity. Saturation capacity is the weight ratio of water to soil in a saturated paste (U.S. Department of Agriculture, 1954). Saturation capacity has been found to correlate well to the texture of soils (Stiven and Khan, 1966). Because the relation between θ and soil ψ_m is dependent largely on soil texture when soil ψ_m is less than about −30 kPa, saturation capacity was used as a method to identify soils with similar texture and therefore soil water characteristics.

The θ_g, soil ψ_m, and saturation capacity data from hydric and xeric habitats in Ruby Valley, Nevada (Miller and others, 1982); Badger Wash, Colorado (Branson and others, 1976); Boca Mountain, Colorado (F.A. Branson and R.F. Miller, U.S. Geological Survey, written commun., 1987); and Owens Valley, California, were used to develop an empirical model of general soil water characteristics. These data were grouped by saturation capacity in steps of 0.02 g/g (grams per gram), and plotted on separate graphs (fig. 6). Only data pairs with soil ψ_m greater than 2.3 pF were used for this calculation because those with soil ψ_m less than 2.3 pF commonly do not match the moisture characteristic line predicted by using drier samples because of physical disturbance of the soil sample. Regression lines were drawn for each set of points. The *X*-axis intercept on these lines is an estimate of the adsorption capacity or the maximum quantity of water that can be adsorbed by that group of soils. The *Y*-axis intercept of the lines is an estimate of the maximum soil ψ_m for that group of soils. The regression lines intercept both axes at slightly higher values as saturation capacity increased. An estimate of the change in these axis intercepts was made by plotting *X*- and *Y*-axis intercepts from the lines in figure 6. The resulting points yielded a regression equation of $\psi_m=5.56+0.888$ (adsorption capacity) (fig. 7).

The soil water model (fig. 8) is represented as a series of lines with *X*-axis intercepts at intervals of 0.02 g/g saturation capacity and the *Y*-axis intercepts at the corresponding value of soil ψ_m calculated from figure 7. These lines are a representation of an infinite number of lines that can be calculated by using the equation from figure 7.

The model shown in figure 8 then was used to approximate characteristic curves for any soil measurements of in-situ θ_g and soil ψ_m. The θ_g and soil ψ_m point is plotted on the model (fig. 8) and the *X*- and *Y*-axis intercepts of the characteristic line are calculated by using the following equations:

$$Xint=\frac{-(B-\psi_m-(XM)(\theta_g))+\sqrt{(B-\psi_m-(XM)(\theta_g))^2-4(XM)(-B)(\theta_g)}}{2(XM)} \tag{4}$$

$$Yint=XM(Xint)+B \tag{5}$$

where

B is 5.56 (*Y*-axis intercept of equation in fig. 7),
XM is 0.888 (slope of equation in fig. 7),
θ_g is gravimetric soil water content, in grams of water per gram of soil, and
ψ_m is soil matric potential, in pF.

Although the model shown in figure 8 represents characteristic curves that include soil ψ_m less than 2.3 pF, this part of the curve is not valid because these data were not used to form the model relations. This restriction is not important in studies such as the one in Owens Valley because soil water does not become limiting to plants until soil ψ_m is much greater than 2.3 pF.

APPLICATION AND RESULTS

Application of Soil Water Characteristics Model to Specific Sites in Owens Valley

Selection of Soil Water Characteristic Curves

Two study transects were selected for evaluation of the soil water characteristics model. These two transects at the slow-drawdown sites, B and H, were selected because they had very different soil characteristics that varied from coarse sand to silty clay, and each already had several soil profiles of θ_g and soil ψ_m collected with the hand auger. Transect B1, in the Bishop area, has sandy soil, but was not homogeneous throughout the soil profile. Distinct layers of different textures consist of sand, sandy loam, and loamy sand. The depth and extent of these layers have considerable spatial variation. The soil at transect H1 near Independence was mostly fine grained, varying from silty clay to loamy silt in the upper 2 m of the soil column. The sandy soil below 2 m was much like the soil at transect B1. The soil at transect H1 also was highly layered and varied considerably from one point to another in the study plot.

Theoretically, the soil water characteristics model allows estimation of characteristic curves from θ_g and soil ψ_m derived from each depth at a single augered soil profile. Several factors make this approach impractical. The most important of these is that the soils at the test sites in Owens Valley are heterogeneous, varying considerably in texture with depth and areally. As a result, a soil profile may have characteristics quite different from those in other areas of the same test site. Any one soil profile is assumed to be representative of the average characteristics of the entire area and cannot be used to predict soil characteristics precisely at all depths and locations in an area. To account for this variation in soil characteristics, the two test transects were sampled multiple times from 1983 through 1986 during various soil water conditions. Arithmetic means of all θ_g and soil ψ_m data were computed for each 0.1-m depth increment at each of the two study transects (table 1). Data pairs with a soil ψ_m of less than 2.3 pF were not included in these calculations. These mean values of θ_g and soil ψ_m for each depth were then entered into the model (fig. 8) and the appropriate characteristic curve was selected using equations 4 and 5. Table 1 shows the mean θ_g and soil ψ_m values used in equations 4 and 5 and the resulting *Y*-axis intercept and slope of the estimated characteristic curves. Bulk density was estimated for each depth at each transect by calculating an arithmetic mean of bulk densities determined for each sample.

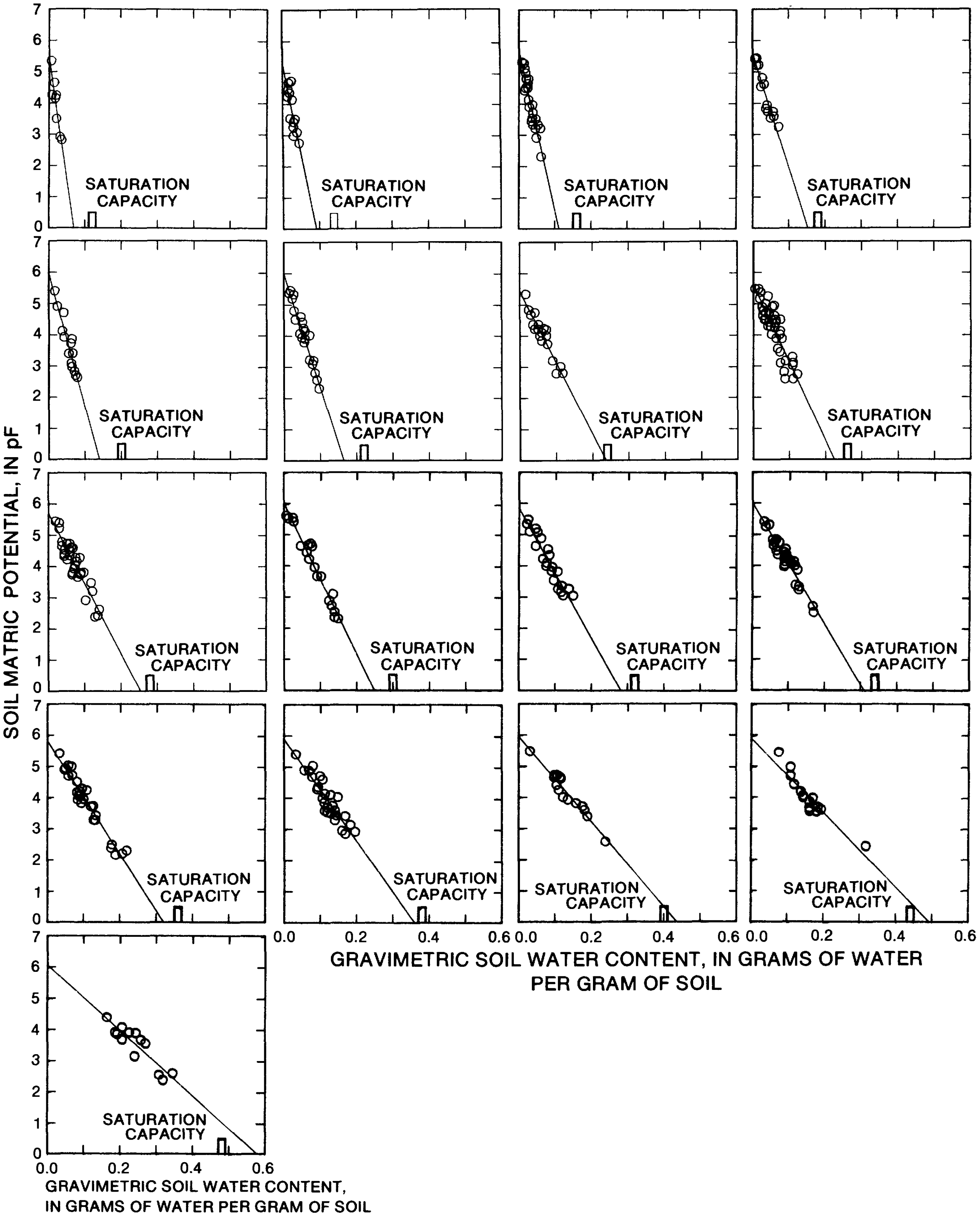


Figure 6. Relation of soil matric potential, determined by the filter-paper method, to water content of soils with similar saturation capacities.

Evaluation of Estimated Soil Water Characteristic Curves

Evaluation of the ability of the soil model to estimate soil ψ_m requires several assumptions and definitions. For this analysis, error is defined as the difference between measured soil ψ_m using the filter-paper method and soil ψ_m derived using the model. The model is assumed to be valid only for soil ψ_m greater than 2.3 pF, as these are the data that were used for calibration. Soil ψ_m less than 2.3 pF indicated by the filter paper was considered to be out of the model calibration range, and a comparison was not made between this value and the soil ψ_m predicted by the model.

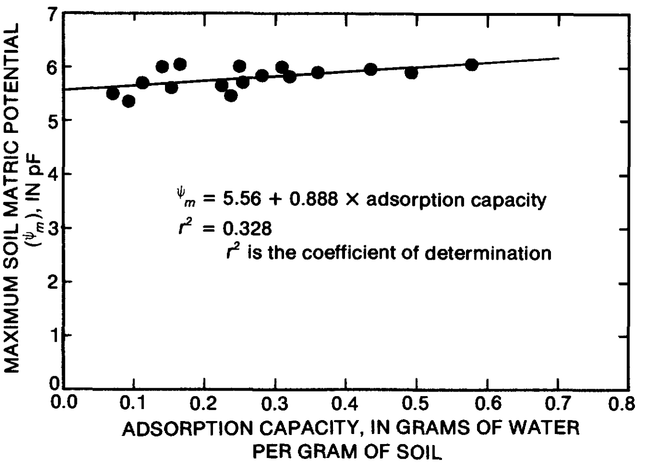


Figure 7. Regression equation used to relate maximum soil matric potential to adsorption capacity.

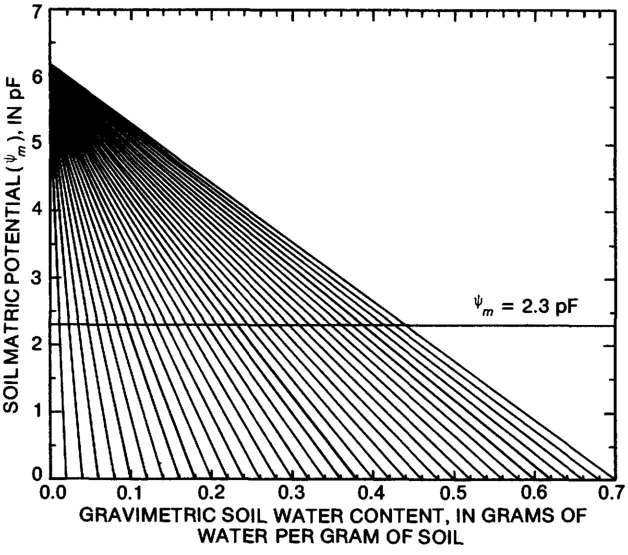


Figure 8. Soil water characteristics model used to estimate characteristic curves.

Table 1. Data used in the soil water characteristics model and Y-axis intercept and slope of characteristic curves for transects B1 and H1

[θ_g, gravimetric soil water content, in grams of water per gram of soil; ψ_m, soil matric potential]

Depth	Bulk density (g/cm^3)	Mean θ_g	Mean ψ_m (pF)	Number of θ_g/ψ_m data pairs	Y-axis intercept	Slope
			Transect B1			
0.05	1.57	0.035	4.07	7	5.67	-45.09
.15	1.57	.038	3.81	4	5.66	-48.40
.25	1.57	.039	4.05	3	5.68	-41.81
.35	1.54	.041	3.98	3	5.68	-41.50
.45	1.54	.048	3.80	2	5.69	-39.34
.55	1.54	.045	3.78	3	5.68	-42.44
.65	1.48	.036	3.64	3	5.65	-55.25
.75	1.48	.031	3.53	3	5.63	-68.57
.85	1.48	.035	3.54	2	5.64	-60.10
.95	1.60	.020	3.44	2	5.61	-108.54
1.05	1.60	.021	3.25	2	5.60	-114.80
1.15	1.60	.017	3.59	1	5.60	-118.35
1.25	1.50	.025	3.07	2	5.61	-101.56
1.35	1.50	.030	3.15	2	5.62	-82.35
1.45	1.50	.022	3.89	1	5.62	-78.79
1.55	1.54	.020	3.96	1	5.62	-83.01
1.65	1.54	.028	4.00	1	5.65	-58.76
1.75	1.54	.030	4.06	1	5.65	-53.15
1.85	1.54	.028	3.84	1	5.64	-64.21
1.95	1.54	.038	3.88	1	5.67	-47.03
2.05	1.54	.023	3.88	1	5.63	-75.91
2.15	1.54	.022	3.63	1	5.62	-90.24
2.25	1.54	.024	3.55	1	5.62	-86.16
2.35	1.54	.028	3.50	1	5.63	-75.92
2.45	1.54	.028	3.24	1	5.62	-84.95
2.55	1.54	.026	3.16	1	5.61	-94.34
2.65	1.54	.024	3.48	1	5.62	-89.00
2.75	1.54	.025	2.98	1	5.61	-105.10
			Transect H1			
0.05	0.74	0.138	4.29	13	5.99	-12.33
.15	.78	.235	3.79	13	6.11	-9.87
.25	.91	.263	3.57	13	6.12	-9.69
.35	1.07	.237	3.66	12	6.09	-10.27
.45	1.19	.227	3.58	12	6.05	-10.92
.55	1.19	.260	3.57	11	6.11	-9.80
.65	1.21	.228	3.66	10	6.07	-10.60
.75	1.28	.157	3.62	10	5.92	-14.62
.85	1.41	.091	3.66	9	5.78	-23.32
.95	1.46	.099	3.72	9	5.81	-21.04
1.05	1.45	.137	3.57	10	5.87	-16.83
1.15	1.45	.144	3.60	9	5.89	-15.90
1.25	1.50	.149	3.23	9	5.85	-17.65
1.35	1.54	.147	3.10	10	5.84	-18.63
1.45	1.58	.161	2.66	6	5.82	-19.64
1.55	1.58	.137	3.14	2	5.82	-19.69
1.65	1.57	(1)	(1)	0	--	--
1.75	1.60	(1)	(1)	0	--	--
1.85	1.58	.098	2.62	1	5.72	-31.64
1.95	1.61	.070	3.04	1	5.69	-37.91
2.05	1.58	.072	3.24	1	5.71	-34.28
2.15	1.62	.068	3.25	1	5.70	-36.04
2.25	1.62	.053	3.47	1	5.68	-41.72
2.35	1.65	.024	3.63	1	5.62	-82.92
2.45	1.67	.025	3.27	1	5.61	-93.73
2.55	1.70	.025	3.57	1	5.62	-82.03
2.65	1.70	.028	3.19	1	5.62	-86.70

[1] Data with soil matric potential greater than 2.3 pF were not available.

An overall evaluation of how well the model-estimated soil water characteristics predicted soil ψ_m was determined by calculating soil ψ_m for each measurement of θ_g from the auger profiles. These calculated values of soil ψ_m derived from the model were compared with soil ψ_m measured using the filter-paper method. Using the criterion that a predicted soil ψ_m value (modeled) within 0.5 pF of the measured value (filter paper) was acceptable, 2.8 percent of the samples had errors greater than 0.5 pF at transect B1. At transect H1, 11.0 percent of the samples were in error.

The next evaluation made was to determine if there were any depths where errors were consistently greater than 0.5 pF. At transect B1, the average error between measured and estimated soil ψ_m for all soil profiles was greater than 0.5 pF at depths 0.65 to 1.05, 1.65 to 1.75, and 1.95 to 2.05 m. This indicates that errors tended to occur in clusters of adjacent depths. These depths are approximately where substantial changes in soil texture occur. Because these interfaces in texture are not at exactly the same depth in each soil profile used to calculate soil characteristics, some variation of the calibration of the model would be expected at these depths. This pattern also occurred at transect H1, where depths of 0.95, 1.55, and 1.95 to 2.05 m had mean errors greater than 0.5 pF.

Additional analyses were made to investigate the effects of two geometrical aspects of the model. Because of the geometric shape of the model, with lines of varying slope fanning out from the soil ψ_m axis, higher soil ψ_m would result in an input point (point used to predict characteristic curve) to the model (fig. 8) that is closer to the soil ψ_m axis, where the lines nearly converge. By selecting a calibration point in this range, small errors in the input values would mean larger errors in the calibration line determined than if the input point were closer to the 2.3 pF point. Using error as the X variable and the mean filter-paper-derived soil ψ_m point as the Y variable, a slight correlation (r=0.255) was found at transect B1. A moderate negative correlation (r=−0.44) was found at transect H1. The fact that one transect showed a slight positive correlation between these factors and the other transect showed a negative correlation indicated that determining a calibration point near the area where the model lines converge has little effect on the accuracy of the model in general but may have some effect at a particular transect.

A second factor relating to the variable geometry of the model is the correlation between the error and the slope of the characteristic line. The greater the slope of the line, the more the estimated soil ψ_m will change as the result of small errors in estimated θ_g. For instance, if the slope of the characteristic line is −45.09, as it is at the 0.5-m depth at transect B1, a change in θ_g of 0.005 g/g results in a change in soil ψ_m of 0.226 pF. If the slope of the characteristic line is −118.35, as it is at the 1.15-m depth at transect B1, a change in θ_g of 0.005 g/g results in a soil ψ_m change of 0.59 pF. A slight correlation was found between the mean error and the slope of the characteristic line (r=0.209) at transect B1, and no correlation (r=0.02) was found at transect H1. The slight correlation at transect B1 may be due to the fact that slopes for most of the depths are much greater than at transect H1. Sites with coarser soils and correspondingly high characteristic curve slopes potentially have more error in the model because of these high slopes.

As an evaluation of the model, an additional test was done to evaluate the correlation between model errors and the number of data points used for calibration at each depth. The number of points used to determine mean θ_g and soil ψ_m varied depending on the number of soil profiles collected and the number of samples with soil ψ_m greater than 2.3 pF. The shallower depths, where soil generally was drier, had more points to use in calibration than did the deeper soils that did not dry beyond 2.3 pF until the plant roots were able to extract this water. Little correlation between error and the number of data points was found (r=0.128 at B1, and r=−0.23 at H1), which indicates that the number of data points used in calibration has little effect on the model for data available in this study.

Verification of Soil Water Characteristics Model

As noted previously, characteristic curves were estimated using soil data collected from 1983 through 1986. To verify these curves with an independent set of data, one additional soil auger profile was collected at each transect (October 1986 at transect B1 and March 1987 at transect H1) and soil ψ_m was calculated from θ_g by using the model-derived characteristic curves. These values of soil ψ_m were compared to soil ψ_m determined from the same soil using the filter-paper method.

By use of the criterion that predicted soil ψ_m within 0.5 pF of the soil ψ_m determined by the filter-paper method was acceptable, 20 of 28 depths (71.4 percent) were acceptable at transect B1 (table 2). At transect H1, 21 of 25 depths (84 percent) of the predicted soil ψ_m were within the acceptable range (table 2). The soil ψ_m at the 1.65- to 1.75-m depths were less than 2.3 pF, and were thus out of the calibration range of the model.

Use of Soil Water Characteristic Curves Estimated from the Model to Estimate Soil Matric Potential from Neutron-Probe Data

Once model-derived site- and depth-specific characteristic curves have been determined and evaluated and the neutron probe has been calibrated, estimates of soil ψ_m can be calculated from neutron-probe-derived estimates of θ_v. A previous section explained the calibration of the neutron probe to provide estimates of θ_v that closely matched θ_v determined from soil auger data. Because the neutron probe is calibrated to estimate θ_v, these values are divided by the

Table 2. Comparison between measured and model-derived soil matric potential at transects B1 and H1

[θ_g, gravimetric soil water content, in grams of water per gram of soil]

Depth (meters)	θ_g	Soil matric potential, ψ_m, in pF: Filter paper	Modeled	Difference
Transect B1 soil profile sampled October 6, 1986				
0.05	0.004	5.32	5.49	0.17
.15	.006	5.11	5.37	.26
.25	.008	5.02	5.35	.33
.35	.011	4.84	5.23	.39
.45	.017	4.61	5.02	.41
.55	.046	4.56	3.73	-.83
.65	.041	4.61	3.39	-1.22
.75	.030	4.53	3.58	-.95
.85	.018	4.45	4.56	.11
.95	.024	4.14	3.00	-1.14
1.05	.017	4.23	3.65	-.58
1.15	.010	4.37	4.42	.05
1.25	.009	4.34	4.69	.35
1.35	.017	4.33	4.22	-.11
1.45	.020	4.29	4.05	-.24
1.55	.016	4.01	4.29	.28
1.65	.019	4.14	4.53	.39
1.75	.024	4.08	4.38	.30
1.85	.023	4.11	4.16	.05
1.95	.020	4.16	4.73	.57
2.05	.018	4.11	4.26	.15
2.15	.027	3.96	3.18	-.78
2.25	.025	3.93	3.46	-.47
2.35	.026	3.95	3.65	-.30
2.45	.023	3.77	3.66	-.11
2.55	.026	3.38	3.16	-.22
2.65	.024	3.38	3.48	.10
2.75	.035	2.76	2.23	-.53
Transect H1 soil profile sampled March 19, 1987				
0.05	0.074	5.02	5.08	0.06
.15	.129	4.62	4.84	.22
.25	.210	4.28	4.09	-.19
.35	.183	4.39	4.21	-.18
.45	.189	4.37	3.99	-.38
.55	.194	4.42	4.21	-.21
.65	.195	4.28	4.00	-.28
.75	.121	4.42	4.15	-.27
.85	.070	4.38	4.15	-.23
.95	.076	4.46	4.21	-.25
1.05	.096	4.37	4.25	-.12
1.15	.116	4.22	4.04	-.18
1.25	.113	4.03	3.86	-.17
1.35	.136	3.91	3.31	-.60
1.45	.151	3.55	2.86	-.69
1.55	.148	3.14	2.91	-.23
1.65	.117	2.18	(1)	(1)
1.75	.098	2.17	(1)	(1)
1.85	.095	2.22	2.71	.49
1.95	.042	3.43	4.10	.67
2.05	.066	2.95	3.45	.50
2.15	.085	2.31	2.64	.33
2.25	.075	2.72	2.55	-.17
2.35	.036	3.33	2.63	-.70
2.45	.025	3.00	3.27	.27
2.55	.025	3.11	3.57	.46
2.65	.024	3.38	3.54	.16

[1] No characteristic curve at this depth.

bulk density (table 1) to determine θ_g for the characteristic curves.

Depth profiles of soil ψ_m measured by using the filter-paper method and the model-derived-characteristic curves are presented in figure 9. The model-derived soil ψ_m are unweighted arithmetic means of that value at the depth indicated and the one above and below. The largest differences between the measured and calculated soil ψ_m are in the shallower depths, where there is generally more uncertainty in the neutron-probe estimates of θ_v due to neutron escape or soil salinity.

The estimates of soil ψ_m derived from this procedure have a certain amount of error associated with them, and greater precision may be required for some applications. This procedure is most useful in studies that require long-term monitoring of soil water characteristics, because once the calibration relations are developed, soil characteristics can be monitored frequently by using the neutron probe with a minimum of labor. In addition, trends in soil water characteristics would be detectable because of the consistent bias of the predicted characteristic curves.

Use of Estimates of Soil Matric Potential in Owens Valley Studies

As a result of being able to estimate depth profiles of soil ψ_m from neutron-probe data, patterns of soil water extraction in a soil profile due to growth of roots downward into newly drained areas can be traced.

An example of how soil ψ_m estimated using neutron-probe data changed over a 10-month period from January through October at transect B1 is shown in figure 10. These data indicate that the upper 1 m of soil was wetted by rainwater between January and March when the maximum θ (lowest soil ψ_m) was measured. Because the model-generated characteristic curves do not accurately estimate soil ψ_m in the wetter range, all estimated values of soil ψ_m less than 2.3 pF were converted to 2.3 pF for this graph. Much of the water infiltrated into the upper meter of the soil profile was extracted between March and June. The entire profile continued to dry throughout the year. Water transmitted into the soil from the water table is located at depths greater than 2.5 m, where soil ψ_m decreases from 4 to 2 pF.

Evaluation of Methods of Estimating Soil Matric Potential

Filter-Paper Method

The use of the filter-paper method outlined by McQueen and Miller (1968) and modified here is the best available method for estimating soil ψ_m for the large number of sites and depths needed in the Owens Valley studies. Direct comparison of the results of the method by taking in-situ measurements of soil ψ_m using other methods was not done because none of the existing standard methods are usable for the wide range covered by the filter-paper method. The method was calibrated using several of the recognized standard procedures to validate the method. In addition, similar calibration relations have been established independently by several other authors (Fawcett and Collis-George, 1967; Al-Khafaf and Hanks, 1974; Hamblin, 1981; Chandler and Gutierrez, 1986; and Greacen and others, 1987).

Patterns of soil water characteristics that can be reasonably predicted are confirmed by profiles of soil ψ_m collected in a large variety of soils throughout Owens Valley. When water tables were lowered under the experimental vegetation sampling transects, the soil drained under the force of gravity to a soil ψ_m of about 2 pF. This closely corresponds to the frequently used field capacity value of −10 to −30 kPa. Drainage in these soils continued for a period of one to several months, but always stabilized near 2 pF except in the zone just above the new water table, which was in capillary contact with the water table. Further decreases in soil ψ_m occurred only when other driving forces were present, such as evaporation in the upper 0.2 to 0.3 m. The largest driving force causing depletion of water from the gravity-drained soil was plant roots that extended into these zones.

Drainage of soil to field capacity is illustrated by the soil profile in figure 11. The soil ψ_m profile from March 1985 was taken about 1 month after the water level was drawn down about 1.5 m. This sandy soil drained to the point where the remaining water produced a soil ψ_m of near 2 pF. During the succeeding summer, the plants in the experimental sampling transects used residual water after the decline of the water table; this caused a shift of the soil ψ_m profile to

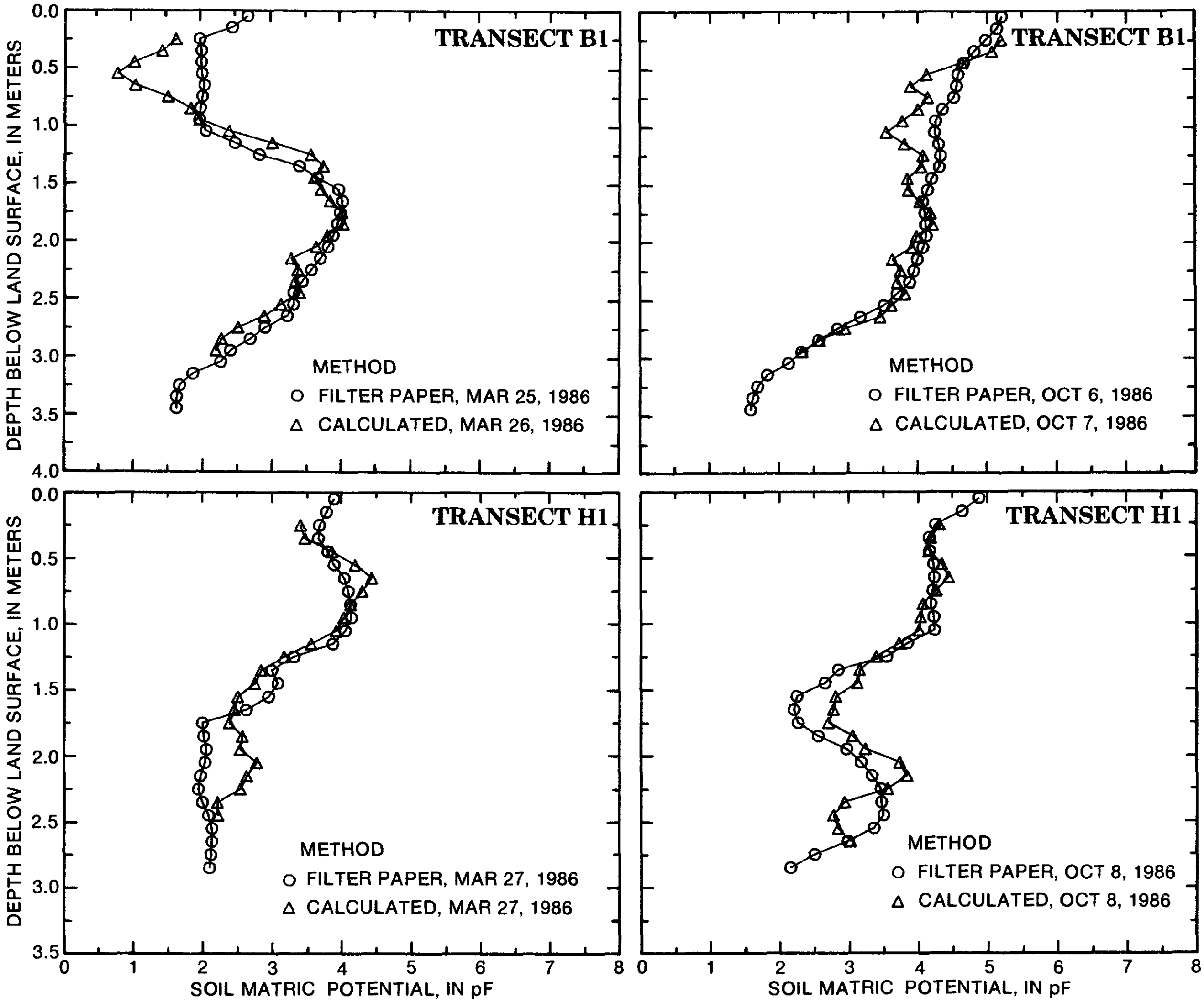


Figure 9. Comparison of soil matric potentials determined by the filter-paper method and estimated by using neutron-probe data.

a maximum soil ψ_m of about 4 pF. Rains during the winter of 1985-86 wetted the upper 1 m of soil to the point where the soil ψ_m returned to 2 pF.

Soil Water Characteristics Model

Calibrating the modeling approach used for this project to estimate soil ψ_m from neutron-probe readings of θ_v requires very careful analysis of soil data derived from the soil augering procedure. Soil samples need to be collected in such a way that reasonable estimates of dry bulk density can be made, and very careful laboratory procedures need to be used to ensure proper estimates of θ_g and soil ψ_m. Small errors in these procedures make it difficult to develop reliable calibrations of the neutron probe and reasonable inputs to the soil model. Another potential limitation of the procedure is the soil itself. The modeling procedure is most accurate in more homogeneous soils without distinct interfaces in texture; these interfaces have been shown to be significant sources of error. The model can be calibrated only in soils that have θ less than field capacity. Therefore, soil water characteristic curves could not be developed in the zone of capillary water above water tables by using field-sampled data.

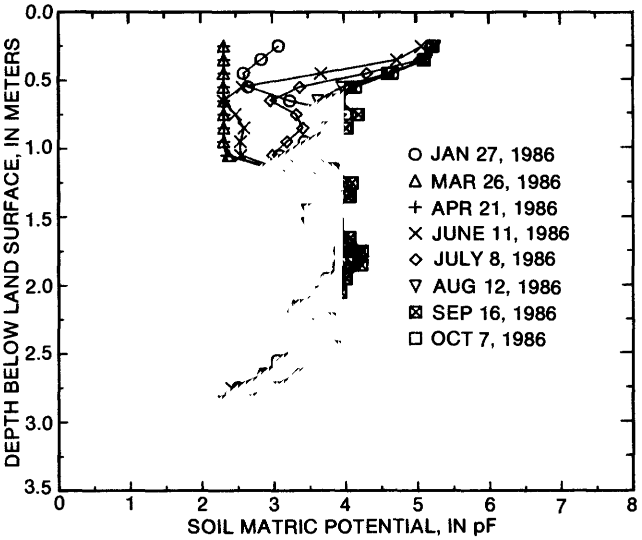


Figure 10. Soil matric potential from January through October 1986 at transect B1. All data were derived from neutron-probe measurements.

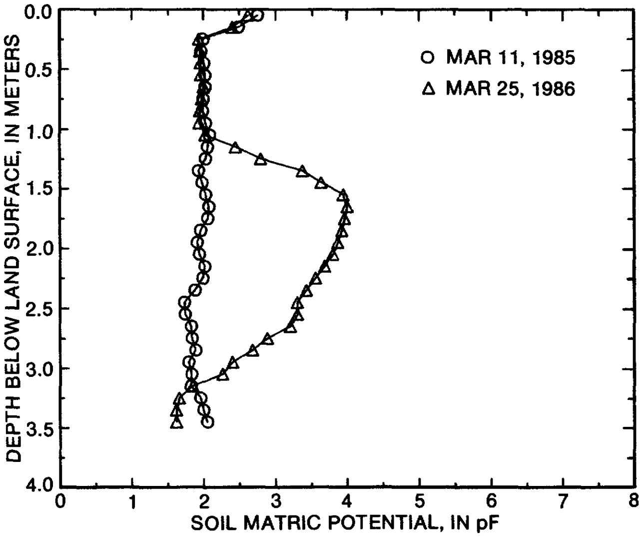


Figure 11. Soil matric potential at transect B1 in March 1985 and March 1986. All data were determined using the filter-paper method.

With careful calibration, this modeling approach can be useful in large studies that need to monitor soil water conditions for a long period of time and where great accuracy at any one particular point is not essential to the use of the data.

CONCLUSIONS

A necessary part of the study of how desert phreatophytes in Owens Valley react and adapt to changes in soil water conditions is the study of soil water characteristics. The ability to monitor soil ψ_m is particularly critical because plants must overcome these matric forces in order to extract water from the soil. Measurement of θ is not sufficient because plants react to the magnitude of soil ψ_m holding water in the soil rather than to the actual quantity of water in the soil.

The filter-paper method was used to measure θ_g and soil ψ_m using soil samples collected by using a hand auger. Newly obtained data from laboratory experiments were used to compute different calibration relations between filter-paper θ_g and soil ψ_m. This method provided accurate soil ψ_m data for a large variation of soil types and soil water conditions, but was very labor intensive and was impossible to use in drier sandy soils that collapse around the hand auger.

In areas where long-term monitoring of soil water characteristics was necessary at a large number of sites, neutron access tubes were installed to allow rapid and repeated measurements of θ_v. Estimates of soil ψ_m then were made by using characteristic curves determined by the empirical model presented in this report. Proper calibration of the soil water characteristics model required several soil profiles collected with the hand auger with as much variation in θ as possible. These measurements need to be accompanied with neutron-probe measurements at the same time. Simultaneous auger profiles and neutron-probe readings produced a calibration of the neutron access tube that allows close estimates of θ_v by using the neutron probe. The auger soil profile also provided θ_g and soil ψ_m data for deriving characteristic curves from the soil water characteristics model.

REFERENCES CITED

Al-Khafaf, S., 1972, Evaluation of the filter paper method for estimating soil water potential: Logan, Utah, Utah State University, unpublished M.S. thesis, 50 p.

Al-Khafaf, S., and Hanks, R.J., 1974, Evaluation of the filter paper method for estimating soil water potential: Soil Science, v. 117, p. 194–199.

Baver, L.D., Gardner, W.H., and Gardner, W.R., 1972, Soil physics: New York, Wiley, 293 p.

Benz, L.C., Willis, W.O., Nielsen, D.R., and Sandoval, F.M., 1965, Neutron moisture meter calibration for use in saline soils: Journal of Agricultural Engineering, June, p. 326-327.

Branson, F.A., and Miller, R.F., 1981, Effects of increasing precipitation and grazing management on northeastern Montana rangelands: Journal of Range Management, v. 34, p. 3–10.

Branson, F.A., Miller, R.F., and McQueen, I.S., 1970, Plant communities and associated soil and water factors on shale-derived soils in northeastern Montana: Ecology, v. 51, p. 391–407.

_____ 1976, Moisture relationships in twelve northern desert shrub communities near Grand Junction, Colorado: Ecology, v. 57, p. 1104–1124.

Branson, F.A., and Shown, L.M., 1975, Soil-moisture stress as related to plant-moisture stress in big sagebrush (*Artemisia tridendata* Nutt.) near Wolcott, Colorado: Journal of Range Management, v. 28, p. 212–215.

Burn, K.N., 1966, Effect of iron on the determination of moisture content by the neutron method: Canada Journal of Earth Science, v. 3, p. 129–132.

Cannell, G.H., and Asbell, C.W., 1974, The effects of soil-profile variations and related factors on neutron-moderation measurements: Soil Science, v. 117, p. 124-127.

Chandler, R.J., and Gutierrez, C.I., 1986, The filter-paper method of suction measurement: Geotechnique, v. 36, p. 265–268.

Fawcett, R.G., and Collis-George, N., 1967, A filter paper method for determining the moisture characteristics of soil: Australian Journal of Experimental Agriculture Animal Husbandry, v. 7, p. 162–167.

Gardner, R., 1937, A method of measuring the capillary tension of soil moisture over a wide moisture range: Soil Science, v. 43, p. 277-283.

Gardner, W.H., 1965, Water content, *in* Black, C.A., and others, eds., Methods of soil analysis, Part 1: American Society of Agriculture, Agricultural Series 9, p. 82–125.

Gornat, B., and Goldberg, D., 1972, The relation between moisture measurements with a neutron probe and soil texture: Soil Science, v. 114, p. 254–258.

Greacen, E.L., and Schrale, G., 1976, The effect of bulk density on neutron meter calibration: Australia Journal of Soil Research, v. 14, p. 159–169.

Greacen, E.L., Walker, G.R., and Cook, P.G., 1987, Evaluation of the filter paper method for measuring soil water suction: International Conference on Measurement of Soil and Plant Water Status, v. 1, p. 137–143.

Groeneveld, D.P., Warren, D.C., Hubbard, P.J., and Yamashita, I.S., 1986, Transpiration processes of shallow groundwater shrubs and grasses in the Owens Valley, California, Phase 1—Steady state conditions: Report prepared for Inyo County, Los Angeles Department of Water and Power, and State of California Water Resources Control Board (Contract No. 3-081-225-0), 131 p.

Hadley, R.F., Frickel, D.G., Shown, L.M., and Miller, R.F., 1981, Methodology for hydrologic evaluation of a potential surface mine—The East Trail Creek basin, Big Horn County, Montana: U.S. Geological Survey Open-File Report 81-58, 73 p.

Hamblin, A.P., 1981, Filter-paper method for routine measurement of field water potential: Journal of Hydrology, v. 53, p. 355-360.

Hillel, D., 1982, Introduction to soil physics: Academic Press, 364 p.

Hollett, K.J., 1987, Additional studies, *in* Rogers, L.S., and others, Overview of water resources in Owens Valley, California: U.S. Geological Survey Water-Resources Investigations Report 86-4357, 34-35.

Holmes, J.W., and Jenkinson, A.E., 1959, Techniques for using the neutron moisture meter: Journal of Agricultural Engineering Research, v. 4, p. 100–109.

Lawless, G.P., Macgillivray, N.A., and Nixon, P.R., 1963, Soil moisture interface effects upon reading of neutron moisture probes: Soil Science Society of America Proceedings, v. 27, p. 502-507.

Los Angeles Department of Water and Power, 1979, Final EIR, increased pumping of the Owens Valley ground-water basin: v. 1, various pagination.

Luebs, R.E., Brown, M.J., and Laag, A.E., 1968, Determining water content of different soils by the neutron method: Soil Science, v. 106, p. 207-212.

McHenry, J.R., 1962, Theory and application of neutron scattering in the measurement of soil moisture: Soil Science, v. 95, p. 294–307.

McQueen, I.S., and Miller, R.F., 1968, Calibration and evaluation of a wide-range gravimetric method for measuring moisture stress: Soil Science, v. 106, p. 225-231.

_____ 1972, Soil moisture and energy relationships associated with riparian vegetation near San Carlos, Arizona: U.S. Geological Survey Professional Paper 655-E, 51 p.

Meinzer, O.E., 1923, Outline of ground-water hydrology with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p.

Miller, R.F., Branson, F.A., McQueen, I.S., and Snyder, C.T., 1982, Water relations in soils as related to plant communities in Ruby Valley, Nevada: Journal of Range Management, v. 35, p. 462–468.

Miller, R.F., and McQueen, I.S., 1972, Approximating recurring moisture relationships in desert soils, *in* Eco-Physical Foundation of Ecosystems Productivity in Arid Zones, International Symposium, June 7-19, 1972: Leningrad, Nauka, p. 119-122.

_____ 1978, Moisture relations in rangelands, United States: Transactions, First International Rangeland Congress, Denver, Colorado, p. 318-321.

Miller, R.F., McQueen, I.S., Branson, F.A., Shown, L.M., and Buller, W., 1969, An evaluation of range floodwater spreaders: Journal of Range Management, v. 22, p. 246-257.

Olgaard, P.L., and Haahr, V., 1968, On the sensitivity of subsurface neutron moisture gauges to variations in bulk density: Soil Science, v. 105, p. 62–65.

Rawls, W.J., and Asmussen, L.E., 1973, Neutron probe field calibration for soils in the Georgia coastal plain: Soil Science, v. 114, p. 262-265.

Schofield, R.K., 1935, The pF of the water in soil: Soil Science, v. 2, p. 37–48.

Shown, L.M., Frickel, D.G., Hadley, R.F., and Miller, R.F., 1981, Methodology for hydrologic evaluation of a potential surface mine—The Tsosie Swale Basin, San Juan County, New Mexico: U.S. Geological Survey Open-File Report 81-74, 57 p.

Shown, L.M., Miller, R.F., and Branson, F.A., 1969, Sagebrush conversion to grassland as affected by precipitation, soil, and cultural practices: Journal of Range Management, v. 22, p. 303-311.

Smith, G.S., 1978, Deepest valley—A guide to Owens Valley, its roadsides and mountain trails: Los Altos, California, William Kaufmann, 227 p.

Stiven, G.A., and Khan, M.A., 1966, Saturation percentage as a measure of soil texture in the Lower Indus Basin: Journal of Soil Science, v. 17, p. 255-263.

U.S. Department of Agriculture, 1954, Soil survey manual: Handbook No. 18, 209 p.

U.S. Department of the Interior, 1975, Vegetation, soil-moisture retention characteristics and soil erodibility: U.S. Bureau of Land Management, Resource and Potential Reclamation Evaluation, Energy Mineral Rehabilitation Inventory and Analysis Reports, Nos. 1, 2, 3, and 4.

____ 1976, Vegetation-soil water relationships: U.S. Bureau of Land Management, Resource and Potential Reclamation Evaluation, Energy Mineral Rehabilitation Inventory and Analysis Reports, Nos. 5, 6, 7, 8, and 9.

Van Bavel, C.H.M., Hood, E.E., and Underwood, N., 1954, Vertical resolution in the neutron method for measuring soil moisture: Transactions of American Geophysical Union, v. 35, p. 595–600.

GLOSSARY

Bulk density: The ratio of the mass of dried soil to its total volume including solids and pores. Coarser textured and tightly compacted soils that contain more void space have higher bulk densities (1.5–1.7 g/cm^3) than finer textured soils (bulk densities as low as 1.1 g/cm^3).

Characteristic curve: A line describing the quantity of water retained by a soil at any equilibrium matric potential.

Gravimetric soil water content (θ_g): The quantity of water contained in a soil on a weight basis, or how many grams of water per gram of soil. Commonly presented as a percent.

Soil matric potential (ψ_m): Negative pressure potential in soil resulting from the affinity of water to the whole matrix of the soil including its pores and particle surfaces together.

Volumetric soil water content (θ_v): The quantity of water contained in a soil on a volumetric basis, or how many cubic centimeters of water per cubic centimeter of soil. Commonly presented as a percent.

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