Soil-Moisture and Energy Relationships Associated With Riparian Vegetation Near San Carlos, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 655-E

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GILA RIVER PHREATOPHYTE PROJECT

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, ***Director***

First printing 1972
Second printing 1979

For sale by the Branch of Distribution, U.S. Geological Survey
604 South Pickett Street, Alexandria, VA 22304

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By I. S. McQueen and R. F. Miller

ABSTRACT

Measurements of soil-moisture content and stress made under and near selected species of riparian trees in Arizona supply additional knowledge about the mechanism of moisture movement and utilization. Solar radiation provides energy to move soil moisture both upward and downward from the upper part of a soil profile. Profiles of chemical analyses show higher concentrations of salts at the surfaces of unshaded sites than at the surfaces of shaded sites, which indicates that evaporation loss is greater at unshaded sites than at shaded sites. This relation is confirmed by moisture-stress profiles. Profiles of soil-moisture stress under saltcedar and willow trees show no evidence of soil-moisture depletion by the trees. At one site, soil moisture increased during the season of maximum plant growth, even though a dense stand of annual grasses was growing on the site. The tree roots may have supplied moisture to the soils to maintain the soil moisture in hydraulic equilibrium with the water table. Cottonwood and mesquite trees, however, deplete soil moisture even when ground water is available.

INTRODUCTION

The use and dissipation of water by riparian vegetation (phreatophytes) in the arid regions of the Western United States has become a subject of intense study. A joint study of the Safford Valley in Arizona by the U.S. Geological Survey and the U.S. Army Corps of Engineers in the early 1940's focused attention on the Gila River and suggested the possibility of salvaging the water used by phreatophytes. The Gila River Phreatophyte Project, initiated by the U.S. Geological Survey in May 1962, was designed to study the effects on the water supply of the basin caused by replacing a large stand of saltcedar (*Tamarix pentandra* Pall.) with a beneficial vegetation (perennial grasses). Studies of soil-moisture and energy relationships were conducted by the authors as a supplement to the major study.

In the principal investigation, a 25.7-kilometer reach of the Gila River above its confluence with the San Carlos River was divided into three subreaches that were instrumented for water-budget determinations. The two upper subreaches have wide, naturally developed flood plains with at least one alluvial terrace, and the flood plains slope gently toward the channel. The lower subreach is a flat plain formed by sediment deposition in the San Carlos Reservoir. The upper subreaches contain 2,630 hectares of phreatophytes, of which about half are saltcedar and half are mesquite. The lower subreach contains 810 hectares of saltcedar.

Stream flow is gaged at four stations on the Gila River and at 62 stations on tributaries. Ground-water levels are measured in 72 wells, and soil moisture is estimated at 72 locations with neutron-scattering soil-moisture meters. Radiation, wind, humidity, and temperature are measured at Coolidge Dam for energy-budget computations. Supplementary energy-budget measurements are made with a portable station.

Objectives of the Gila River Phreatophyte Project, as summarized by the project chief, R. C. Culler (1965), are

(1) to evaluate water conservation by phreatophyte control on a flood plain typical of many areas of existing and proposed applications;
(2) to describe the hydrologic and ecologic variables of the project area for the purpose of transposition of water conservation evaluations to other sites;
(3) to test and develop methods for evaluating hydrologic variables on a large area.

In connection with the third objective of the Gila River Phreatophyte Project, the authors conducted the supplementary investigation reported here. This investigation had several interrelated objectives. (1) Measure the moisture and energy gradients in the soils under and adjacent to the dominant types of riparian vegetation in the Gila River Phreatophyte Project area. (2) Determine the effect of shading on soil-moisture migration and dissipation by comparing soil-moisture and energy data from adjacent shaded and unshaded sites. (3) Determine the moisture-use characteristics of dominant riparian species by comparing soil-moisture and energy data obtained before and after the annual maximum-growth season. (4) Interpret shading and moisture-use data in terms of probable effects of vegetation modification on the water supply. (5) Develop, calibrate, and test equipment and methods for measuring moisture and energy gradients in the soil. (6) Define relationships between moisture migration through soils and patterns of soil chemistry under and adjacent to dominant types of riparian vegetation in the Gila River Phreatophyte Project area.

This report presents a new look at soil moisture in a semiarid flood-plain environment and the role of phreatophytes in moisture utilization. Some of the methods used are new and have not yet received general acceptance. These methods produce data that have not been obtainable by commonly used methods and require new forms of data presentation and analysis. Therefore, there may be no background for parts of this report in bibliographies of previous investigations.

Traditional soil-physics terminology has been modified to conform more closely to dictionary definitions and to permit bringing together two theories of moisture retention. It is hoped that the data, methods, and interpretations reported herein will be useful to those studying moisture and energy relationships in soils.

Water use by phreatophytes has been studied by several agencies using various types of evapotranspirometers, including tanks, tents, weather instruments, and lysimeters. Many of these devices are discussed in other chapters of this professional paper series. For details of laboratory techniques used in measuring or controlling the moisture-retention forces in soils, the reader is referred to numerous reports, such as those by Richards (1949), Slater and Bryant (1946), and Eckardt (1960). The effects of temperature gradients on soil moisture have been reported by Gardner (1955), Rao and Ramacharlu (1955), Philip and DeVries (1957), Hutcheon (1958), Kulick (1967), and others. Basic theories of soil moisture and its energy have been discussed by Edlefsen and Anderson (1943) and summarized recently by Remson and Randolph (1962), Stallman (1964), and Kuzmak and Sereda (1958). In the present study, a new method (McQueen and Miller, 1968) was used to measure the moisture-retention forces existing in soil samples obtained under vegetation and in adjacent clear areas; the measurements were then used to define the probable effect of tree removal on the thermal and moisture regimes.

ACKNOWLEDGMENTS

Special thanks are extended to L. M. Shown, who assisted in the field sampling, and to F. R. Steputis, who assisted in maintenance and reading of field instruments. Karl Ratzlaff and William Buller assisted in laboratory analyses of soil samples. The authors gratefully acknowledge constructive criticism and review of the manuscript by L. M. Shown, M. L. Sorey, R. C. Culler, R. L. Hansen, J. W. Cary, R. L. Harlan, R. F. Hadley, C. C. McDonald, and D. A. Webster.

THEORIES OF MOISTURE RETENTION AND MIGRATION

An extensive review of the literature on soil-moisture retention and migration disclosed considerable confusion and some disagreement on basic theories. Published methods for estimating moisture movement in the unsaturated zone are applicable only to homogeneous isotropic sediments with known hydrologic properties, but one dominant characteristic of flood-plain soils is heterogeneity. For these reasons and because in the present study the moisture stresses above a shallow water table were measured for the first time by a wide-range method, this part of the report is devoted to soil-moisture theories and their application to a flood-plain environment.

MOISTURE RETENTION

Two of many possible forces for retaining water in soil seem to be dominant and amenable to study in the range of temperatures and of pressures normally found in natural soils: the capillary retention force, and the adsorbed-film retention force. Water of crystallization, or combined water, and water trapped within impermeable rock units are not usually considered important. Osmotic potentials influence pressures and moisture movement in the vapor phase, so they must be considered in all measurements of moisture-energy relationships.

CAPILLARY RETENTION

The primary characteristic of a capillary-force system is a curved air–liquid interface, usually with atmospheric pressure on the concave or vapor side of the interface and with negative pressure, equal to the capillary stress, on the convex or liquid side. The radius of curvature of the interface is related to the moisture stress by the equation for the height of rise in a capillary tube:

$$h = 2\tau/r\rho g$$

where

h = stress, or height of rise,
τ = surface tension,
r = radius of curvature of the meniscus,
ρ = density of fluid, and
g = gravitational constant.

This equation usually includes the cosine of the angle of wetting. However, for water and soils the capillary meniscus is anchored to a multimolecular film adsorbed to the solid particles, and the angle of wetting must be nearly zero; therefore, its cosine is 1 (Remson and Randolph, 1962, p. 6; Stallman, 1964, p. 12, 13). For porous media with complex curved interfaces the radius of curvature is usually expressed as an equivalent radius.

The curved air–water interface of a capillary meniscus is the expression of a pressure difference between the air and the water. Before the capillary formula is applied indiscriminately, pressure, temperature, and phase relationships of water must be studied. Basic physics states that whenever the saturation vapor pressure of a liquid exceeds the confining pressure on the liquid, bubbles of vapor form within the liquid as the liquid changes phase, or starts to boil (Worthing and Halliday, 1948, p. 302). This condition can be induced either by heating the liquid to a higher saturation vapor pressure or by reducing the confining pressure to the saturation vapor pressure.

When water is at 20°C the saturation vapor pressure is 17.5 mm (millimeters) of mercury or 23.77 cm (centimeters) of water. Standard atmospheric pressure at sea level is 1,032.27 cm of water. Therefore, in a capillary system at 20°C with standard atmospheric pressure on the vapor side, whenever the tension or pressure reduction within the water approaches 1,008.5 cm, which is equivalent to 23.77 cm absolute pressure, the water must change phase or boil, and the capillary menisci can no longer exist. This suggests a limit on the capillary moisture stress and on the height of capillary rise. Dissolved gases may start to form bubbles within the liquid at tensions below this limit. Bolt and Miller (1958) discussed the possible existence of tensions in soil water and suggested that soil water should have tension limitations similar to those in other hydraulic systems. They stated on page 928: "We suspect that the fraction of water which is actually in tension is never large except perhaps at very high water contents and small tensions." They concluded: "We regard apparently large values of soil moisture tension or soil suction to be artifacts accounted for by the influence of the electrical double layer" [adsorption to surfaces].

ADSORBED-FILM RETENTION

Moisture is attracted to and adsorbed on particle surfaces by molecular forces. The quantity of moisture adsorbed is a function of the attractive forces between molecules, but it may be influenced by electrical charges and chemical valence forces. Widtsoe (1914) discussed soil moisture from the standpoint of film thickness, indicating several stages in water movement over soil grains. Meinzer (1923b, p. 18–22) discussed the molecular forces of water in rocks and included several diagrams illustrating basic principles. He indicated (p. 20) that "the force of molecular attraction is believed to extend through several times the space occupied by one molecule * * * ." The thermodynamics of adsorbed films of moisture was discussed extensively by Edlefsen and Anderson (1943, p. 195–243).

Langmuir (1916 and 1917) proposed that moisture was adsorbed to soil-particle surfaces by chemical valence forces only and, therefore, could only be one molecular layer thick. Smith (1936) and other proponents of the universal application of the capillary theory still accept this monolayer limitation on adsorption in spite of evidence for multimolecular adsorption presented by workers in physical chemistry (Young and Crowell, 1962).

Capillary water bodies and adsorbed multimolecular films are both involved in soil-moisture retention. The problem is defining the range of applicability of each theory. Data obtained with the method used in this study to measure moisture tensions indicate that at stresses above pF 2.30 (0.2 bar) [1] moisture is retained primarily as films adsorbed on the particle surfaces. A capillary meniscus (at sea level with water at 20°C) can exist at stresses below a theoretical upper limit of pF 3 (1 bar). Therefore, the two theories overlap in the range from pF 2.3 to 3.0 (0.2 to 1 bar). This is a small part of the total range of stresses, but it is important. Russell (1959) said: "50 percent or more of the water used by plants is held at tensions less than 1 atmosphere."

[1] pF is the common logarithm of the moisture tension measured in centimeters of water (Schofield, 1935).

OSMOTIC POTENTIAL

Osmotic pressure as applied to soils is defined as:

> That pressure to which a pool of water, identical in composition to the soil water, must be subjected in order to be in equilibrium, through a semipermeable membrane, with a pool of pure water (semipermeable means permeable only to water). [Osmotic pressure] may be identified with osmotic potential * * *. (Soil Science Society of America Committee on Terminology, 1965, p. 348.)

To this definition should be added the concept that where two solutions are separated by a semipermeable membrane, the pressure difference is proportional to the difference in concentration (osmotic potential) of the two solutions.

In order for a pressure to exist because of minerals dissolved in water, there must be a difference in the dissolved-mineral concentrations of two solutions separated by a semipermeable membrane. Plant tissues may act as semipermeable membranes and, therefore, may develop osmotic gradients that aid or resist absorption of water from the soil. Salt concentrations in plant fluids will usually be slightly higher than those in the soil moisture, so the osmotic pressure gradients will usually aid moisture flow into the plant. Osmotic gradients will usually be small because concentration differences are usually small.

An air–water interface is a semipermeable membrane with zero osmotic potential on the vapor side and the full solution potential on the liquid side. The osmotic gradient in this case will oppose evaporation and may induce condensation if the vapor pressure of the air approaches saturation.

Certain pseudomembranes associated with differences in salt concentrations at liquid–solid interfaces have been described (Day and others, 1967; Cary and Taylor, 1967). However, the presence and function of the pseudomembranes in transporting moisture have not been adequately defined by controlled experiments. Kemper (1961) pointed out that osmotic gradients are probably not very effective in transporting water where moisture stress is less than 1 bar (pF 3.0). No data were obtained during this study to further define moisture movement in response to osmotic pressure gradients.

PRESSURE IN THE VAPOR PHASE

The vapor pressure of the soil atmosphere is a function of the forces retaining moisture in the soil. This is true if the moisture is present only as adsorbed films, if capillary moisture is present, or if osmotic forces are present.

The relationship between vapor pressure and moisture stress has been presented by numerous authors, including Edlefsen and Anderson (1943), Smith (1936), Remson and Randolph (1962), Stallman (1964), and Croney and others (1952):

$$h = -(RT/Mg)\ln P/P_0,$$

where

h = moisture stress in centimeters of water,
R = gas constant (8.315×10^7 ergs mole^{-1} °C^{-1}),
T = absolute temperature of soil moisture (°K),
M = molecular weight of water (18.0 g (grams) mole^{-1}),
g = gravitational constant (981 ergs g^{-1} cm^{-1}),
ln = natural or Naperian logarithm (base e),
P = partial pressure of water vapor in soil atmosphere (millibars), and
P_0 = vapor pressure over pure distilled water.

At 20°C, P_0 = 23.347 and pF = 6.502 + log (1.368 − log P), where log = common logarithm (base 10).

MOISTURE MIGRATION

Moisture migrates through soils as a liquid or as a vapor in response to energy gradients. Liquid and vapor migration can be in concert or in opposition. In order to predict or define moisture migration, the gravitational, moisture-stress, and thermal-energy gradients, as well as the liquid and vapor conductivities of the soils, must be defined.

MIGRATION AS LIQUID, AND THE FIELD-CAPACITY CONCEPT

In any hydraulic system, flow occurs whenever a pressure difference is not compensated by a positional (elevation) difference. Moisture-stress measurements are usually referred to an arbitrary datum of a flat free-water surface. In a system containing a water table or a phreatic surface, this surface can be used as the datum. When the moisture retention force, either capillary or adsorptive, is equal to the height above the water table, then the moisture-stress in the sample is said to be in equilibrium with the gravity potential. Departures from equilibrium (differences between the stress in the sample and its height above a water table) represent either excess moisture that is on its way to the water table or deficiencies in soil moisture induced by evapotranspiration processes. Moisture-stress measurements must be adjusted for height above (or below) the datum to define energy gradients.

The term "field capacity" has been defined as "the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased, usually 2 or 3 days after irrigation." (Veihmeyer and Hendrickson, 1931, p. 181). This definition implies that at a certain moisture content in a soil there is an abrupt change in moisture flow and probably a change in the moisture stress–moisture content relationship. Two values are given for moisture stress at field capacity. One-third atmosphere (pF 2.52) is the accepted value for normal, or fine-grained, soils, and one-tenth atmosphere (pF 2.00) is the value for sandy soils. Data obtained in Geological Survey laboratories (Prill and Johnson, 1959; McQueen, 1963) point out the reason for a range of values. The standard centrifuge moisture-equivalent test, used to establish relationships between moisture stress and field capacity or specific retention, permits heating which dehydrates sand samples. Also, clay samples may not reach equilibrium in the time allowed for a standard centrifuge test (Croney and others, 1952). When temperature and humidity in the centrifuge are controlled and samples are run for 6 hours instead of 1 hour, there is little difference in stress between coarse and fine samples.

Meinzer (1923a), in discussing subsurface water, divided the zone of aeration into three belts: the belt of soil water, the intermediate belt, and the capillary fringe.

The belt of soil water is that part of the soil subjected to moisture depletion by evaporation and transpiration. Moisture content and retention forces vary with the seasons and with the utilization characteristics of the plants. The depth of this belt is limited to that part of the zone of aeration occupied by plant roots or, if there are no roots, to that part of the profile influenced by diurnal temperature fluctuations.

The capillary fringe is that part of the zone of aeration immediately above the water table where the moisture content exceeds field capacity.

The intermediate belt is a moisture transmission zone between the belt of soil water and the capillary fringe. Moisture-stress values are thought to be relatively constant, and moisture content is assumed to be a function of soil characteristics. Meinzer (1923a, p. 26) referred to the intermediate belt as "the residual part of the zone of aeration." He described the belt of soil water and the capillary fringe as having finite thicknesses and the intermediate belt as the part between the two, if any exists. Water is supposed to move through the intermediate belt under gravity gradients and then only when the moisture content exceeds field capacity.

The wide-range method for measuring the moisture stress existing in soil samples, combined with standard methods for estimating field capacity, permits a new look at moisture relationships in an arid flood-plain environment and enables an evaluation of the field-capacity concept.

Data obtained in this study indicate a change in energy status of soil moisture at a stress of 0.21 bar (pF 2.32) (McQueen and Miller, 1968). We have chosen this value (pF 2.32) as the best estimate of the stress at field capacity.

The intermediate belt, if it exists, should appear on the pF profile as an appreciable depth increment at a pF of about 2.3, with increasing stress above it and decreasing stress below it. The capillary fringe may extend as much as 2 meters above the water table. The belt of soil water is often less than 2 meters deep, but it may extend as deep as 20 to 25 meters if there are deep-rooted plants present (Meinzer, 1927).

MIGRATION AS VAPOR

Numerous investigators have shown that thermal gradients are capable of moving moisture through soils. Rates of moisture movement are often much greater than those predicted by theory (Philip and DeVries, 1957; Hutcheon, 1958). There are indications that most of the moisture moved by thermal gradients migrates in the vapor phase (Kuzmak and Sereda, 1958) and that temperature has little influence on capillary-held water. Hutcheon (1958, p. 130) concluded:

> A temperature gradient imposed on a soil column, initially of uniform moisture content and temperature, will create a relatively large gradient of vapor pressure from warm to cold regions, but only a very slight gradient of moisture tension within the liquid phase in the same direction.

An examination of two basic formulas shows why this must be true. In the capillary formula $h = 2\tau/r\rho g$, only the surface tension (τ) and the density (ρ) are influenced by temperature. Dorsey (1940, p. 516) gave the rate of change of surface tension with temperature at 20°C as −0.151 dyne per centimeter per degree Celsius (−0.00015 gram per centimeter per degree Celsius). The density of water does not change at a uniform rate, but at 20°C its rate of change is given as −0.00002 gram per cubic centimeter per degree Celsius. The effect of a small temperature change on the capillary tension is obviously small.

In the equation for the relationship between total stress and vapor pressure of the soil air ($h = RT \ln p_v/P_0$), a small change in temperature may cause a relatively large change in stress, because the variables are all temperature dependent. The effect of temperature on moisture films adsorbed on particle surfaces is not known because adsorption relationships are not well defined.

Although numerous studies have been made of moisture movement under thermal gradients, the exact mechanisms involved are not well defined or understood. One thing common in these studies is that the moisture moved by a thermal gradient exceeds that allowed by theories of vapor diffusion.

Hutcheon (1958, p. 131) said: "For moisture conditions above the permanent wilting percentage, the observed coefficients of vapor diffusion were from 6 to 8 times greater than those calculated from known relationships for isothermal conditions."

Philip and DeVries (1957) tabulated data from several previous reports and computed ratios of the observed movement to the value predicted by simple theory. They then proposed a theory of combined liquid and vapor movement that included condensation into one side of a capillary "contact" water body, flow through the water body, and evaporation on the other side of the water body. Their theory would have been more plausible if they had allowed flow of multimolecular adsorbed films instead of trying to restrict liquid movement to flow through capillary water bodies that probably do not exist at stresses of pF 3.0 (1 bar) and certainly do not exist at the higher stress they cited.

Thermal energy is supplied to the soil surface by solar radiation and conduction from the air in a complex cyclic function involving annual and diurnal primary frequencies modified by an irregular storm-frequency pattern and possibly by longer climatic-cycle patterns. Some energy is available from below the soil as indicated by the geothermal gradient. Energy is removed from the soil by evaporative cooling and by radiation. Attenuation of the cyclic patterns of thermal-energy that move moisture in soils is influenced by the amount of moisture available for movement and by the frequency of the energy fluctuations. The diurnal cycle, having the higher frequency, is attenuated at shallower depths than the annual cycle and, therefore, influences less of the soil mantle. The effectiveness of cyclic temperature fluctuations in transporting soil moisture may depend upon the moisture content and the depth of the water table, as well as the frequency of the fluctuations. The direction of movement will usually be in the direction of decreasing temperature, but this may be modified by stress gradients.

Whenever moisture is moved through a porous medium there is a concurrent transfer of energy. When the movement includes capillary flow or film flow, there is a very small change of hydraulic energy to heat because of frictional resistance. If the movement involves evaporation and condensation, the heat of vaporization and condensation must be included in the energy transferred. When temperature and energy measurements can be made with sufficient precision, flow of soil moisture may be defined by thermometric measurements. Unfortunately, the precision required was beyond the limitations of this study.

PROCEDURES

Procedures used in this study were developed in the Soil and Moisture Conservation Program of the U.S. Geological Survey for use on arid lands. Many of the procedures are based on popular or standard argicultural methods, but some were developed to cover the broader scope of conditions that exist on range lands.

Soils on river flood plains are often extremely variable. Cobbles and clays may be found adjacent to each other. The sampling procedures and laboratory methods were chosen to define this variability and to define energy relationships without interference from the variability. Sampling depth increments were kept small enough to define trends and abrupt changes. Each increment was handled as an individual sample.

The usual methods involve defining the moisture-retention characteristics of representative samples, measuring the moisture content, and then determining the stress from the characteristic curve. These methods were considered inadequate. The wide-range method used in this study permits measuring both the moisture content and the moisture tension of each sample.

As part of a continuing program of development and testing of soil-moisture instrumentation and methods, four experimental plastic columns, each containing 42 electrical-resistance moisture-stress transducers and 42 thermisters, were installed on May 10 and 11, 1964, in the sampling pits for sites 64OT and 64UT [2] in section 23 of the Gila River Phreatophyte Project area. These columns were later destroyed by submergence in rising waters of the San Carlos Reservoir. Before their destruction they yielded valuable information on temperature gradients, and they enabled a qualitative evaluation of electrical-resistance moisture instruments.

METHODS OF MEASURING MOISTURE-RETENTION FORCES

A graph showing the relationship between the moisture content of a soil and the magnitude of the forces retaining the moisture in the soil, commonly called a moisture-retention curve or a moisture-

[2] Site number code consists of sampling year (62=1962), shading on site (O, unshaded; U, shaded), and trees associated with site (T, saltcedar; C, cottonwood; M, mesquite; W, willow; and S, mixed community).

characteristic curve, is essential in estimating moisture movement in soils. Many laboratory procedures have been developed to define this relationship. A few methods have been developed for measuring existing moisture-retention forces in the field. The principles involved in these measurements are discussed here because they aid understanding of moisture movement, and they help to explain the writers' choice of methods.

The forces of moisture retention can be measured directly as the pressure in the liquid phase or as the pressure in the vapor phase, or they can be measured indirectly as some moisture-dependent property of an inert porous material in contact with the soil moisture. Some examples of available methods and their characteristics follow.

METHODS OF MEASURING PRESSURE IN THE LIQUID PHASE

The capillary tensiometer, which was developed at Utah State Agricultural College under the direction of J. A. Widtsoe, measures negative pressure within the liquid phase. A porous bulb in contact with the soil is connected to a manometer or aneroid vacuum gage. The bulb and connecting lines are filled with distilled water, and the system is sealed. Water flows from the bulb into the soil until the negative pressure in the instrument equals the capillary tension in the soil water. The tensiometer is limited to measuring a stress of less than about pF 2.9 (0.8 bar) because vapor bubbles form in the instrument when the absolute pressure in the water approaches the saturation vapor pressure of the water. The porous bulb of a tensiometer tends to act as an imperfect osmotic membrane; therefore, the instrument may respond to the osmotic component of the soil moisture until diffusion of salts through the cup equalizes the solution concentrations.

A tension table is a porous surface used in laboratories to impose a negative pressure on the water in soil samples. The samples are placed on the porous surface and a negative pressure is maintained beneath the porous surface by means of a hanging water column or a controlled vacuum pump. The tension table is subject to the same stress limitation as the tensiometer. However, it is normally operated well below its limit. (60 cm of water, or pF 1.8, has become a standard stress in many laboratories).

Pressure methods, suggested by Woodruff (1940) and developed by Richards (1941, 1947), are similar to the tension-table method in that they involve the application of pressure differentials to soil samples to establish points on the moisture-characteristic curves of the soils. There is one important difference between the two methods. In the tension-table method, decreased pressure is applied to the liquid phase, and the sample and its vapor phase are allowed to remain at atmospheric pressure; in the pressure methods, increased pressure is applied to the sample and its vapor phase, and the liquid phase is allowed to remain at atmospheric pressure. Allowing the liquid phase to remain at atmospheric pressure bypasses the capillary-limit problem, but it introduces an error into the results that has been noted and discussed by Chahal and Yong (1965). Within the pressure device, the capillary water, retained as rings around contact points between particles, develops radii of curvature that are smaller than those permitted by the capillary limit. When the samples are returned to atmospheric pressure, vapor bubbles form in the capillary-retained water, and the rings are disrupted so that the water contained in them flows into the adsorbed films. The films are then thicker than they should be for the pressure difference applied, and the actual stress is lower than the intended stress.

The centrifuge has been used in soils laboratories since the early 1900's to determine the moisture-holding power of soils. Two methods are in use. One, called the moisture-equivalent test, was proposed by Briggs and McLane (1907); the other employs modeling techniques in which the soil sample becomes part of a model of a soil column with a controlled water table. The moisture-equivalent test determines one point on the retention-relationship curve, whereas the modeling techniques are capable of defining the relationship from pF 2.3 to about pF 4.5. Higher values are possible, but the time and energy requirements become prohibitive.

In the moisture-equivalent test, capillary moisture is removed readily from soils by centrifugal force, whereas adsorbed films are removed slowly if at all. By properly choosing the amount and duration of energy applied, the capillary moisture can be removed and the adsorbed films left. The moisture content retained against centrifugal force is called the moisture equivalent and is accepted as a laboratory estimate of the field capacity, or the moisture a soil will retain against gravity drainage.

In the centrifuge modeling techniques, soil samples are supported on porous blocks or sand beds in special centrifuge cups. A drain is provided so that water remains in the outer ends of the cups, and a controlled water table or zero stress datum is simulated. The centrifugal force applied to the model distorts the equilibrium stress profile so that the stress at a given distance from the zero datum is equal to the distance multiplied by the relative centrifugal force. A sample supported 5 cm from the cup drain when spun at a relative centrifugal force of 1,000 times the force of gravity would have an equilibrium stress of 5,000 cm, or pF 3.7.

Results of centrifuge moisture measurements are influenced by temperature and humidity in the centrifuge; speed and duration of centrifuging; dimensions of the sample, sample container, and centrifuge head; and the time allowed between stopping the centrifuge and weighing the sample.

Freezing-point methods, such as the dilatometer technique described by Bouyoucos (1917), measure pressure in the liquid phase. The freezing temperature of water decreases as the pressure on the water increases, so a lowered freezing point would be found in water that is retained under positive pressure. Moisture adsorbed to particle surfaces is under positive pressure, but capillary absorbed moisture is under negative (gage) pressure or tension; therefore, a lowered freezing point could not be a result of capillary absorbed moisture. Dissolved salts also lower the freezing point of water, so the osmotic component would be included in freezing-point methods. The relationship between the freezing point and the moisture stress is given (Croney and others, 1952) as

$$h = L(t_0 - t)/Tg,$$

where

h = moisture stress in centimeters of water,
L = latent heat of fusion of pure water (3.336×10^9 ergs g^{-1}),
$(t_0 - t)$ = freezing-point depression (°C or °K),
T = absolute temperature of freezing point of pure water (273°K), and
g = gravitational constant (981 ergs g^{-1} cm^{-1}).

On the pF scale

$$pF = 4.095 + \log_{10}(t_0 - t).$$

METHODS OF MEASURING PRESSURE IN THE VAPOR PHASE

Measurements of pressure in the vapor phase are possible with several types of instruments. However, in order to measure moisture stress, extreme accuracy must be possible in the range of P/P_0 from 0.98 to 1.00 (98 to 100 percent relative humidity). An instrument that has been successful in laboratory use is the thermoelectric psychrometer (Monteith and Owen, 1958; Richards and Ogata, 1958; Spanner, 1951). Accuracy requirements have so far prevented development of a successful field instrument. Laboratory measurements of stresses below pF 3 should be considered of questionable accuracy because they are near the limits of accuracy of the best laboratory equipment.[3]

INDIRECT METHODS OF MEASUREMENT

Moisture-retention forces can be measured by indirect methods employing materials such as electrical resistance blocks (gypsum, fiberglass, and nylon, for example), gravimetric blocks, air permeability cones (Kemper and Amemiya, 1958), and, as in this study, filter paper (McQueen and Miller, 1968). All these methods are dependent upon the stability and accuracy of the calibrations of the instruments. Usually, a direct determination of the quantity of water absorbed by an inert absorbent will be more accurate than a secondary calibration, such as electrical conductivity or air permeability. Characteristics of indirect methods are varied. In general they are less accurate than direct methods, but they cover a wider range of stresses

The wide-range gravimetric method, which was used in this study, uses filter paper as sensors and measures stress from pF 0 to pF 6.2 (0 to 1,500 bars). Data obtained with this method, including the data presented in this report, show that its accuracy is good and that the variability between samples is small.

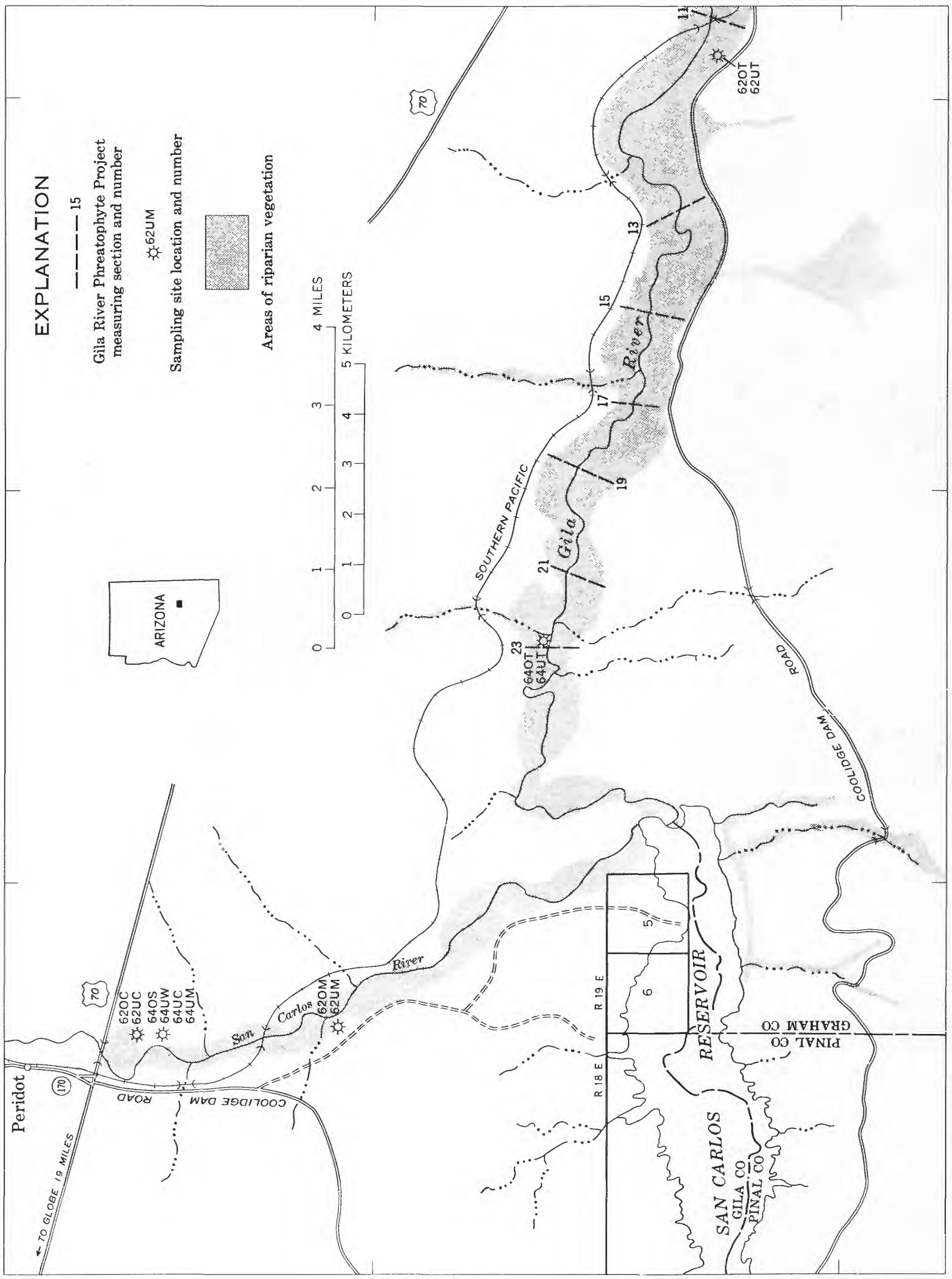
SAMPLING PROGRAM

Records of precipitation for southern Arizona show that a dry period usually exists from May to the middle of July. Trees along the Gila River start to leaf out in April and May and reach their full growth by July. Consequently, all sampling for this study was conducted during the months of May and July.

Initial sampling on May 26–30, 1962, was of shaded and unshaded sites associated with saltcedar (*Tamarix pentandra* Pall.; fig. 2), cottonwood (*Populus fremontii* Wats.; fig. 3), and honey mesquite (*Prosopis juliflora* (Swartz) DC; fig. 4). The two saltcedar sites were near section 11 of the Gila River Phreatophyte Project area (Culler, 1965). The cottonwood sites were near where U.S. Highway 70 crosses the San Carlos River at Peridot. The mesquite sites were south of the Southern Pacific Railroad bridge on the San Carlos River. Site locations are shown on the map in figure 1.

In 1964, four sites near the 1962 cottonwood sites were chosen so that one was unshaded, a second was shaded by a willow tree (*Salix gooddingii* Ball), a third

[3] At pF 3.0, $P/P_0 = 0.99927$, wet bulb depression is less than 0.01°C, and the emf produced by the thermojunctions is about 0.6 microvolts.



Base from U.S. Geological Survey San Carlos Reservoir, 1:62,500, 1962 and San Carlos, 1:24,000, 1966

FIGURE 1.—Index map of the area of confluence of the Gila and San Carlos Rivers, showing locations of sites sampled for soil-moisture characteristics.

FIGURE 2.—Sampling sites associated with saltcedar trees near section 11 of the Gila River Phreatophyte Project area. Sampled May 30, 1962. *a*, unshaded site 62OT; *b*, shaded site 62UT.

was shaded by a cottonwood tree, and a fourth was shaded by a mesquite tree (fig. 5). These sites were sampled May 13–14, when the trees were leafing out, and again July 18–20, when moisture use was beginning to decline.

Two sites were selected near section 23 of the Gila River Phreatophyte Project area, one of them shaded by a saltcedar tree and the other one in the open (fig. 6). They were sampled May 10–11 and July 16–17, 1964.

FIELD PROCEDURES

At each of 18 sites sampled during this study, soil-moisture samples were obtained from a column of soil extending from the surface to the water table. Tinned sample boxes were forced into the undisturbed soil and then excavated to provide relatively undisturbed samples. A disk of treated filter paper was placed in each sample, and the sample boxes were sealed with plastic tape to prevent moisture loss during transport and storage. Additional soil to be used for chemical and other laboratory analyses was obtained at each sampling depth. Soil temperatures were measured in place with either a dial thermometer or a thermister probe. Root concentrations, soil horizons, and soil

A

B

FIGURE 3.—Sampling sites associated with cottonwood trees on the San Carlos River flood plain. Sampled May 28–29, 1962. *A*, unshaded site 62OC; *B*, shaded site 62UC.

A

B

FIGURE 4.—Sampling sites associated with mesquite trees on the San Carlos River flood plain. Sampled May 26–27, 1962. *A*, unshaded site 62OM; *B*, shaded site 62UM.

A

B

FIGURE 5.—Sampling sites associated with willow, cottonwood, and mesquite trees on the San Carlos River flood plain. Sampled May 13–14 and July 18–20, 1964. *A*: *a*, unshaded site 64OS; *b*, shaded site 64UW under willow trees; *d*, shaded site 64UM under mesquite trees. *B*: *a*, unshaded site 64OS; *c*, shaded site 64UC under cottonwood trees.

FIGURE 6.—Sampling sites and experimental moisture-stress and temperature measuring units associated with saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 10–11 and July 16–17, 1964. *a*, unshaded site 64OT; *b*, shaded site 64UT.

structure were determined by visual observation of the profile. Soil textural classification was determined by standard field methods (U.S. Dept. Agriculture, 1951; Shaw, 1928).

LABORATORY PROCEDURES

Tests to determine the chemistry of the soils were similar to those described in U.S. Department of Agriculture Handbook 60 (Richards and others, 1954) except as noted. Saturated soil paste was prepared from samples obtained for chemical analysis (method 2). Paste conductivity (method 5), paste pH (method 21a), and saturation moisture content (method 27a) were determined. For the conductivity measurements, a two-electrode probe was used in place of the Bureau of Soils electrode cup. Saturation extracts were obtained using a pressure extractor. Soluble calcium plus magnesium was determined by titration with versenate, and soluble sodium was measured with a Beckman Model DU flame photometer.

Centrifuge moisture retention was determined for the May 1964 samples using a moisture-equivalent centrifuge with a drum head and square soil boxes that held samples weighing 40 to 50 grams. This permitted larger grain sizes to be included in the samples. The air in the centrifuge was maintained at 20°C and 100 percent relative humidity, and a relative centrifugal force of 1,000 times the force of gravity was applied for 6 hours (McQueen, 1963).

Moisture contents and moisture tensions were determined using the wide-range gravimetric method described by McQueen and Miller (1968). Moisture samples were stored in a constant-temperature chamber at 20°C (± 2°C) for at least 2 weeks to allow equalization of moisture-retention forces between the soil sample and the filter-paper sensor disk. After equilibration, the disks were separated from the samples and placed in small weighing boxes. Moisture contents of the samples and of the sensor disks were determined gravimetrically. Moisture stresses were computed from the moisture contents of the filter papers using the calibration relationships:

$$pF = 6.24617 - 7.23\ M$$

for disks with moisture-weight ratios (M) less than 0.54,

and

$$pF = 2.8948 - 1.025\ M$$

for disks with moisture-weight ratios (M) greater than 0.54.

These relationships are shown in figure 7 along with confidence limits determined from the data by statistical analyses.

Any given measurement consists of the true value plus or minus each of the inaccuracies involved in the measurements. In soil samples obtained from a continuous column, the differences between measurements on contiguous samples include the difference between true values plus or minus the inaccuracies. As the depths of sampling increments are reduced by increasing the number of samples taken, the differences between true values approach zero, and the differences in measured values approach the total variability of the measuring methods. The standard deviation of the differences between the measured stresses in contiguous samples becomes an indication of the variability of the method used to measure stress.

Differences in moisture contents of the sensor disks from contiguous samples were computed for the 18 soil columns sampled during this study. These differences were grouped according to the moisture content of the disk from the deeper sample. The class intervals in the range from 0 to 55 percent moisture content were 5 percent, and from 55 to 205 percent they were 10 percent. The mean and the standard deviation were

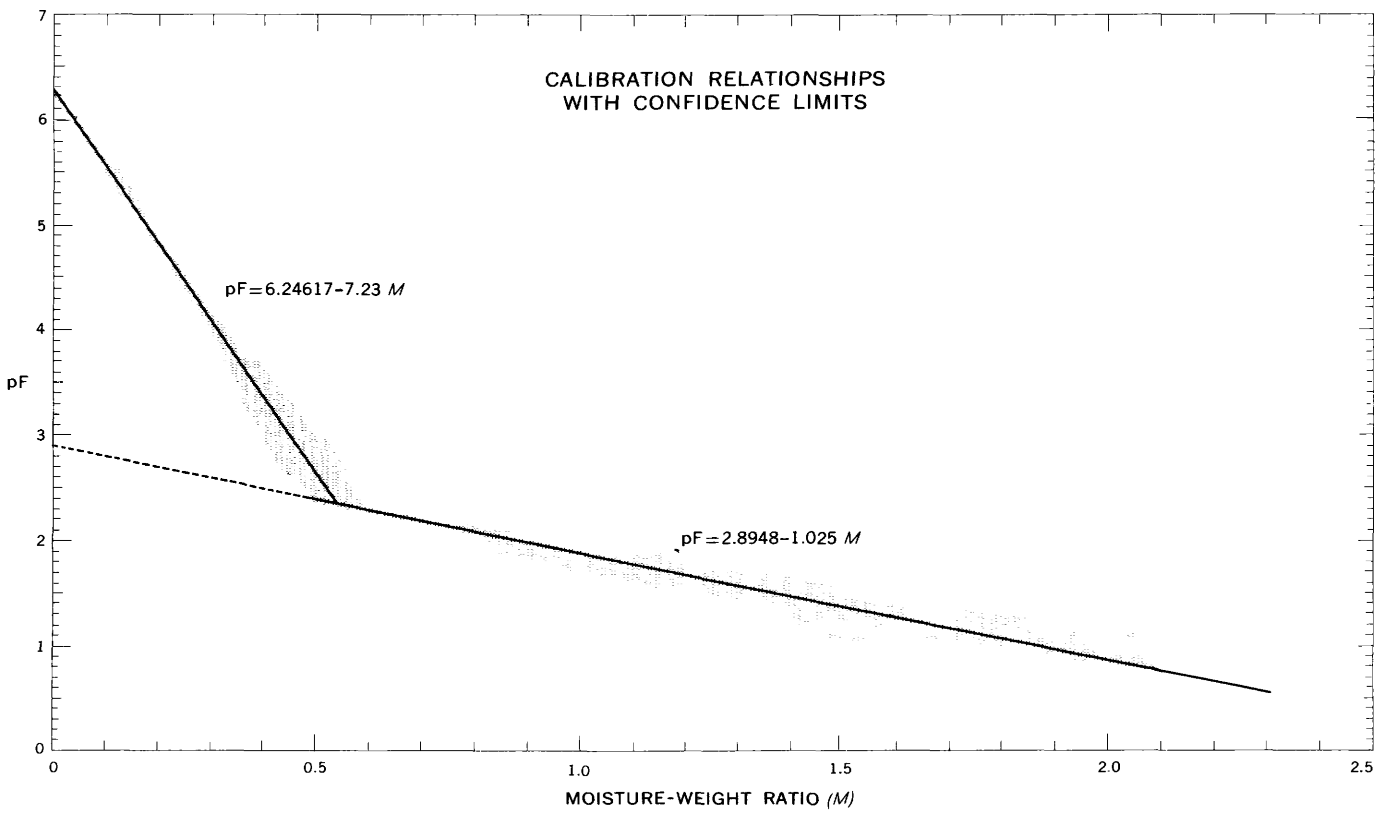


FIGURE 7.—Calibration relationships for wide-range gravimetric method of measuring soil-moisture stress. Confidence-limit envelope (shaded) represents one standard deviation of total variability on both sides of calibration line.

computed for each class interval. These standard deviations were plotted on both sides of the calibration curve (fig. 7) to indicate a confidence-limit envelope for the wide-range gravimetric method used in this study for measuring moisture stress.

The differences between the true values for the samples cannot be distinguished from the measured differences because of practical limitations on sampling. So, in this analysis, the indicated variability exceeds the actual variability. Because the indicated variability is generally less than that for other available methods, we consider the confidence limits shown to be acceptable.

Moisture-stress measurements made for this study are reported as the log of the stress, in centimeters of water, or pF as proposed by Schofield (1935). If the log of the height above a water table is subtracted from the log of the stress, the difference is the log of the ratio of the measured stress to the equilibrium stress:

$$\log S - \log H = \log \frac{S}{H} = \Delta\text{pF}$$

In order to simplify chart headings, we have labeled this ratio ΔpF. Where ΔpF is negative, the stress is less than equilibrium and there is an excess of moisture. Where ΔpF is positive, the stress is higher than equilibrium and there is a moisture deficiency. Measurements showing equilibrium with, or departures from equilibrium with, a water table have not been made successfully in the past. The wide-range filter-paper method used in this study for measuring moisture stress makes these measurements possible.

RESULTS

Descriptive data are given in table 1 for each site sampled during this study. Locations are given to the nearest minute of latitude and longitude. Section, township, and range are not given because the standard land grid has not been established for the Indian reservation lands upon which this study was conducted. Elevations were estimated from topographic maps. Relative saturation data were computed from moisture contents and saturation moisture capacities as a dimensionless ratio.

TABLE 1.—*Descriptions of sites sampled during this study*

Site No.	Location		Elevation (ft)	Date sampled	Trees	Shading [1]	Ground cover	Depth to water (cm)	Depth sampled (cm)	Relative saturation (dimensionless)
	Lat (N.)	Long (W.)								
62OT	33°12′	110°14′	2,520	May 30, 1962	Saltcedar	O	Bare	159	180	0.734
62UT				do	do	U	Dense annual grasses	160	180	.573
62OM	33°16′	110°27′	2,540	May 27, 1962	Mesquite	O	Bare	400	393	.373
62UM				May 26, 1962	do	U	Woodland mulch	420	440	.473
62OC	33°17′30″	110°27′	2,500	May 28, 1962	Cottonwood	O	Shrubs and annual weeds	175	180	.232
62UC				May 29, 1962	do	U	Sparse annual grasses	174	190	.401
64OT	33°13′	110°22′	2,460	May 10, 1964	Saltcedar	O	Bare	198	200	.417
				July 16, 1964	do	O	do	290	210	.362
64UT	33°13′	110°22′	2,460	May 11, 1964	do	U	Annual grasses	190	210	.499
				July 17, 1964	do	U	do	290	210	.514
64OS	33°17′30″	110°27′	2,500	May 13, 1964	Mixed	O	Sparse annual weeds	140	140	.526
				July 19, 1964	do	O	do	180	180	.320
64UW	33°17′30″	110°27′	2,500	May 13, 1964	Willow	U	Bare	130	125	.587
				July 18, 1964	do	U	do	180	175	.471
64UC	33°17′30″	110°27′	2,500	May 14, 1964	Cottonwood	U	do	140	135	.529
				July 20, 1964	do	U	do	165	165	.389
64UM	33°17′30″	110°27′	2,500	May 14, 1964	Mesquite	U	do	130	125	.544
				July 20, 1964	do	U	do	175	175	.323

[1] O = unshaded; U = shaded.

TABLE 2.—*Soil textures derived from field notes and laboratory tests*

Site No.	Date sampled	Depth increment (cm)	Soil texture	Average saturation moisture capacity (g/g)	Particle surface area (m²/g)
62OT	May 30, 1962	0–7	Loam	0.48	146
		7–80	Fine sand	.32	72
		80–90	Silt loam	.37	96
		90–105	Sand	.24	23
		105–140	Clay	.60	190
		140–180	Sand and gravel	.20	< 10
62UT	May 30, 1962	0–13	Loam	.51	157
		13–24	Silt loam	.40	111
		24–120	Sandy loam	.33	76
		120–180	Clay	.60	190
62OM	May 27, 1962	0–30	Silt loam	.37	96
		30–75	Loam	.50	154
		75–95	Silt loam	.41	114
		95–125	Clay	.52	162
		125–145	Silt loam	.40	111
		145–175	Sandy loam	.33	76
		175–200	Clay	.54	169
		200–265	Sandy loam	.30	60
		265–400	Sand	.20	< 10
62UM	May 26, 1962	0–105	Silt loam	.42	120
		105–120	Fine sand	.26	37
		120–135	Sandy loam	.35	87
		135–155	Sand	.19	< 10
		155–175	Silt loam	.39	106
		175–195	Loam	.49	152
		195–235	Sandy loam	.34	82
		235–440	Sand and gravel	.19	< 10
62OC	May 28, 1962	0–30	Sandy silt loam	.36	91
		30–60	Loam to sand	.40	111
		60–180	Sand and gravel	.22	< 10
62UC	May 29, 1962	0–17	Sandy silt loam	.37	97
		17–30	Silt loam	.43	125
		30–45	Sandy loam	.36	92
		45–80	Loam	.44	129
		80–105	Sandy loam	.37	97
		105–175	Sand	.27	42
		175–190	Coarse sand	.23	< 10

TABLE 2.—*Soil texture derived from field notes and laboratory tests*—Continued

Site No.	Date sampled	Depth increment (cm)	Soil texture	Average saturation moisture capacity (g/g)	Particle surface area (m²/g)
64OT	May 10, 1964	0–5	Clay	0.61	192
		5–20	Silt loam	.40	111
		20–60	Sandy loam	.32	72
		60–70	Gravel	.19	< 10
		70–100	Sandy loam	.32	72
		100–120	Silt loam	.40	111
		120–190	Sand and gravel	.20	< 10
		190–205	Silt loam	.40	111
	July 16, 1964	0–10	Loam	.52	162
		10–20	Sandy silt loam	.35	87
		20–110	Fine sand	.27	43
		110–140	Sandy loam	.36	92
		140–170	Coarse sand	.23	< 10
		170–195	Sand to silt	.36	92
		195–205	Sandy loam	.35	87
		205–210	Sand	.26	37
64UT	May 11, 1964	0–5	Clay (organic)	.85	290
		5–15	Silt loam	.39	106
		15–25	Sandy loam	.28	49
		25–75	Sand	.21	< 10
		75–80	do	.33	77
		80–130	Sandy loam	.36	92
		130–180	Sand	.22	< 10
		180–210	Silt loam	.37	96
	July 17, 1964	0–5	Clay (organic)	.59	186
		5–15	Silt loam	.40	111
		15–100	Sandy loam	.30	60
		100–135	Sand to loam	.41	116
		135–165	Loam to silt loam	.44	129
		165–180	Fine sand	.30	60
		180–210	Silt loam	.42	120
64OS	May 13, 1964	0–65	Silt loam	.40	111
		65–140	Fine sand	.30	60
	July 19, 1964	0–20	Loam	.54	169
		20–60	Silt loam	.45	134
		60–85	Sandy loam	.34	82
		85–175	Sand	.26	36

TABLE 2.—*Soil textures derived from field notes and laboratory tests*—Continued

Site No.	Date sampled	Depth increment (cm)	Soil texture	Average saturation moisture capacity (g/g)	Particle surface area (m²/g)
64UW	May 13, 1964	0–40	Loam	0.50	154
		40–75	Clay	.63	200
		75–125	Sandy loam	.31	65
	July 18, 1964	0–45	Loam	.50	154
		45–80	Clay	.63	200
		80–140	Sandy loam	.34	82
		140–175	Sand	.25	23
64UC	May 14, 1964	0–15	Clay loam	.53	166
		15–30	Silt loam	.44	129
		30–45	Clay	.58	183
		45–95	Fine sand	.27	43
		95–105	Silt loam	.39	106
		105–115	Sandy loam	.31	65
		115–135	Sand	.23	10
	July 20, 1964	0–15	Clay loam	.57	180
		15–30	Loam	.53	166
		30–85	Clay	.65	208
		85–165	Sand	.25	23
64UM	May 14, 1964	0–35	Loam	.52	162
		35–80	Sand	.24	24
		80–85	Silt loam	.38	102
		85–125	Sand	.26	36
	July 20, 1964	0–35	Loam	.52	162
		35–45	Silt loam	.45	134
		45–80	Sand	.27	43
		80–90	Sandy silt loam	.35	87
		90–155	Sandy loam	.29	54
		155–175	Sand	.25	23

Flood-plain soils are extremely heterogeneous because they form on the deposits of aggradation mixed with the residues of violent flood events. The soil textures in each soil column are summarized in table 2. The textural designations were determined from field observations and saturation moisture capacities. The particle surface areas were estimated from the saturation moisture capacities using a tentative statistical relationship.

Laboratory and field data obtained from soil samples during this study are presented graphically as function profiles. Individual data points are plotted at the midpoints of the sampling depth increments, or the data are given in bar graphs where the bar width represents the sampling depth increment. Occasionally an error in a laboratory measurement or in a computation created an apparently erroneous point on a profile. Where no source of error could be found in the data, the values were retained.

Three general types of data are presented: thermal, chemical, and moisture.

THERMAL DATA

Soil temperatures are a dynamic variable that fluctuates with the energy available and the changing thermal properties of the soil. Records of soil temperatures are significant only if they illustrate principles involved in energy transmission. For this reason, a few temperature measurements have been selected to show typical patterns of energy transfer within the soil.

Soil temperatures were obtained during sampling at all sites. Data from selected sites are presented in figures 8 and 9.

Four experimental moisture-stress measuring columns installed at sites 64OT and 64UT near section 23 in May 1964 included individual thermisters at 5-cm

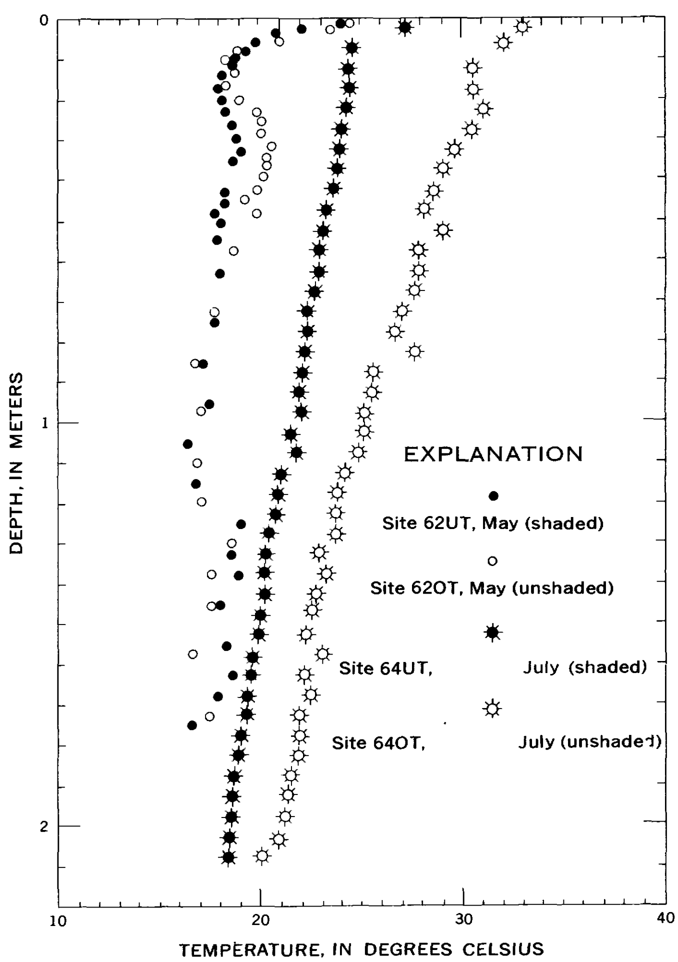


FIGURE 8.—Soil-temperature profiles for shaded and unshaded sites associated with saltcedar trees near sections 11 and 23 of the Gila River Phreatophyte Project area. Sites 62OT and 62UT sampled May 30, 1962; sites 64OT and 64UT sampled July 16–17, 1964.

depth increments. Selected data from these units are presented in figures 10 and 11.

Conduction of heat in a solid or a porous mass is not instantaneous but progresses at a finite rate; so if a variable source of heat is applied to a surface, a temperature profile within the mass will be a record of the fluctuations in heat applied at the surface. Because some heat is absorbed or used in the solid, the temperature record is attenuated so that at some depth in the mass no changes in temperature can be detected. The soil temperature profiles in figures 8, 9, and 10 show diurnal temperature cycles as sharply attenuated sine waves superimposed on the longer wave length annual temperature cycles. The sampling depth was too small to include more than a small fraction of the annual cycle.

Evaporation of soil moisture is inhanced by cyclic fluctuations in soil temperature, so the depth required to attenuate the diurnal temperature cycle may be the effective depth of evaporative moisture depletion. Complete attenuation of the diurnal fluctuations may be assumed where their wave forms cannot be distinguished from the annual fluctuation wave form. These depths, as indicated in figure 9 for the mixed community, were about 40 cm at the shaded sites and about 60 cm at the unshaded site. These depths are corroborated by data from other projects where continuous temperature recordings have been made, by depths of diurnal influence frequently reported in the literature, and by the depths of evaporative loss inferred from the stress data of this report.

The seasonal pattern of temperature fluctuations for five depths shown in figure 11 indicates a reversal of gradients in September or October. The other reversal occurs in April or May, although it was not shown in the data obtained. The temperature profiles obtained in May 1962 and 1964 (figs. 8 and 9) show almost uniform temperature with depth, and this event would occur at the time of gradient reversal.

Moisture moves in the direction of decreasing temperature. In the top 40 to 60 cm, movement would be

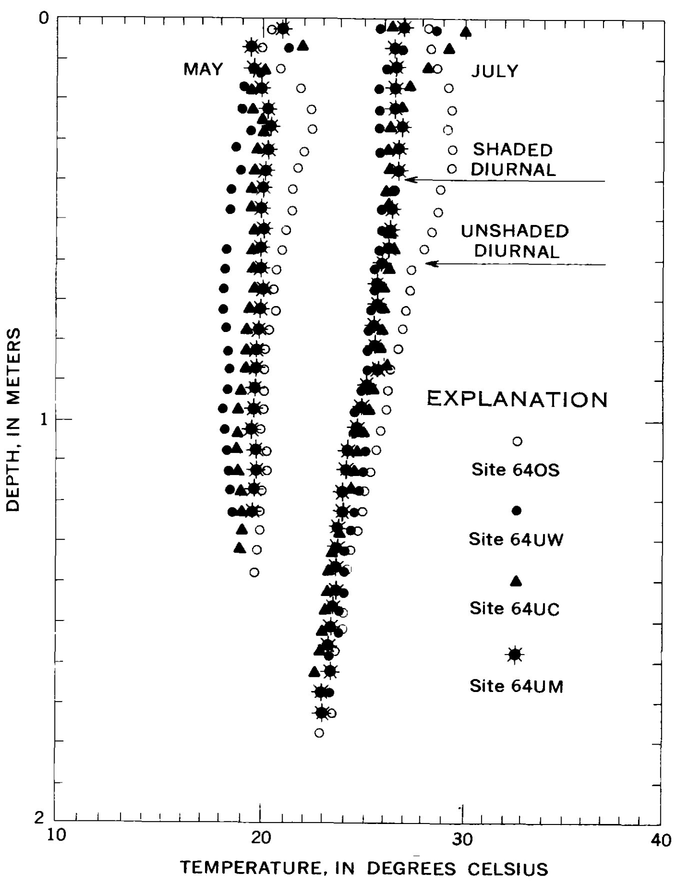


FIGURE 9.—Soil-temperature profiles for shaded and unshaded sites associated with willow, cottonwood, and mesquite trees on the San Carlos River flood plain. Sites 64OS, 64UW, 64UC, and 64UM sampled May 13–14 and July 18–20, 1964.

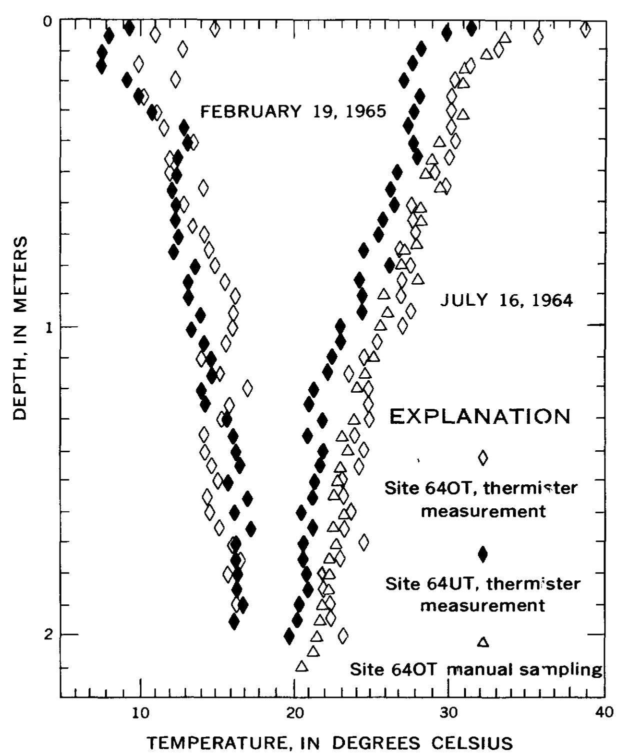


FIGURE 10.—Soil-temperature profiles obtained with thermisters in experimental moisture-stress measuring columns installed at sites 64OT and 64UT near section 23 of the Gila River Phreatophyte Project area. A temperature profile obtained by manual sampling methods at the unshaded site 64OT is included for comparison of methods. Measurements were obtained on July 16, 1964, and February 19, 1965.

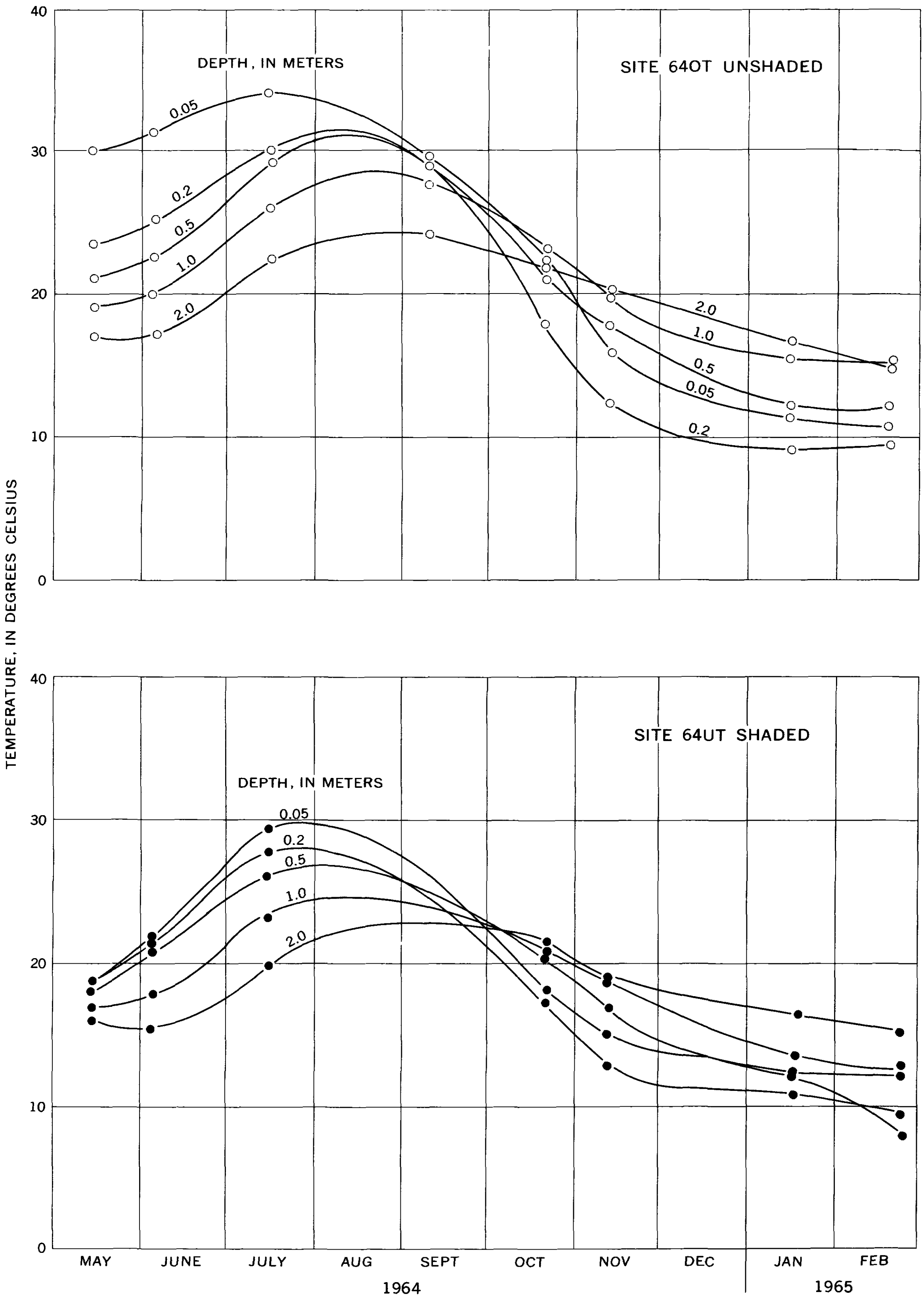


FIGURE 11.—Seasonal temperature fluctuations at selected depths for the period May 15, 1964, to February 25, 1965, at sites 64OT and 64UT near section 23 of the Gila River Phreatophyte Project area. Measurements were obtained with thermisters in experimental moisture-stress measuring columns.

downward during the day and upward during the night. Below 40 to 60 cm, movement in response to thermal gradients would be downward during the summer and upward during the winter. The quantity of moisture moved during a single diurnal cycle is not measurable with any method presently available. Also, the quantity of moisture moved by thermal gradients annually is not measurable because it is usually masked by recharge events and moisture utilization by plants.

Elimination of shading would result in increased downward movement of moisture in the vapor phase in response to increased thermal gradients. However, this downward movement in response to thermal gradients may be offset by increased capillary flow upward where the water table is less than 2 meters below the surface.

SOIL-CHEMISTRY DATA

Studies of the ratio between monovalent and divalent soluble cations ($Na^{+1}/Ca^{+2} + Mg^{+2}$) and the TSC (total soluble cations) measured with depth in soils indicate that a chemical imprint is produced in the soil by migrating moisture. Some basic principles, which apply to the processes involved, have been reported by Miller and Ratzlaff (1965):

1. The chemical pattern left in soils by moving moisture is influenced more by drying processes than by wetting processes.
2. Ion-exchange phenomena cause an increase in monovalent ions and a concomitant decrease in multivalent ions in the direction of moisture movement.
3. If water that contains an excess of monovalent ions is being supplied, principle 2 may be reversed, and monovalent ions may decrease in the direction of water movement (Brooks and others, 1958).
4. Where water movement occurs as film flow at tensions greater than 1 bar, a process of "salt sieving" (Kemper, 1960; Miller and Ratzlaff, 1965) may cause a decrease in TSC in the direction of water movement.
5. Where moisture movement is dominated by movement in the vapor phase, salts are left behind because their concentration soon exceeds solubility levels and they precipitate out. The result is an increase in salts in the direction of water movement. Such a concentration of salts is often found near the soil surface, where evaporation occurs.

Interpretations of water-movement patterns have been made from profiles of soluble-sodium percentage, sodium-adsorption ratio, cation-valence ratio, and pH compared with TSC. The cation-valence ratio ($Na^{+1}/Ca^{+2} + Mg^{+2}$) and the TSC ($Na^{+1} + Ca^{+2} + Mg^{+2}$) are plotted as logarithms against depth, in meters, in figures 12 through 20. In each figure, data for two related profiles are plotted for easy comparison.

In a soil column with a shallow water table (less than 2 meters), little drying may occur beyond a stress of 0.2 bar except at the surface, where evaporation withdraws moisture and stress exceeds 0.2 bar; so principle 1 may apply only near the surface. The salt sieving of principle 4 may only operate near the surface, where tensions exceed 1 bar.

Principles 2 and 3 may yield opposite interpretations, depending upon the cation concentration of the water supplied. The ground water in the Gila and San Carlos River flood plains is variable chemically, so interpretations of chemistry profiles become extremely complex. Because of these and other considerations, detailed analyses of chemical data by the methods of Miller and Ratzlaff (1965) were considered impractical at this time. However, the data are presented to make them available for further study.

Soluble salt concentrations may be greater at or near the soil surface than at depth owing to either of two processes: capillary supplied evaporation, or guttation (exudation). Where the water table is near the soil surface, evaporation of water supplied from the saturated zone by capillary rise will leave a deposit of salts near the surface. This should produce the highest concentration of salts at unshaded sites at the depths where evaporation occurs at the most rapid rate. Some species of trees are known to guttate or exude salt solutions, whereas other species transpire only pure water vapor. Salts will be deposited on the surface of soils under those trees that guttate. The profiles of total soluble cations presented in figures 12 through 20 show the results of these processes.

Capillary rise and evaporation have increased the salts near the surface of unshaded sites on the San Carlos River. See figure 13 and compare figure 17 with figures 18, 19, and 20. Capillary rise is not effective where the water table is deeper than 2 meters below the surface. See figures 14, 15, and 16.

Salts are deposited on the soil surface under saltcedar trees. See figure 12 and compare figures 15 and 16. Cottonwood trees also appear to deposit salts on the soil surface by guttation. See figure 13 and compare figure 19 with figures 18 and 20. There is no evidence of salts being deposited on the soil surface under willow and mesquite trees. See figure 14 and compare figures 18 and 20 with figures 15, 16, and 17.

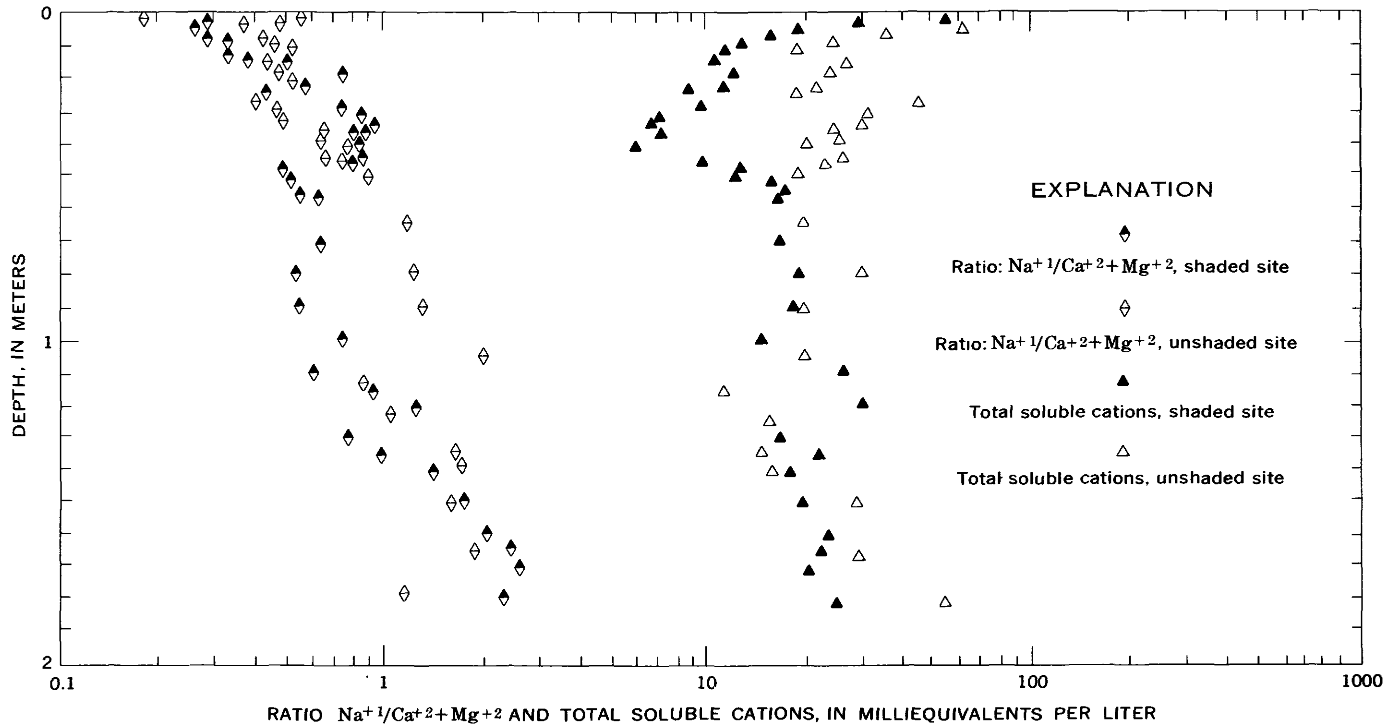


FIGURE 12.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded and unshaded sites 62UT and 62OT associated with saltcedar trees near section 11 of the Gila River Pheatophyte Project area. Sampled May 30, 1962.

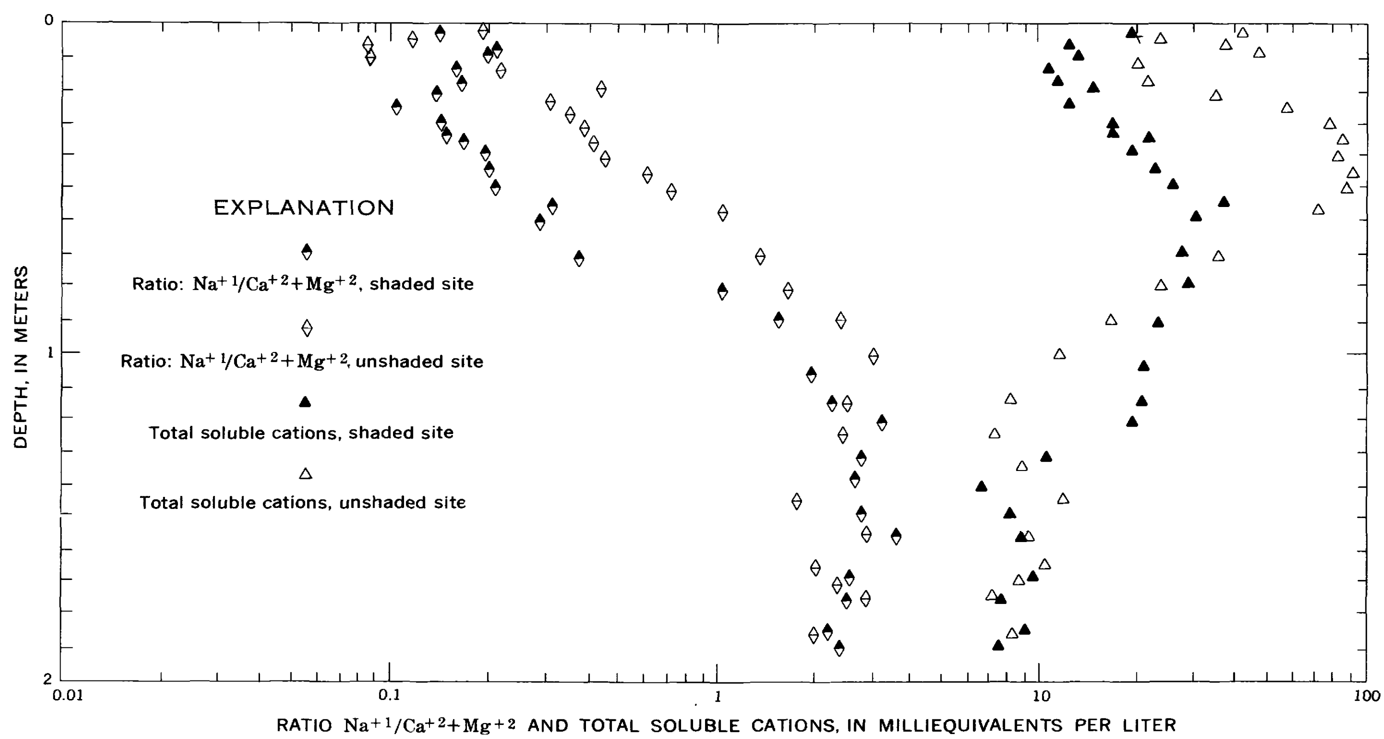


FIGURE 13.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded and unshaded sites 62UC and 62OC associated with cottonwood trees on the San Carlos River flood plain. Sampled May 28–29, 1962.

The chemical quality of the ground water appears to control the chemical imprint in the soils for an appreciable height above the water table. The quality of the ground water is reported to be extremely variable, and this variability makes interpretations difficult. Gatewood, Robinson, Colby, Hem, and Halpenny (1950, p. 61) said: "An outstanding characteristic of the Gila River in Safford Valley is the rapidity with which the concentration of dissolved solids in the water may change * * *." Hem (1950, p. 49) in discussing the chemical quality of water in the shallow alluvium of the Gila River, said:

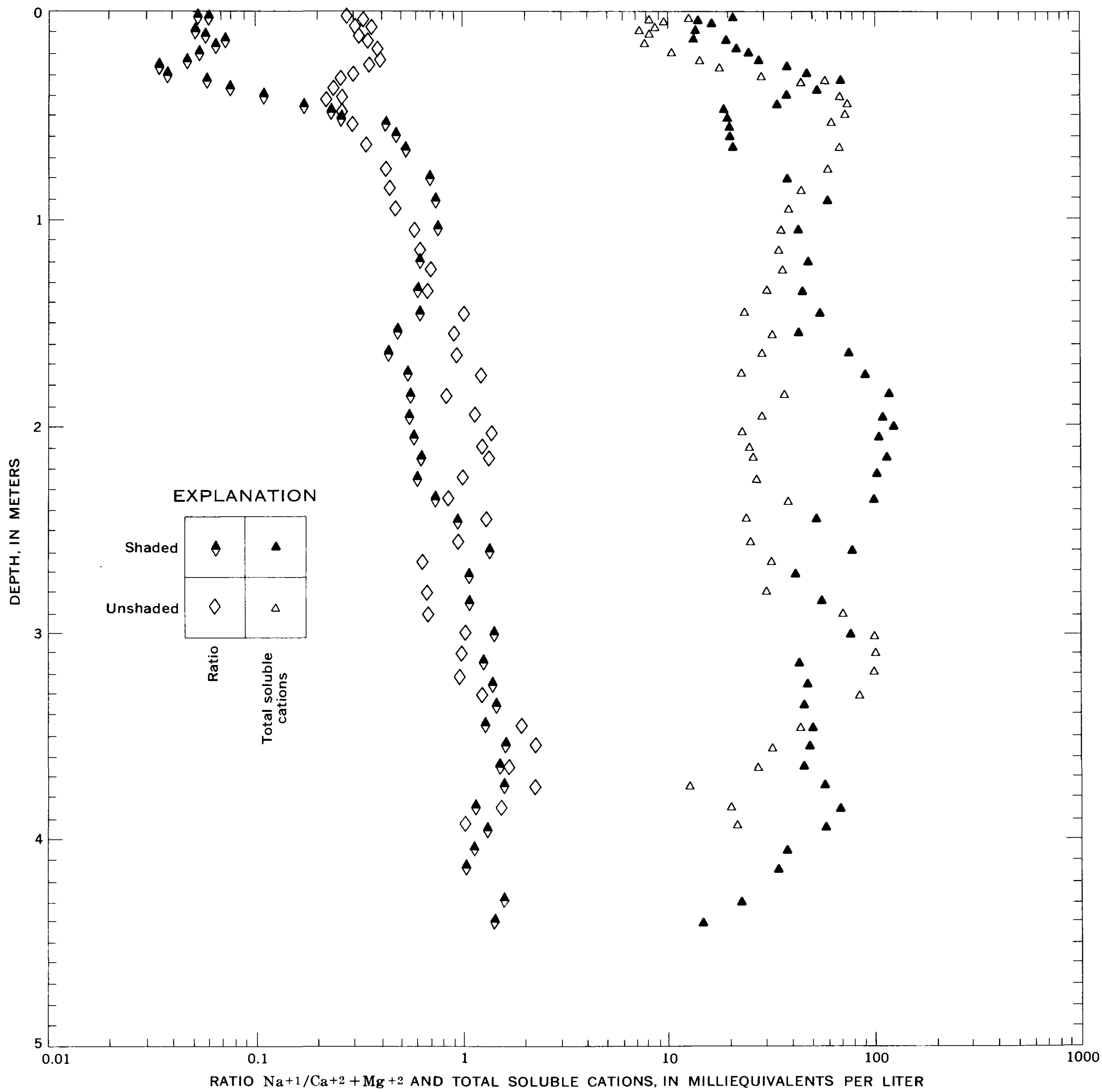


FIGURE 14.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded and unshaded sites 62UM and 62OM associated with mesquite trees on the San Carlos River flood plain. Sampled May 26–27, 1962.

The shallow ground waters from various parts of the valley, however, differ greatly in chemical character and concentration, and in a few instances water from a single well has been known to change 50 percent or more in concentration over a period of a few months.

A comparison between shallow ground water in the San Carlos River and that in the Gila River is difficult because of this variability. However, Hem (1950) did indicate that the dissolved-solids concentrations in the San Carlos waters may have a higher sodium ratio. These characteristics are evident in the chemical data obtained in this study.

MOISTURE AND MOISTURE-STRESS DATA

Moisture-tension profiles have been obtained in the past only from tensiometer installations. These profiles have been limited in detail and have included tensions only up to the practical limit of the instruments, which is about 0.5 bar. Attempts have been made by previous workers to estimate moisture stress from moisture-content measurements by using moisture-retention curves for "representative" samples, but natural variability and hysteresis factors have made results unsatisfactory. The wide-range gravimetric method used in this study for measuring moisture stress provides accurate detailed stress data over the total range of naturally occurring stresses.

Two useful measures of the moisture-retaining capacity of a soil are the CMR (centrifuge moisture retention) and the SMC (saturation moisture capacity). These properties are statistically related, and each is valuable for analysing the hydrology of soils. Both properties were determined for the samples obtained in May 1964. For all other samples, the CMR was not determined. The MC (moisture content) and the pF (moisture stress) existing in the samples at the time of sampling are presented in this section along with the CMR and the SMC. The CMR and SMC are both measures of the soil texture and are included to help explain the seeming disparity between MC and pF. This disparity exists because of variability in soil texture.

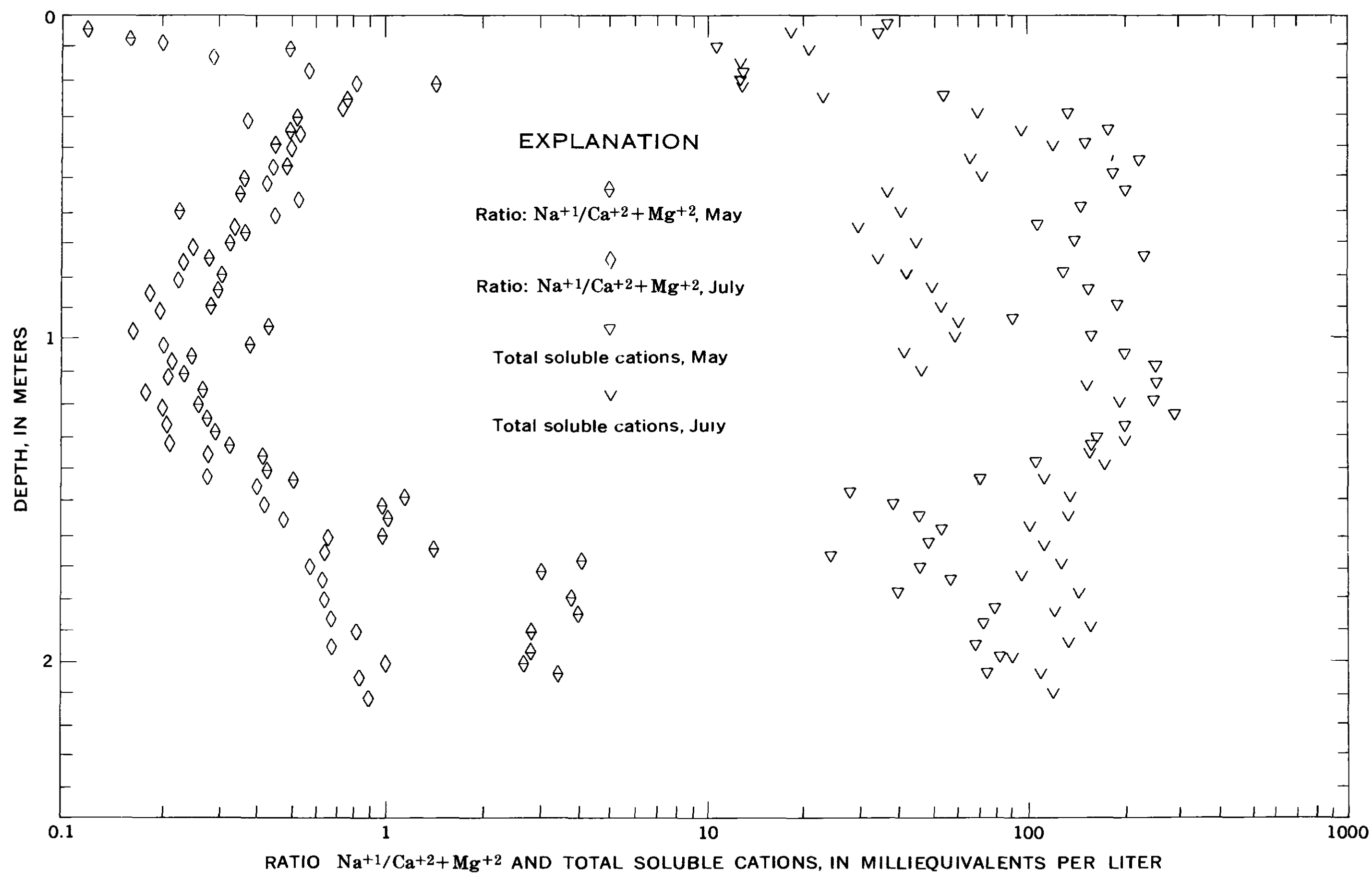


FIGURE 15.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for unshaded site 64OT associated with saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 10 and July 16, 1964.

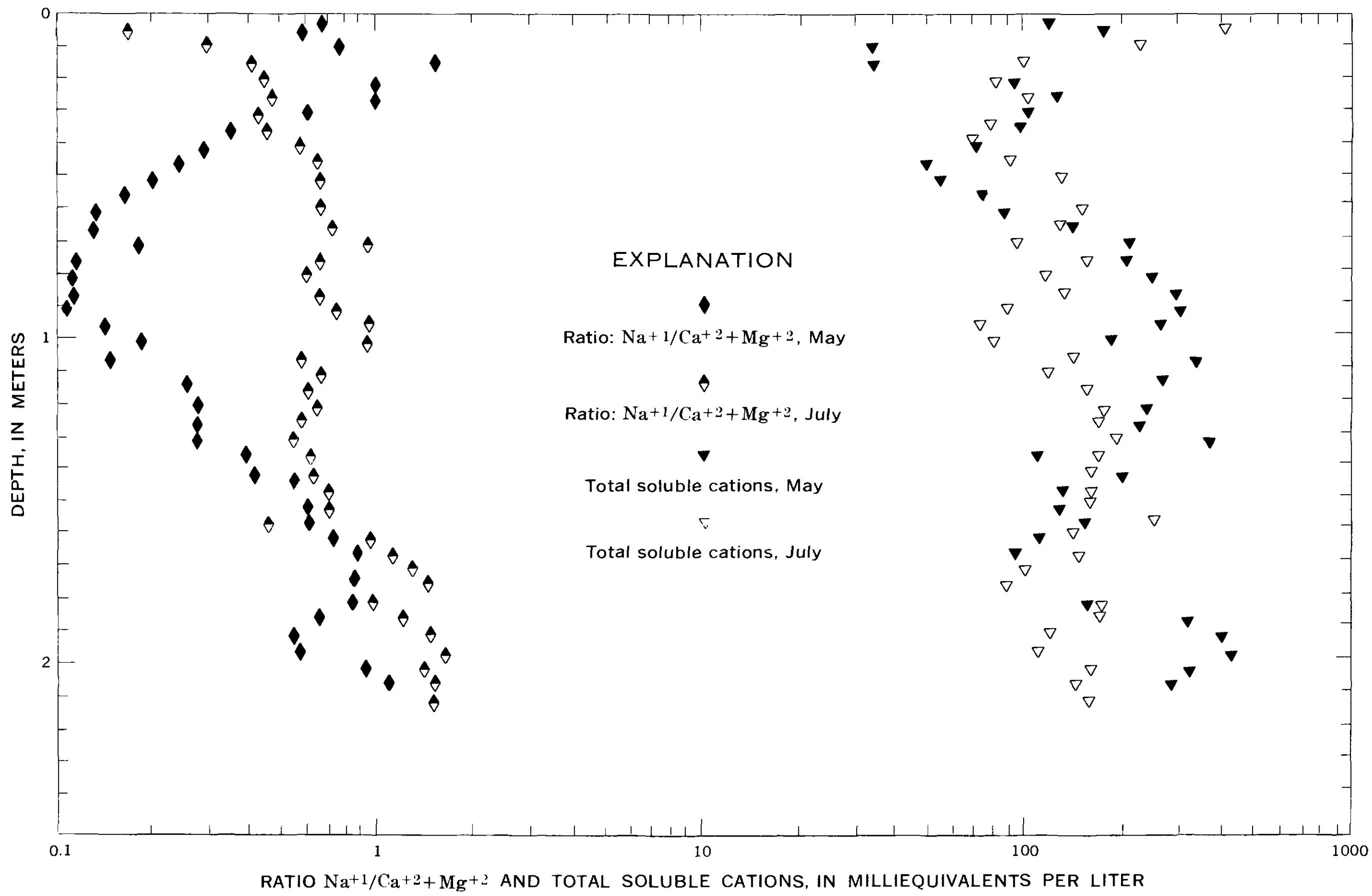
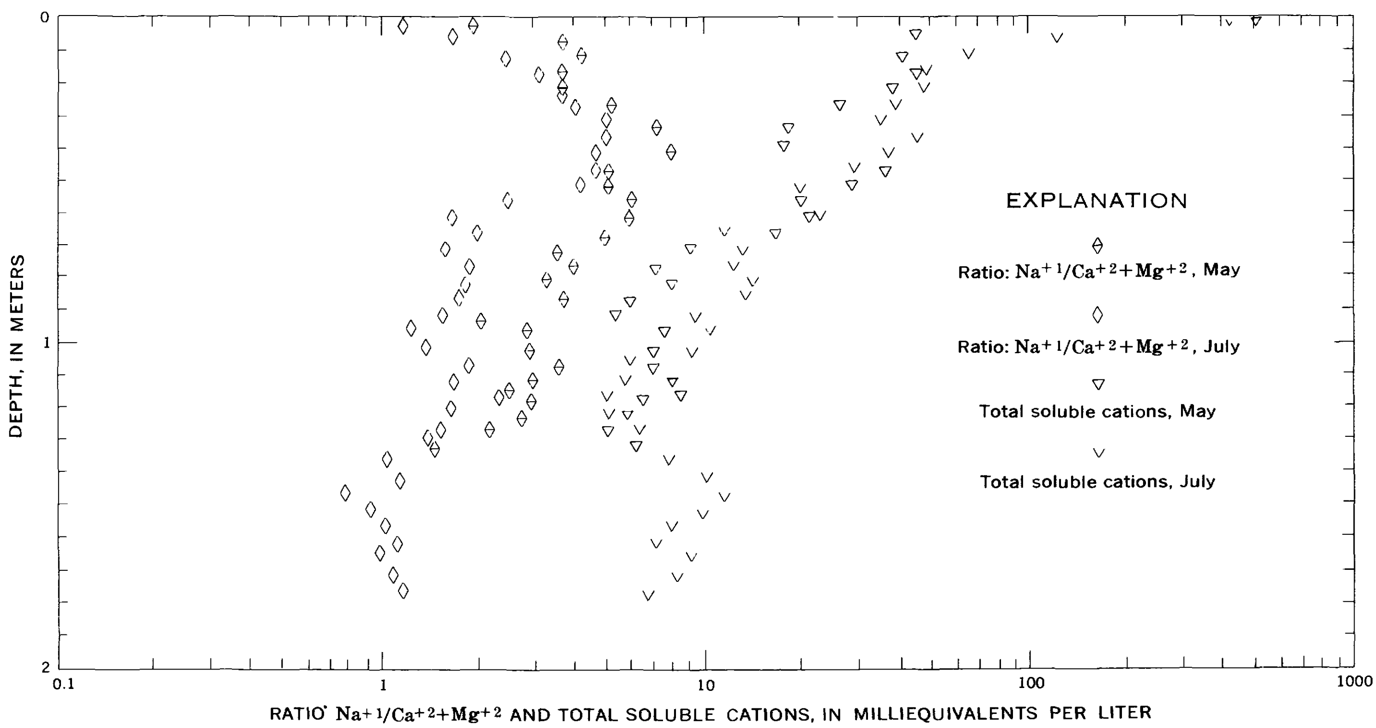


FIGURE 16.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded site 64UT under saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 11 and July 17, 1964.



Stress data obtained during this study were compared with stress data for equilibrium conditions. For hydraulic equilibrium, the measured moisture stress for a sample should equal the height of the sample above the water table. If the log of the height (in centimeters) of a sample above the water table is subtracted from the pF, the remainder is the log of the ratio of measured stress to equilibrium stress. We have labeled this ratio ΔpF to signify departures from equilibrium stress. When Schofield (1935, p. 46) introduced the concept of pF, he said, "In all cases we can apply the principle that water will not move except where there is a pF gradient (due allowance being made for gravity)." The ΔpF computation is one way of making allowance for gravity.

Because ΔpF is a log-ratio function, variability would appear greatest near the water table, where effects of errors or fluctuations in water-table elevation would be greatest.

Several principles of moisture movement and utilization are illustrated by the moisture data of this study. A detailed examination of the moisture and stress-departure profiles should help to define these principles.

1962 SALTCEDAR SITES

Saltcedar sites sampled in 1962 (figs. 21, 22, and 23) show the influence of abrupt changes in soil texture where the water table may be changing and where a recharge event has occurred relatively recently (in terms of days). Moisture in clay layers at depths from 0.8 to 0.9 meter and 1.05 to 1.4 meters at the unshaded site, and from 1.2 to 1.8 meters at the shaded site, was not at equilibrium with the water table. During

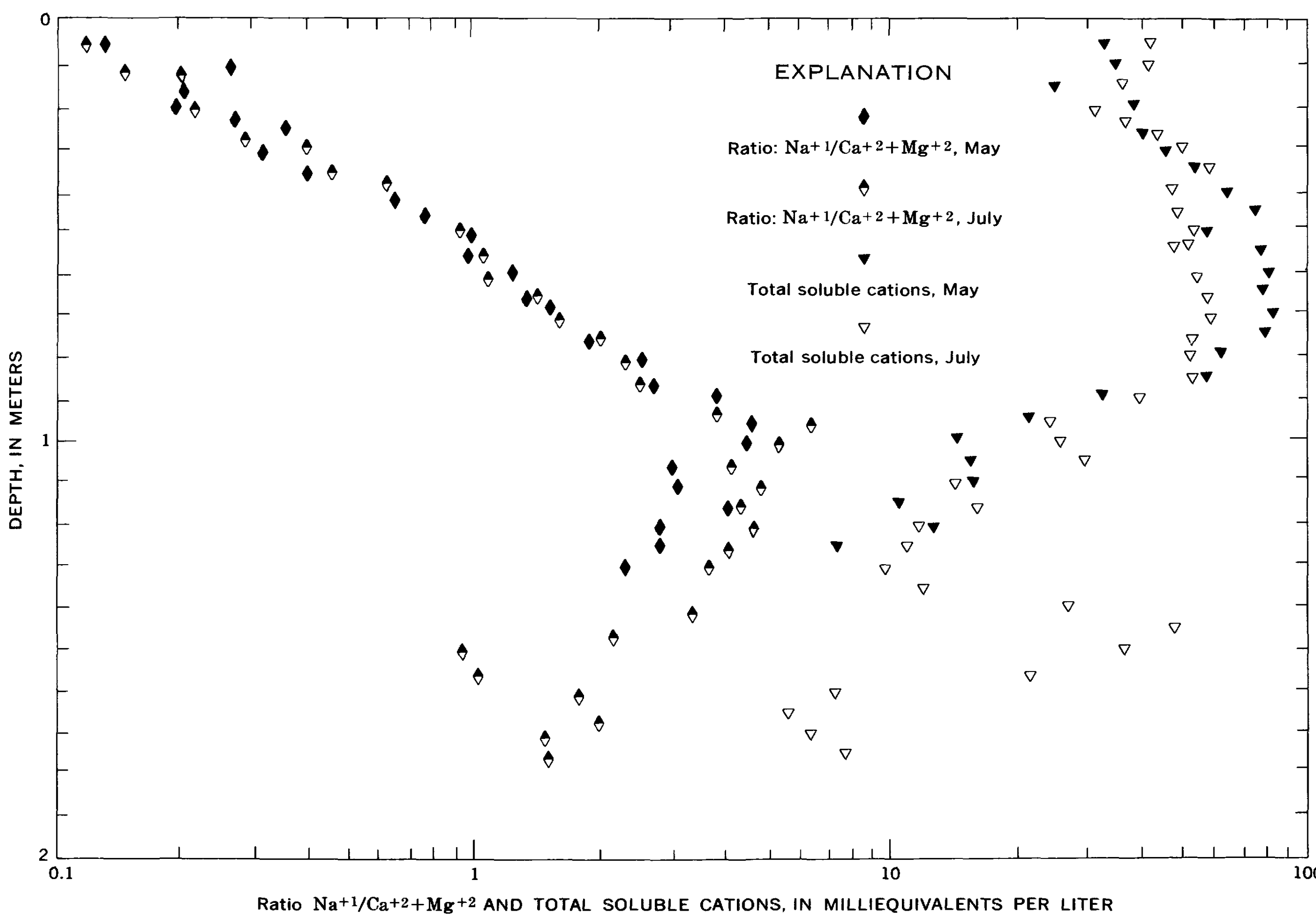


FIGURE 18.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded site 64UW under willow trees on the San Carlos River flood plain. Sampled May 13 and July 18, 1964.

◁ FIGURE 17.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for unshaded site 64OS associated with willow, cottonwood, and mesquite trees on the San Carlos River flood plain. Sampled May 13 and July 19, 1964.

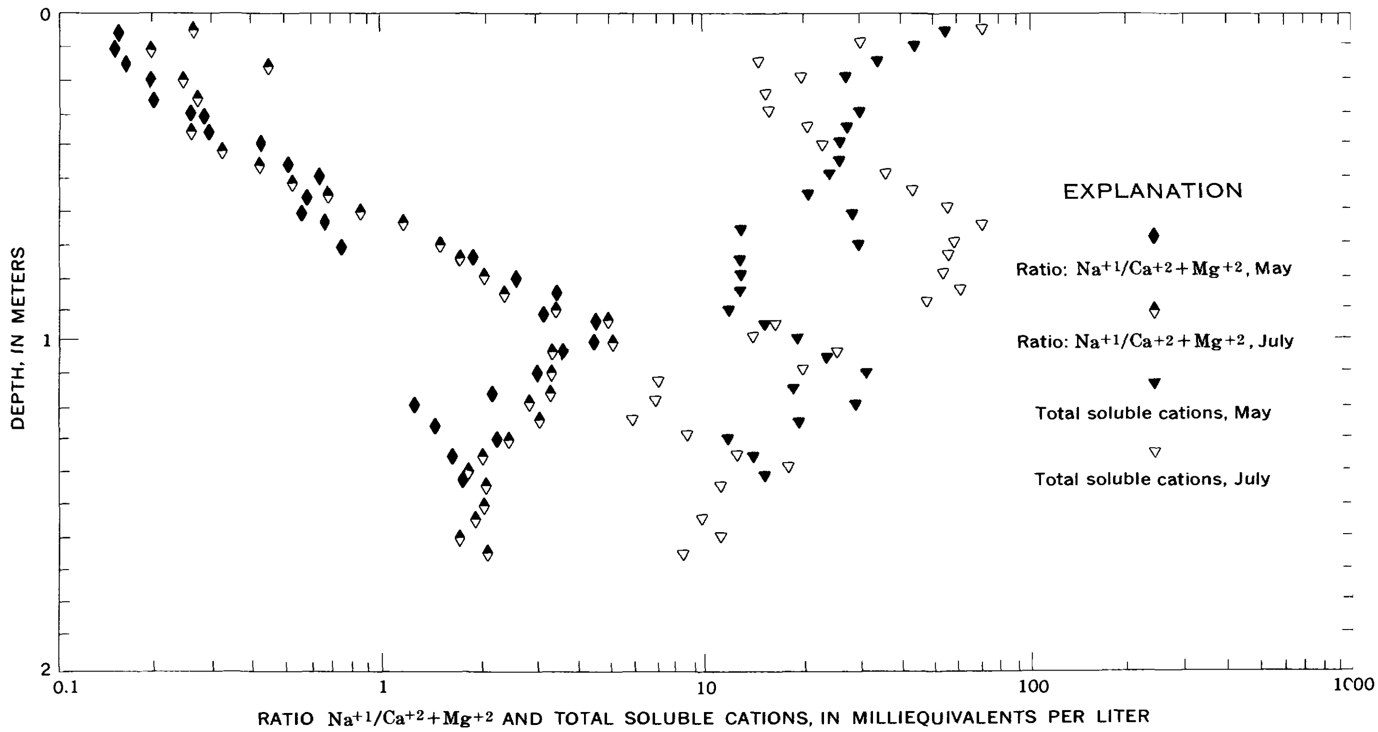


FIGURE 19.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded site 64UC under cottonwood trees on the San Carlos River flood plain. Sampled May 14 and July 20, 1964.

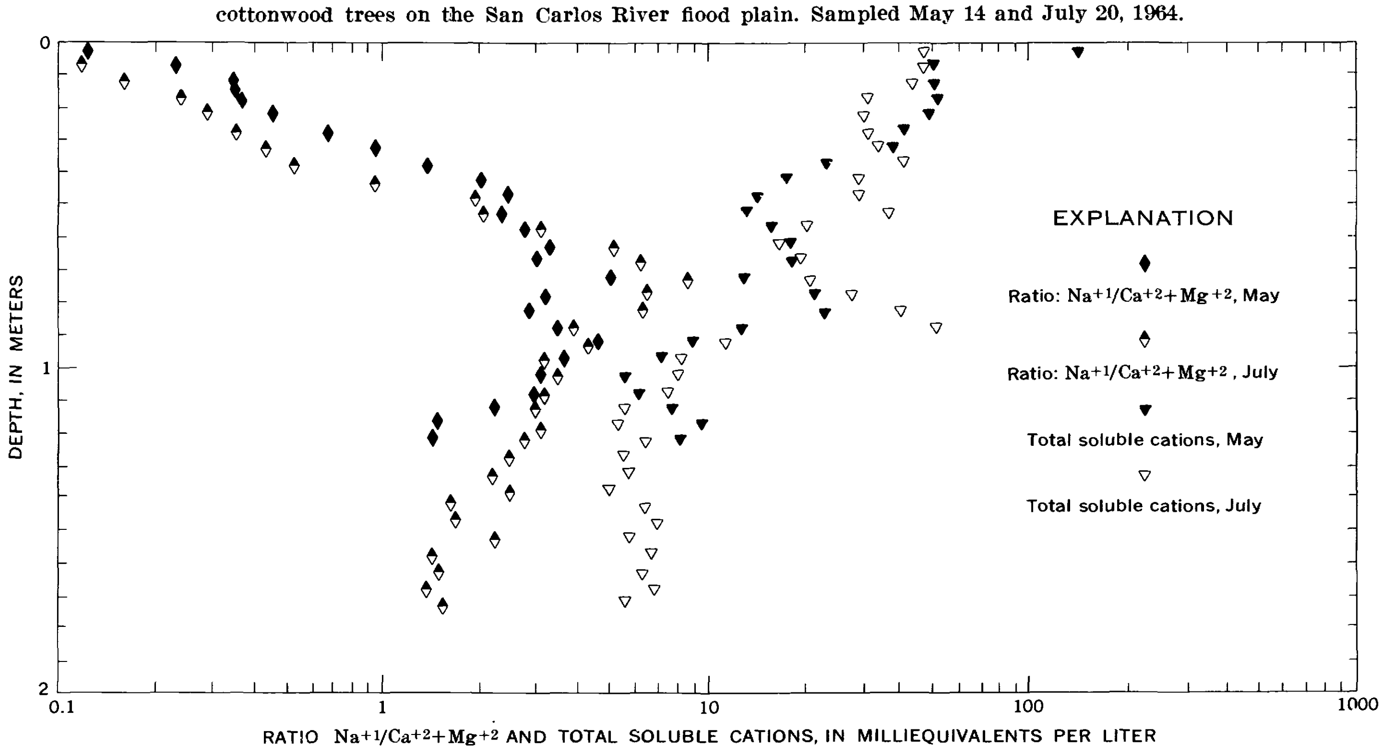


FIGURE 20.—Logarithmic profiles of the ratio of monovalent to divalent cations and the TSC for shaded site 64UM under mesquite trees on the San Carlos River flood plain. Sampled May 14 and July 20, 1964.

the sampling, water rose in the auger hole when the coarse material below the clay layers was penetrated. These clay zones also contained fewer roots than the more permeable parts of the material at the sites. The moisture-content profiles show no indication of moisture deficiencies in the clay zones, but the pF and ΔpF profiles show higher stress in these zones.

Moisture from 0.05 to 0.3 meter at the shaded site was depleted and had a stress level of pF 3.5 to 4.2, indicating moisture loss by transpiration. The dense stand of annual grasses visible in figure 2 is probably responsible for this depletion. The zone of depletion is defined on the stress-departure profiles (fig. 23).

1962 MESQUITE SITES

No evidence of flooding or recent recharge was found at the 1962 mesquite sites, and the moisture data show a moisture deficiency (figs. 24, 25, and 26).

Moisture stresses were higher at the unshaded site than at the shaded site. The moisture stress at depths from 0.60 meter to 2 meters at the unshaded site was nearly constant at pF 4.4 (25 bars). This value indicates depletion by a plant with high moisture-stress competence. At the shaded site the stress was nearly constant at pF 3.9 (8 bars) from 0.50 meter to 1.5 meters and at pF 3.5 (3 bars) from 1.7 to 3.2 meters. These values tend to indicate a lower stress competence for the plant roots at the shaded site. This situation might be explained by the field observation that the roots at the shaded site were mature primary roots and those at the unshaded site were active root hairs. Moisture had been depleted to a greater depth at the shaded site than it had at the unshaded site, as shown in the stress-departure profiles.

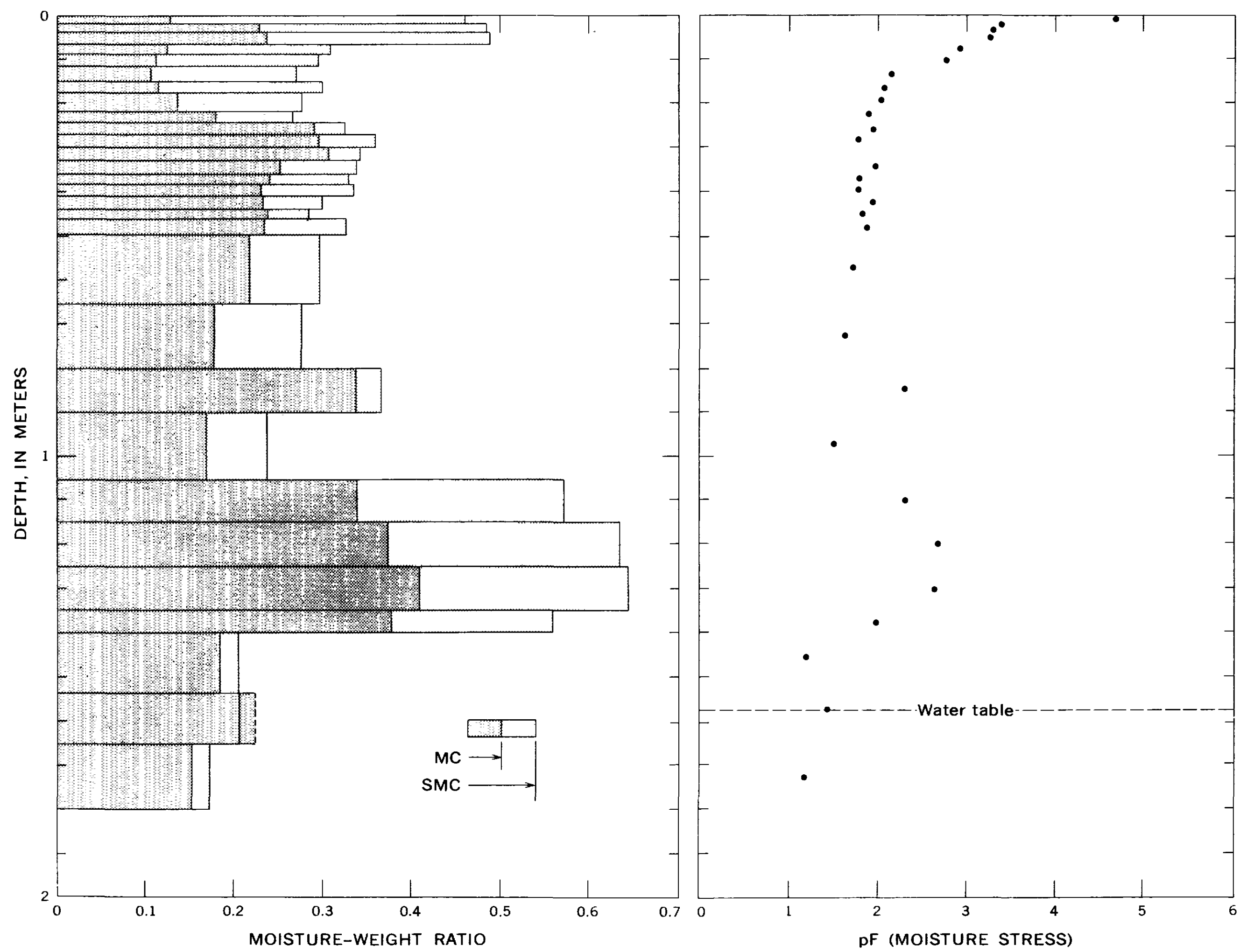


FIGURE 21.—Profiles of MC, SMC, and pF at unshaded site 62OT associated with saltcedar trees near section 11 of the Gila River Phreatophyte Project area. Sampled May 30, 1962.

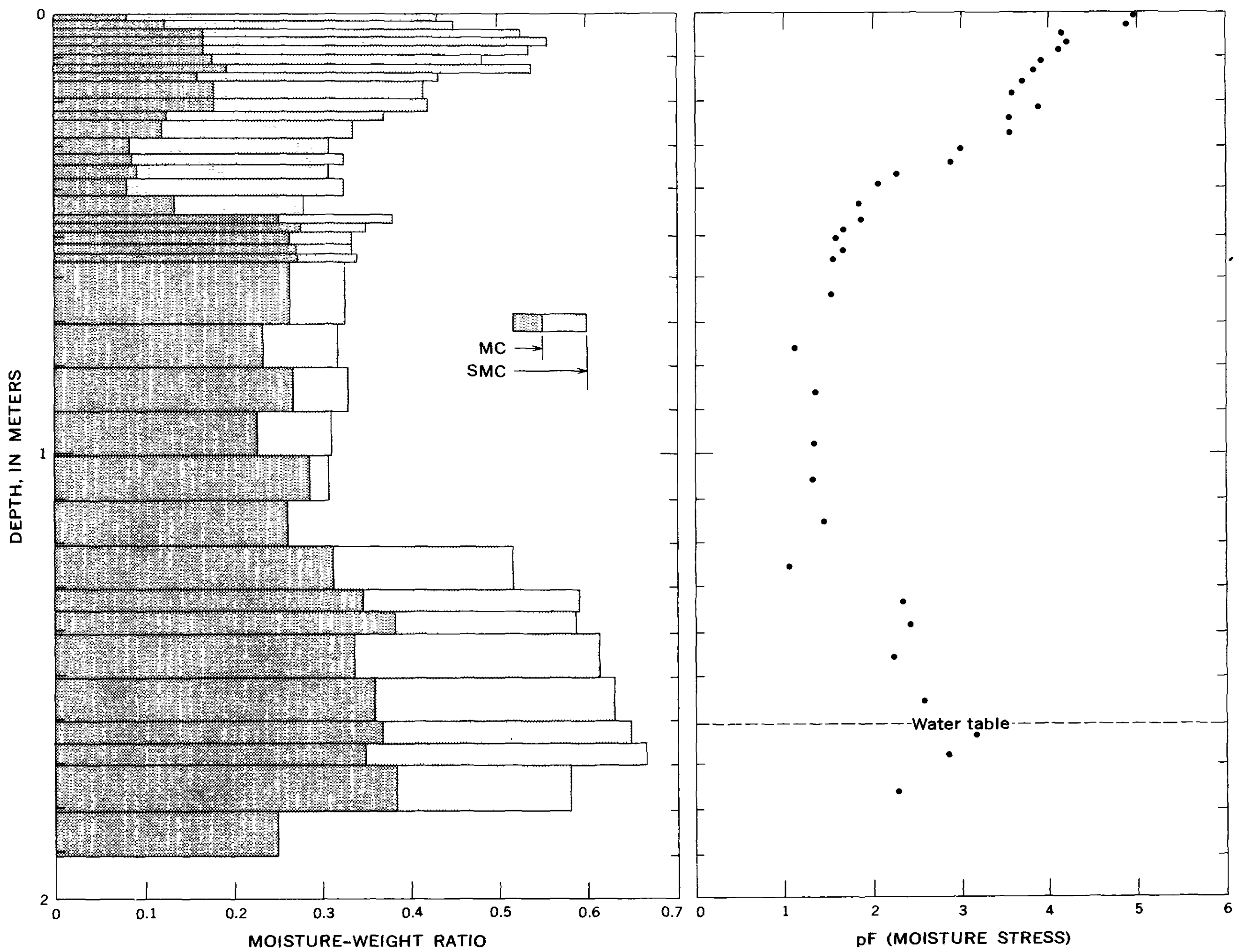


FIGURE 22.—Profiles of MC, SMC, and pF at shaded site 62UT under saltcedar trees near section 11 of the Gila River Phreatophyte Project area. Sampled May 30, 1962.

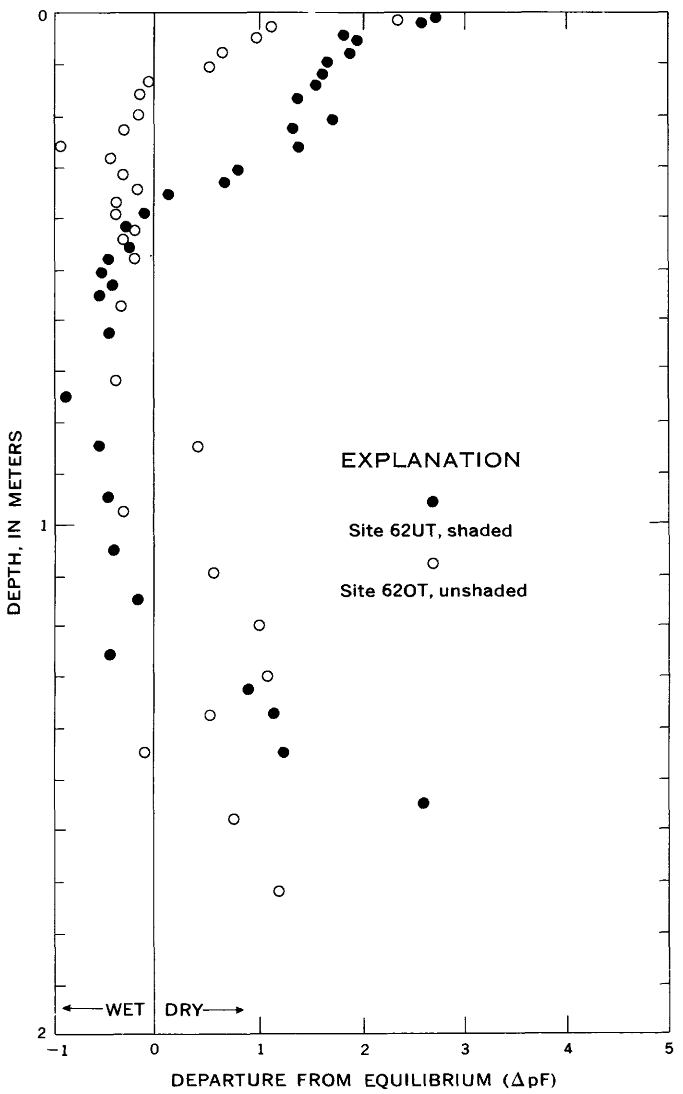


FIGURE 23.—Profiles of ΔpF for shaded and unshaded sites 62UT and 62OT associated with saltcedar trees near section 11 of the Gila River Phreatophyte Project area. Sampled May 30, 1962.

1962 COTTONWOOD SITES

Cottonwood sites sampled in 1962 (figs. 27, 28, and 29) show depletion of soil moisture by grasses and annual weeds and loss by evaporation. The unshaded site had a nearly constant stress of pF 4.2 (20 bars) at depths from 0.2 to 0.55 meter. The shaded site showed two stress levels: pF 4.0 (10 bars) from 0.15 to 0.4 meter and pF 3.5 (3 bars) from 0.45 to 1.0 meter. The top 0.1 meter of the unshaded site appears to have been influenced by a light rainstorm.

1964 SALTCEDAR SITES

Moisture at the 1964 saltcedar sites (figs. 30, 31, 32, 33, 34, and 35) remained at equilibrium with the water table except near the surface, where diurnal temperature fluctuations probably increased evaporation loss. The unshaded site showed a decrease in soil moisture in the top 0.60 meter during the growth period, from May to July. This loss appears to have been due to increased evaporation. The shaded site showed an increase in soil moisture in the top 0.4 meter during the growth period. There is no record of significant recharge of soil moisture either from precipitation on the sites or from flooding during the period May 15 to July 15, 1964. A light rainstorm on the night of July 17–18, 1964, influenced the soil moisture near the surface of the unshaded site. The shaded site was sampled prior to the rain, so it was not influenced.

A high water flow of 1,000 cubic feet per second in the Gila River occurred about 12 hours before the July 16 sampling of the unshaded site. Although neither the unshaded nor the shaded site was inundated by the flooding, some excess moisture, perhaps due to the flooding, was recorded from 1.2 to 1.3 meters at the unshaded site on July 16 and at 1.1 meters and below 1.8 meters at the shaded site on July 17

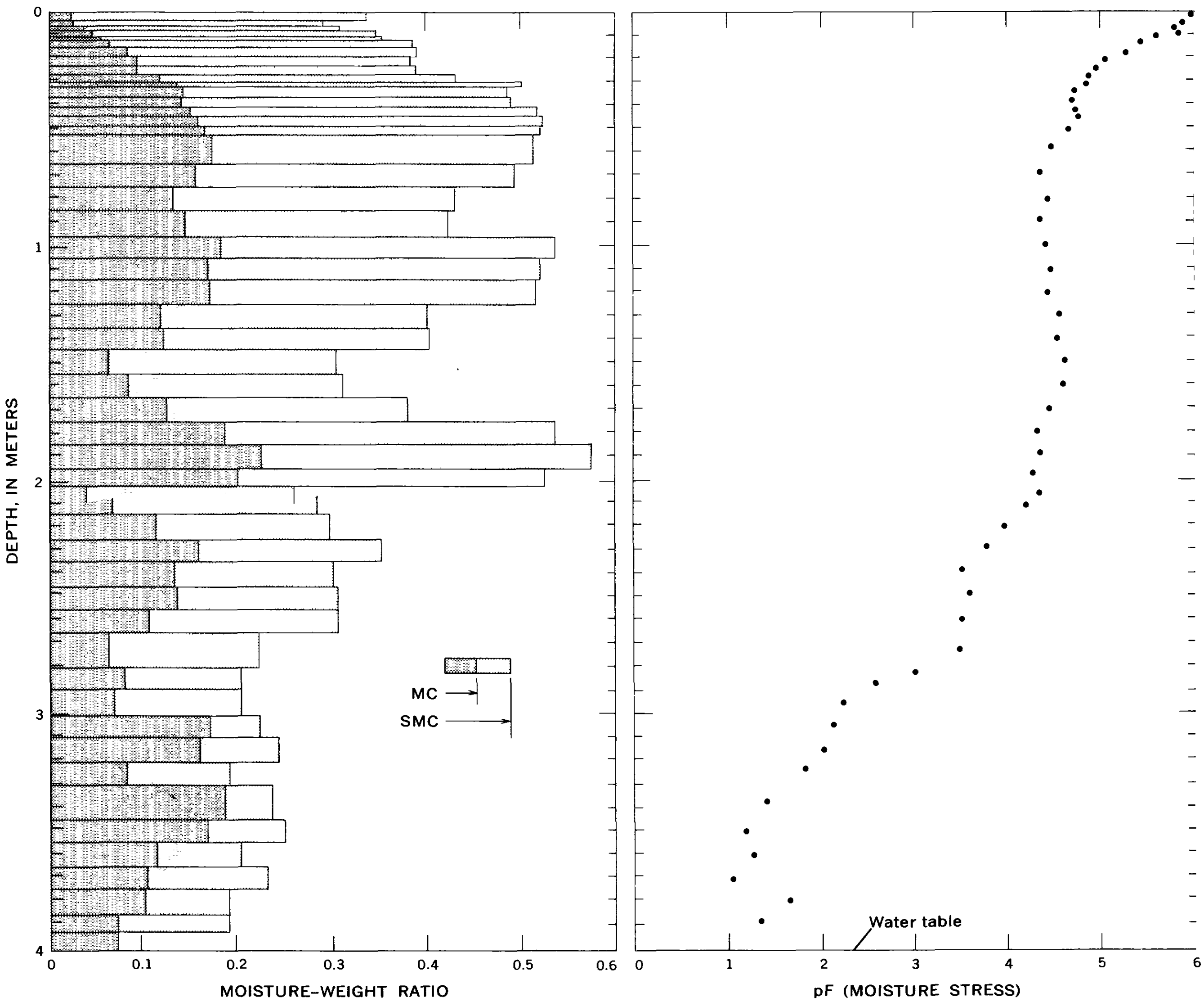


FIGURE 24.—Profiles of MC, SMC, and pF at unshaded site 62OM associated with mesquite trees on the San Carlos River flood plain. Sampled May 27, 1962.

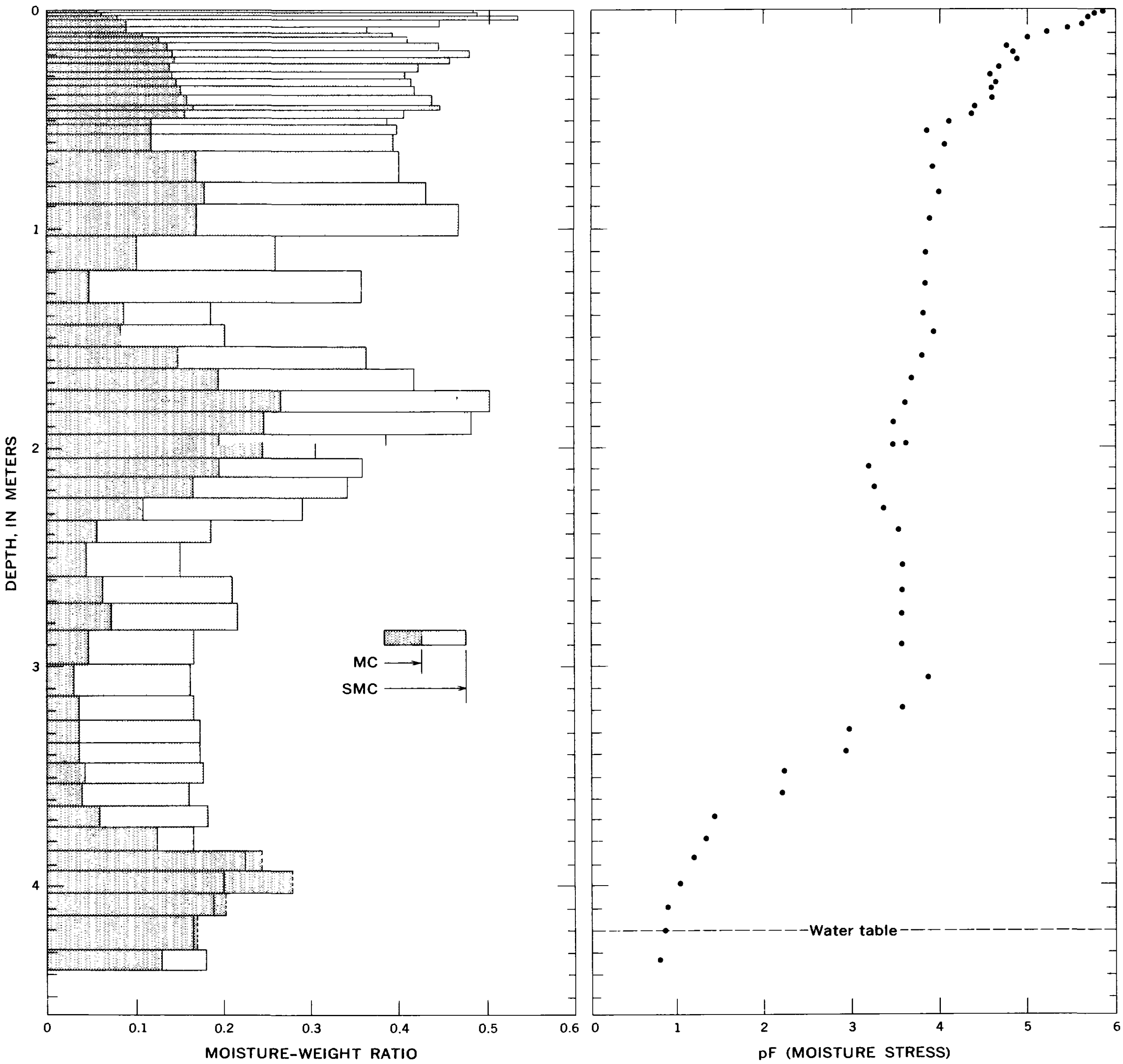


FIGURE 25.—Profiles of MC, SMC, and pF at shaded site 62UM under mesquite trees on the San Carlos River flood plain. Sampled May 26, 1962.

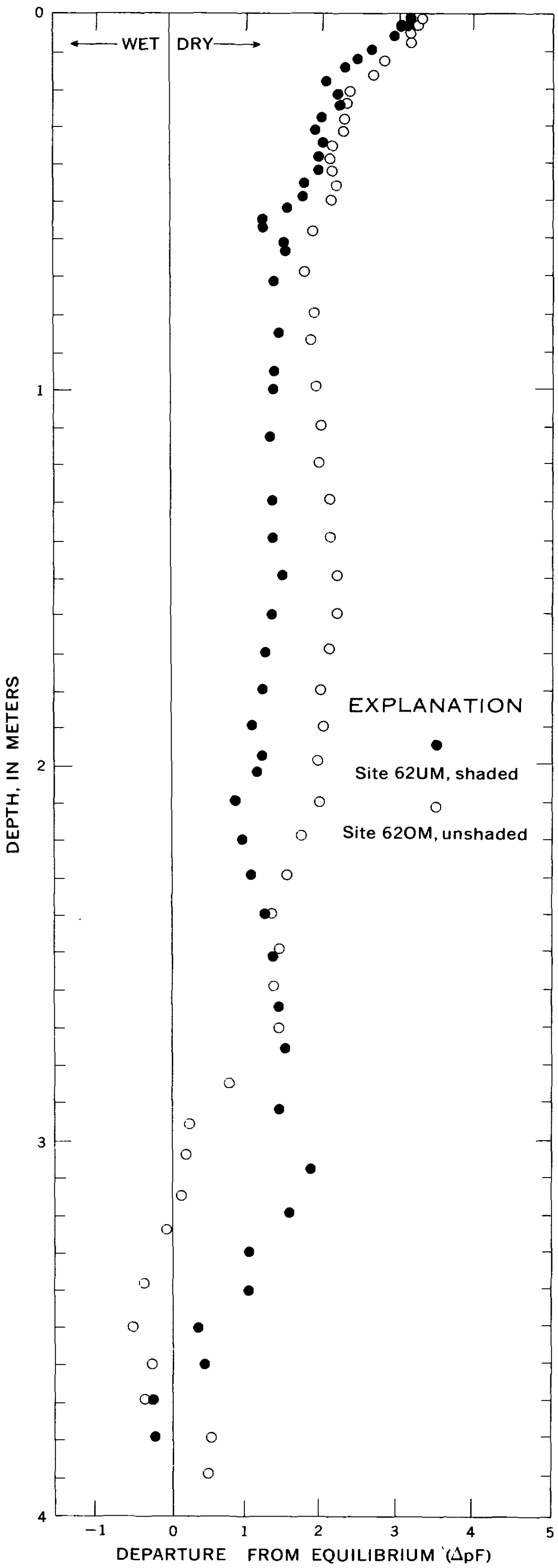


FIGURE 26.—Profiles of ΔpF for shaded and unshaded sites 62UM and 62OM associated with mesquite trees on the San Carlos River flood plain. Sampled May 26–27, 1962.

(figs. 32 and 35). Stress departures were computed from ground-water levels prior to the flooding.

1964 UNSHADED MIXED-COMMUNITY SITE

The stress-departure profile for the May 1964 sampling at the unshaded mixed-community site shows the effect of the spring runoff in the San Carlos River and of the falling water table at the time of sampling (figs. 36, 37, and 38). Excess moisture was present from 0.25 meter to 1.2 meters. Evaporation that caused depletion influenced only the top 0.05 meter.

The July sampling showed that evaporation had depleted moisture to a depth of 0.4 meter. Recharge from a light rainstorm on the night of July 17–18 influenced the top 0.2 meter at this site. Excess moisture present at the time of the May sampling had drained by the time of the July sampling, and equilibrium conditions had been established below 0.4 meter.

1964 WILLOW SITE

Soil at the 1964 willow sites (figs. 39, 40, and 41) contained excess moisture below a depth of 0.8 meter in May and July. No evidence was found of soil-moisture depletion by transpiration during the growth period. Evaporation had removed moisture to a depth of 0.20 meter in May and 0.3 meter in July. Recharge from a light rainstorm on the night of July 17–18 influenced the top 0.2 meter.

1964 COTTONWOOD SITE

Soil at the 1964 cottonwood site (figs. 42, 43, and 44) had excess moisture below a depth of 0.65 meter in May. By July the soil moisture had been depleted to a depth of 1.15 meters; no evidence was found that soil moisture was in equilibrium with the water table or that field capacity had been established. Recharge from a light rainstorm on the night of July 17–18 influenced the top 0.1 meter. Soil-moisture utilization during the growth period was extensive. A nearly constant pF of 3.75 (5.6 bars) from 0.4 to 0.6 meter in July may indicate the stress capabilities of cottonwood trees; the 1962 cottonwood profiles show pF levels of 3.5 to 4 (3 to 10 bars).

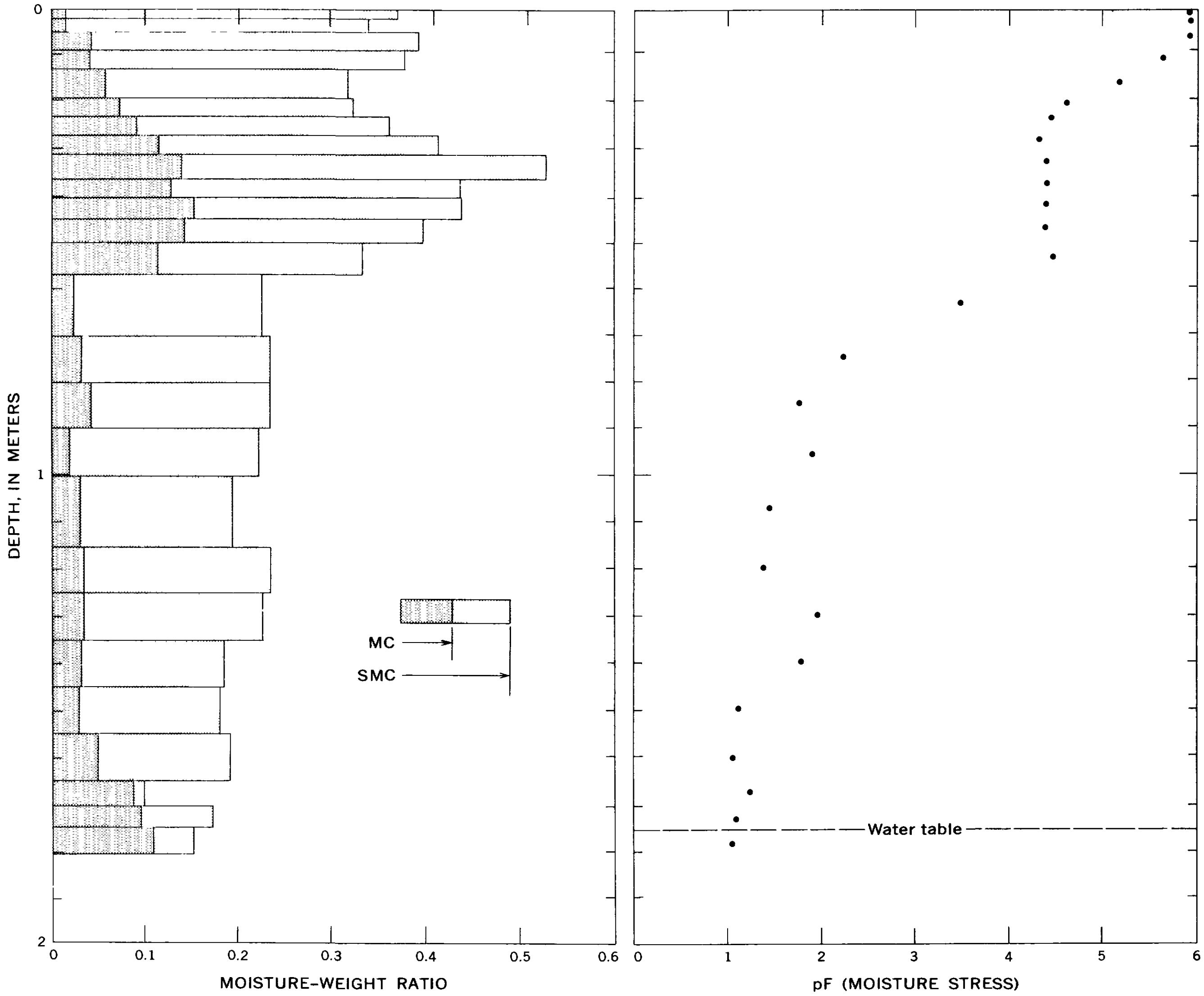


FIGURE 27.—Profiles of MC, SMC, and pF at unshaded site 62OC associated with cottonwood trees on the San Carlos River flood plain. Sampled May 28, 1962.

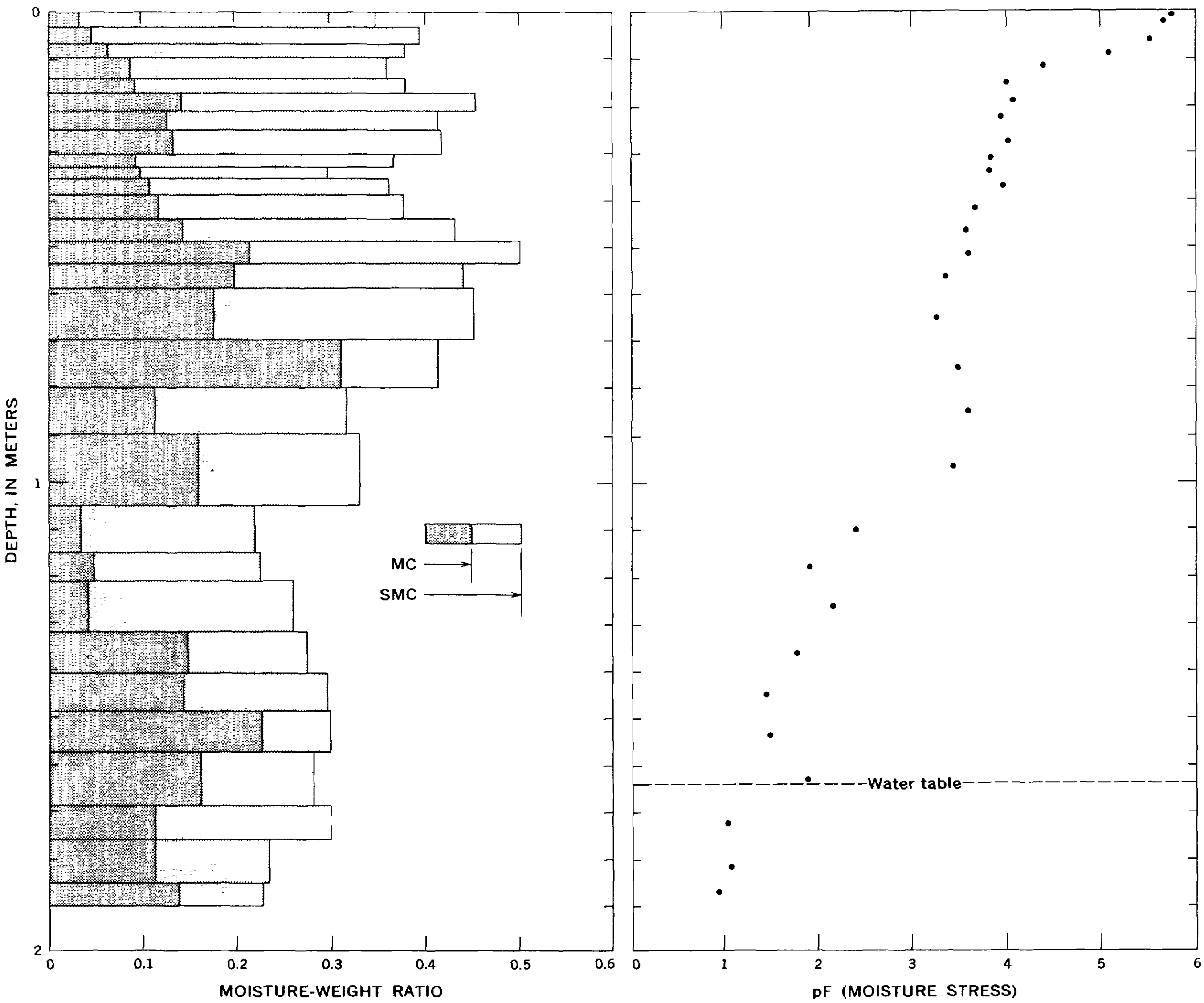


FIGURE 28.—Profiles of MC, SMC, and pF at shaded site 62UC under cottonwood trees on the San Carlos River flood plain. Sampled May 29, 1962.

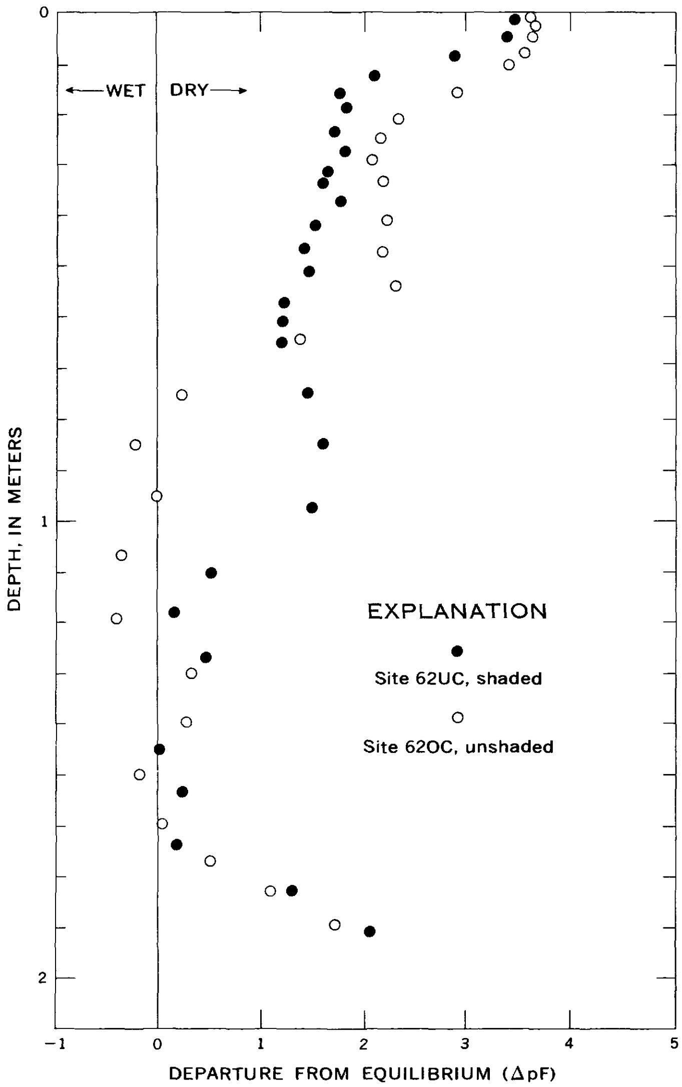


FIGURE 29.—Profiles of ΔpF for shaded and unshaded sites 62UC and 62OC associated with cottonwood trees on the San Carlos River flood plain. Sampled May 28–29, 1962.

1964 MESQUITE SITE

Excess moisture was present below a depth of 0.4 meter in May at the 1964 mesquite site (figs. 45, 46, and 47). Moisture was near equilibrium below 0.7 meter in July. Moisture dissipation during the growth season was evident from the surface to 1.2 meters. Recharge from the light rain on the night of July 17–18 did not affect the soil-moisture record, but this site was protected from direct rainfall by intercepting vegetation.

DISCUSSION OF MOISTURE USE AND DISSIPATION

Some new ideas on movement and utilization of soil moisture are discussed here without rigorous proof because proof is not within the scope of this project. The authors hope that these ideas and the new methods used in this study will contribute to the development of the science of soil moisture.

The depths where soil moisture is depleted by evaporation and (or) transpiration can be inferred from the ΔpF profiles. A positive ΔpF with a high value at the surface that approaches the zero, or equilibrium, line at a uniform high rate usually indicates evaporation loss. A positive ΔpF value that remains nearly constant or shows slight decrease with depth may indicate transpiration. In any given profile, both forms of moisture dissipation may be evident.

Transpiration can remove moisture from any depth where the soil is occupied by live roots. Annual grasses, weeds, and other ground-cover plants deplete soil moisture to a depth of about 0.6 meter (fig. 27). Depletion was evident under a mesquite tree to a depth of 3.4 meters (figs. 25 and 26).

In many profiles, depletions due to evaporation may be indistinguishable from those due to transpiration.

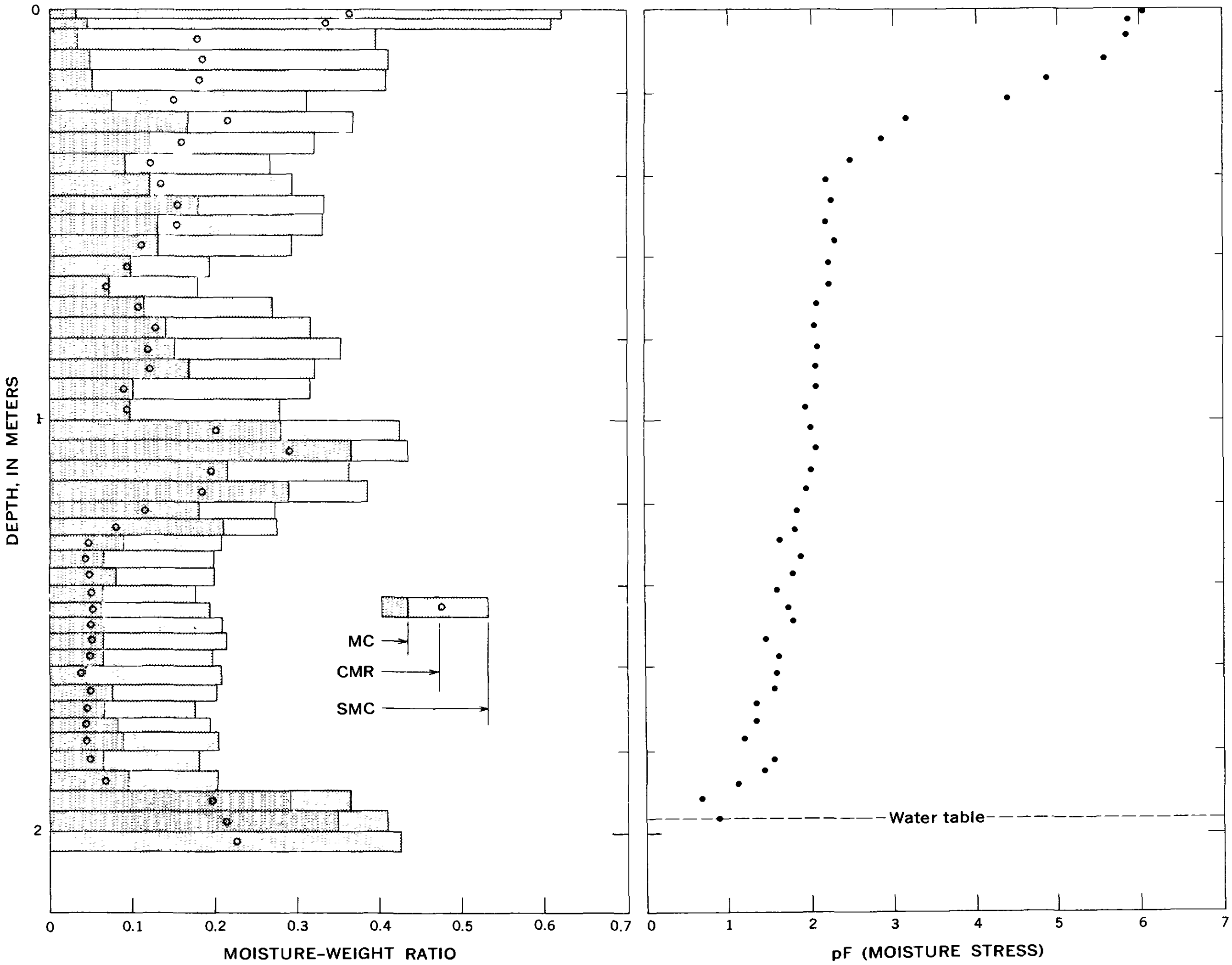


FIGURE 30.—Profiles of MC, SMC, CMR, and pF at unshaded site 64OT associated with saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 10, 1964.

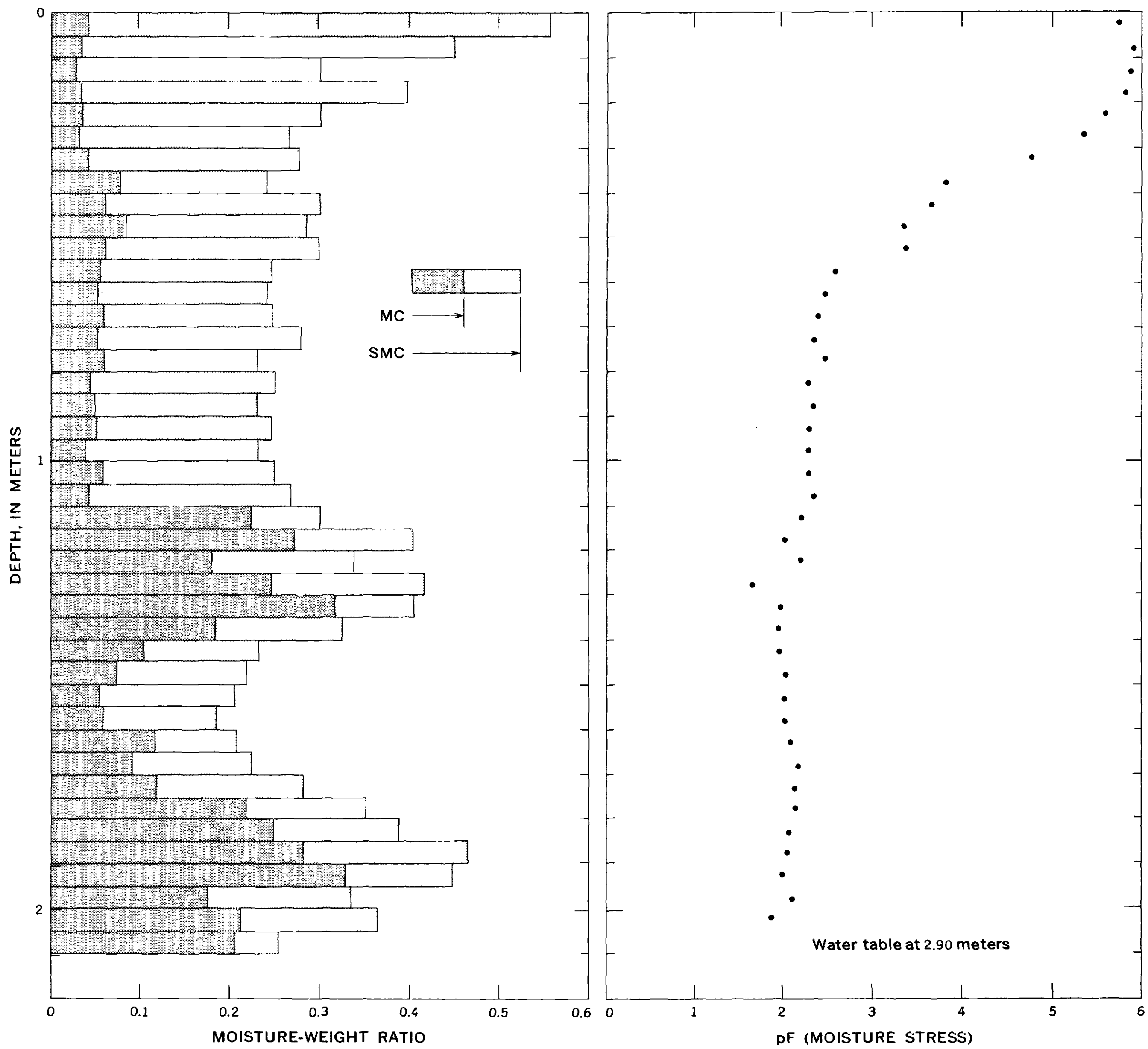


FIGURE 31.—Profiles of MC, SMC, and pF at unshaded site 64OT associated with saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled July 16, 1964.

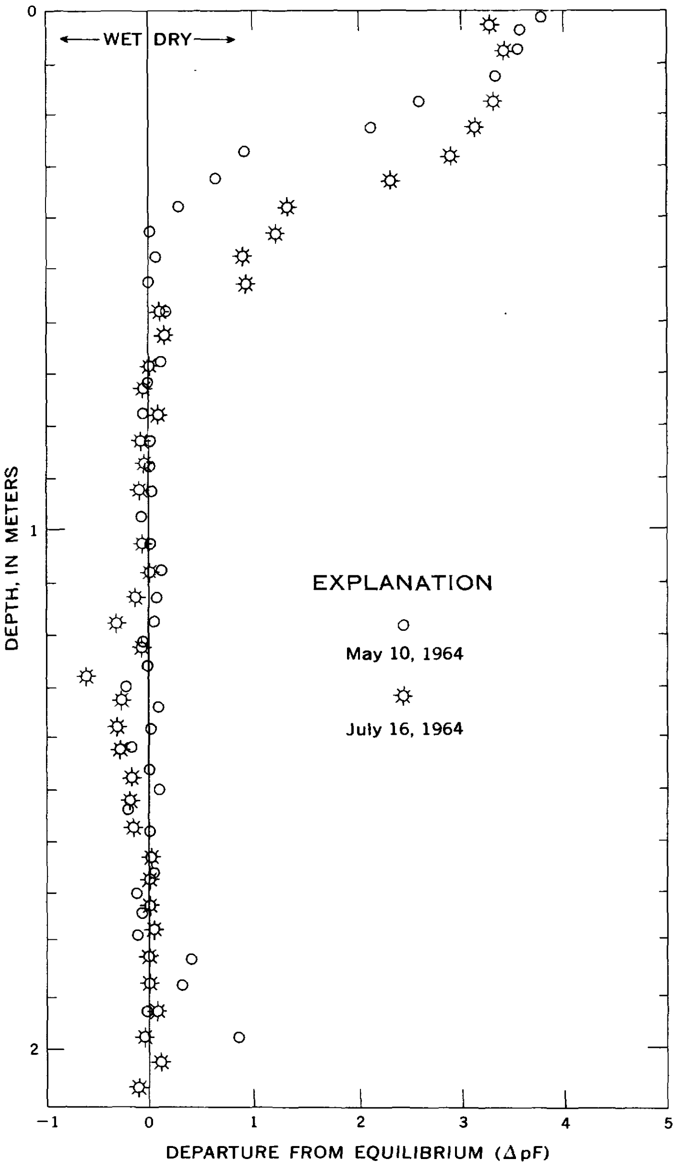


FIGURE 32.—Profiles of ΔpF for unshaded site 64OT associated with saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 10 and July 16, 1964.

The combined term "evapotranspiration" was coined because the two types of depletion are difficult to separate. The moisture stress data for the 1962 saltcedar sites (figs. 21 and 22) show decreasing stress with depth that is typical for evaporation depletion, but the depth of depletion and the stresses are greater for the shaded site than for the unshaded site. The ΔpF data for these sites (fig. 23) offers an explanation for this anomaly because transpiration is indicated as possible for the depth interval 0.05 to 0.3 meter at the shaded site. Field data show a heavy stand of grass at the shaded site (fig. 2). A stress of pF 3.5 to 4.2 (3 to 16 bars), as shown for the 0.05 to 0.3 meter depth interval (fig. 22), would be about right for an area of annual grass in a rapid growth stage.

Relatively impermeable clay layers in a soil may have ΔpF values that are high or low depending upon the direction of movement of the water table. Clay layers at the 1962 saltcedar sites at depths of 1.05 to 1.40 meters at the unshaded and 1.20 to 1.80 meters at the shaded site have high ΔpF values which are probably due to slow response to a rising water table (figs. 21, 22, and 23).

Evaporation of soil moisture appears to be proportional to the amplitude of the soil temperature fluctuations. Attenuation of the diurnal cycle of temperature depends both upon the amount of radiation received at the soil surface (degree of shading) and upon the moisture content. These relationships are indicated in the stress profiles. Moisture stresses decrease rapidly to the depth where diurnal fluctuations are attenuated. Below this depth, the stress values form an equilibrium curve related to the water table or to a transpiration stress level imposed by plants. The depth which corresponds to the transition from the evaporation segment of the curve to the equilibrium or transpiration segment is greater in July than it is in May, and it is greater at the unshaded sites than it is at the shaded sites. There is one exception to the first generalization. The depth corresponding to the transition at the

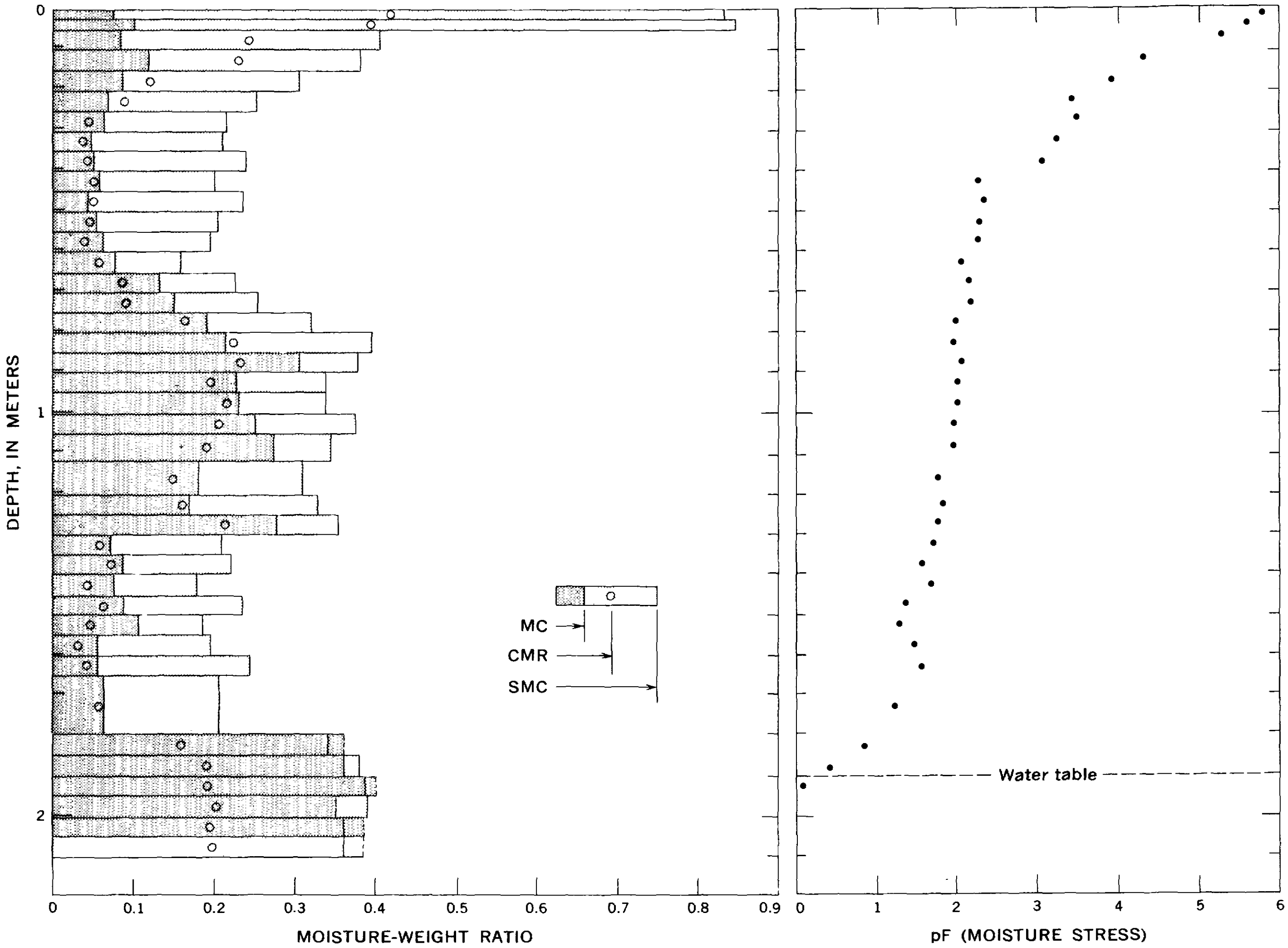


FIGURE 33.—Profiles of MC, SMC, CMR, and pF at shaded site 64UT under saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 11, 1964.

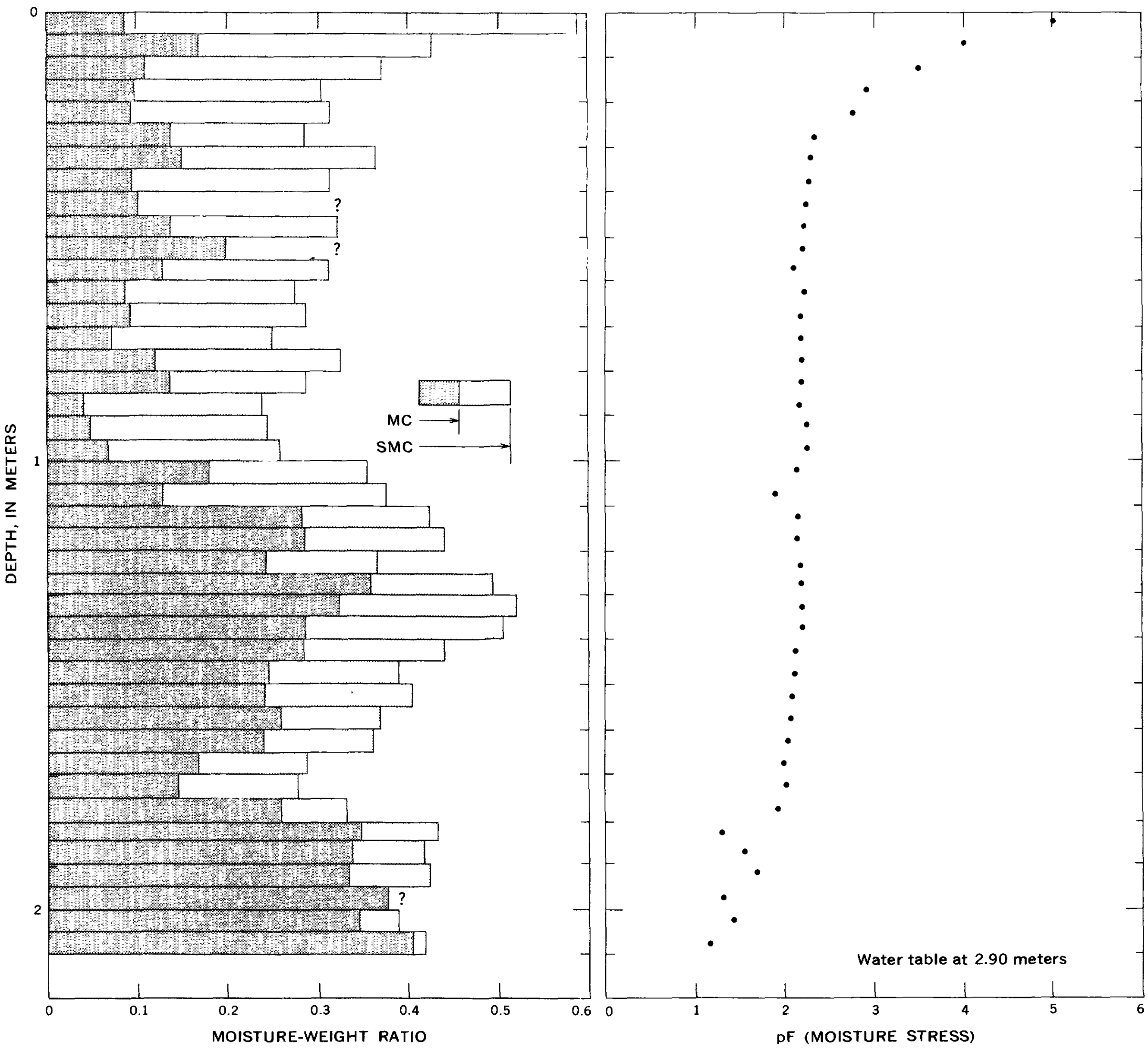


FIGURE 34.—Profiles of MC, SMC, and pF at shaded site 64UT under saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled July 17, 1964.

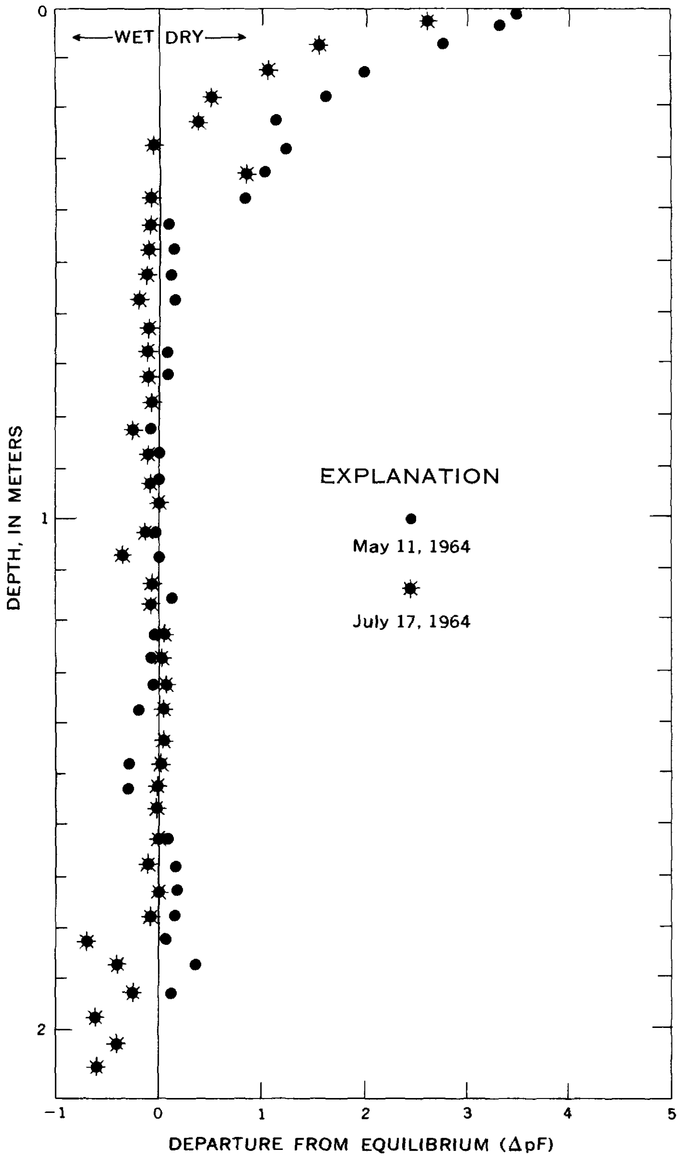


Figure 35.—Profiles of ΔpF for shaded site 64UT under saltcedar trees near section 23 of the Gila River Phreatophyte Project area. Sampled May 11 and July 17, 1964.

shaded saltcedar site is greater in May than in July. The reason for this exception is discussed in a following section of this report.

Trees and other perennials may deplete soil moisture around the perimeter of their root system sooner than in the center, near the older, established roots. Stress measurements made under and near mesquite trees in May 1962 showed lower stress under the trees than in the open, where there was little or no vegetation (fig. 2). Both sampling sites were permeated by roots, but the roots at the unshaded site were smaller and more numerous than those at the shaded site. The moisture-stress profile for the unshaded site (fig. 24) shows a nearly uniform stress of pF 4.4 (25 bars) from 0.6 to 2.0 meters. The stress in June or July, after an active growth season, would probably be much higher, indicating that the mesquite tree is capable of competing for soil moisture with many plants that are classed as xerophytes. The shaded site had a stress of about pF 3.9 from 0.5 to 1.5 meters. Moisture contents at the two sites were similar, but slightly more moisture occurred under the tree.

The two sites sampled under and near cottonwood trees in May 1962 were influenced by smaller plants growing on the sites. The unshaded site (fig. 3) was far enough from the cottonwood trees to be free of tree roots. The smaller plants growing on and near the site induced a stress of pF 4.3 (20 bars) at depths from 0.2 to 0.55 meter. Moisture at the site was near equilibrium from 0.7 meter to the water table at 1.75 meters (fig. 29). The moisture and stress profiles of the site shaded by cottonwood trees indicate evaporation loss to only 0.15 meter, transpiration loss to 1.15 meters, and equilibrium from 1.15 meters to the water table at 1.64 meters (figs. 28 and 29).

Moisture at the sites associated with saltcedar trees sampled in May and July 1964 appeared to be maintained at equilibrium with the water table except in the top 60 cm, where evaporation was high because of diurnal temperature fluctuations.

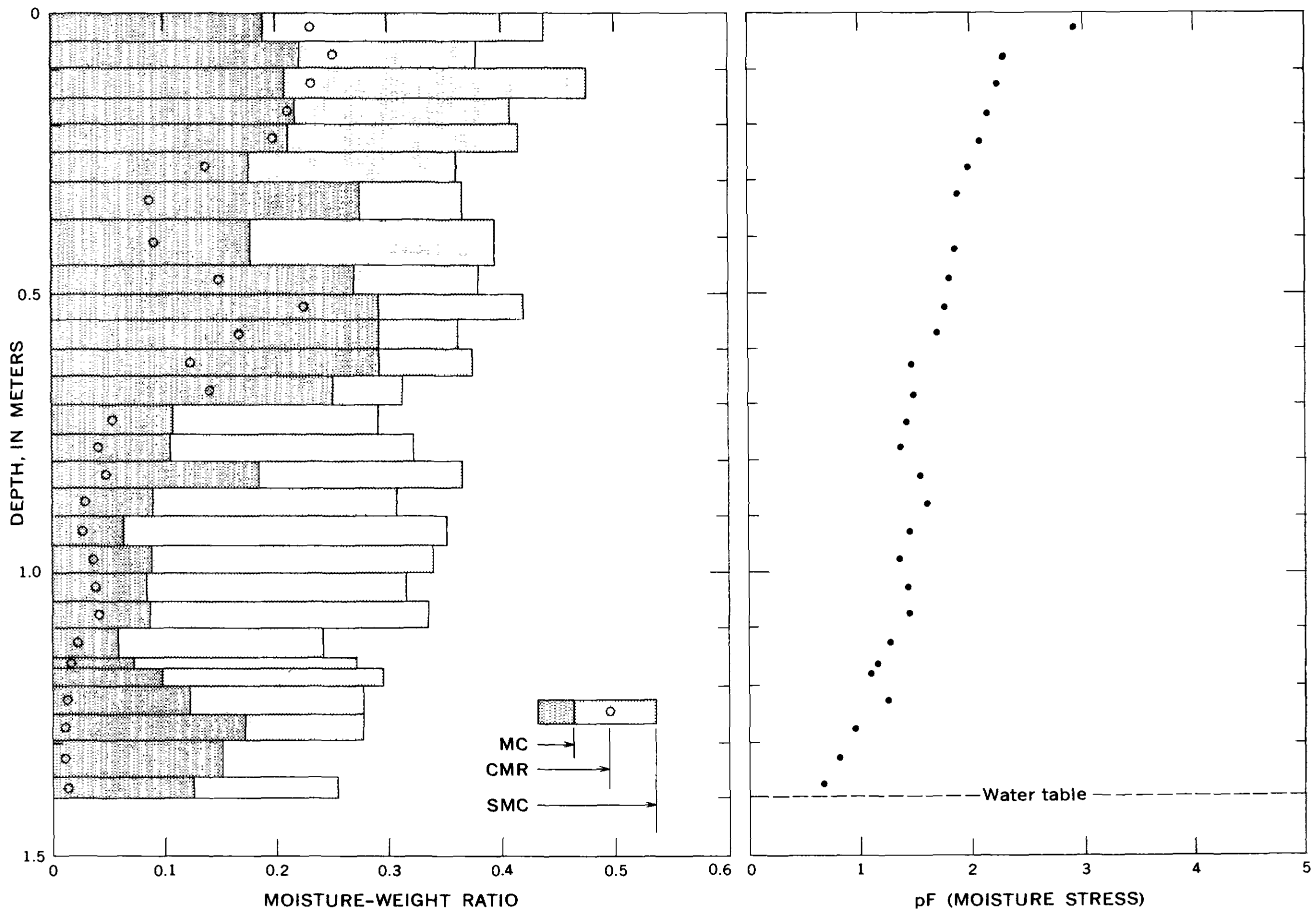


FIGURE 36.—Profiles of MC, SMC, CMR, and pF at unshaded site 64OS associated with willow, cottonwood, and mesquite trees on the San Carlos River flood plain. Sampled May 13, 1964.

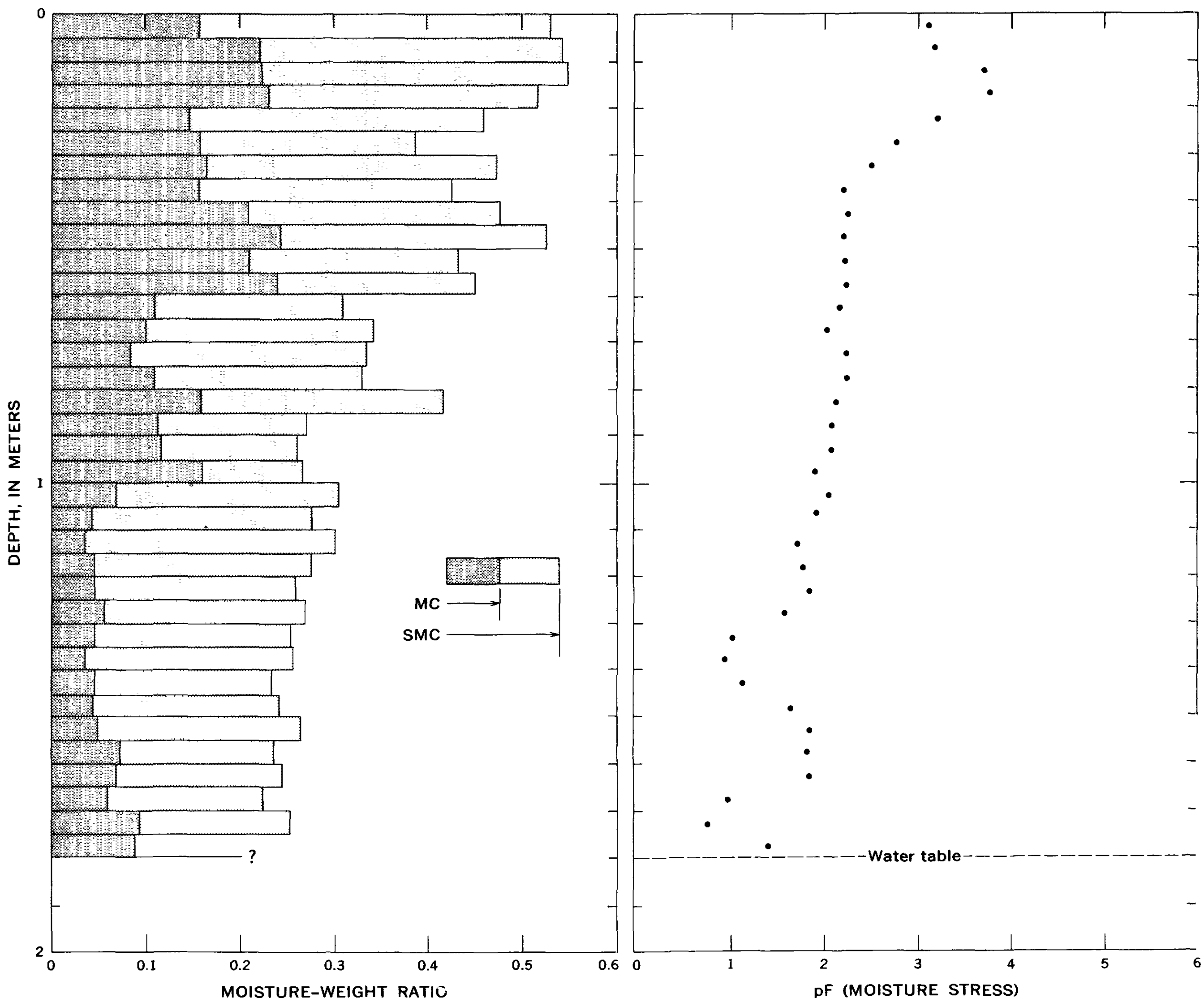


FIGURE 37.—Profiles of MC, SMC, and pF at unshaded site 64OS associated with willow, cottonwood, and mesquite trees on the San Carlos River flood plain. Sampled July 19, 1964.

The saltcedar trees did not deplete soil moisture from May 11 to July 17, 1964. At the site under the trees, an increase in soil moisture occurred during this period, especially in the top 0.4 meter. Part of this increase may be attributed to physical differences in the soils of the two sampled columns. However, the soil-moisture stress is independent of the soil texture, as indicated by the moisture-stress and saturation-capacity profiles, and the pattern of equilibrium with the water table is so well defined in the six profiles for sites associated with saltcedar trees that some mechanism of moisture translocation through the root systems must be considered to explain the data. This mechanism will be discussed in a following section of this report.

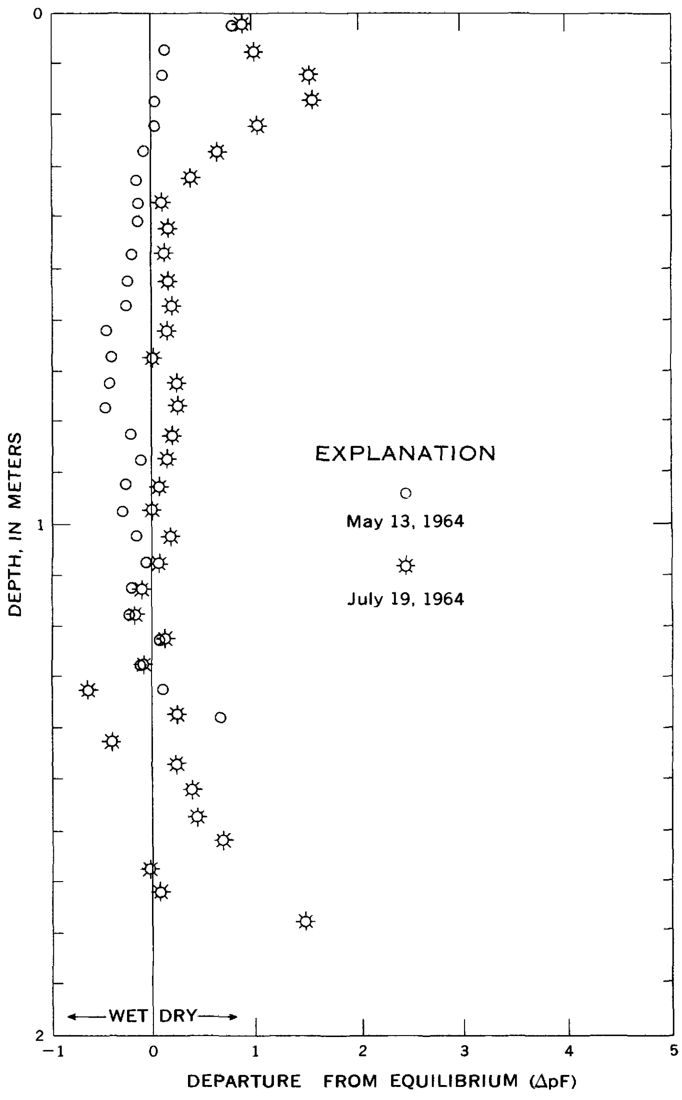


FIGURE 38.—Profiles of ΔpF for unshaded site 64OS associated with willow, cottonwood, and mesquite trees on the San Carlos River flood plain. Sampled May 13 and July 19, 1964.

The field-capacity concept implies that for a given soil there is a moisture-retention force and a corresponding moisture content at which there is an abrupt change in the rate of moisture movement induced by gravity gradients. The moisture retained by a soil sample in a centrifuge is assumed to be approximately equal to the field capacity. The retention force at field capacity is in the range pF 2.0 to 2.5 (0.1 to 0.3 bars).

As a qualitative test of the methods for determining field capacity, it is assumed that a column of soil containing moisture in equilibrium with the water table should have a depth at which the moisture content (MC) is equal to the centrifuge moisture retention (CMR). Furthermore, this depth should coincide with the depth at which the moisture stress is equal to the stress at field capacity, for which an average value of pF 2.3 may be assumed. Also, the most frequently occurring stress in a group of soil columns should be the field-capacity stress (pF 2.3). An examination of the moisture data shows that these conditions exist within reasonable limits. The depth correspondence data for those sites for which centrifuge data are available are given in table 3.

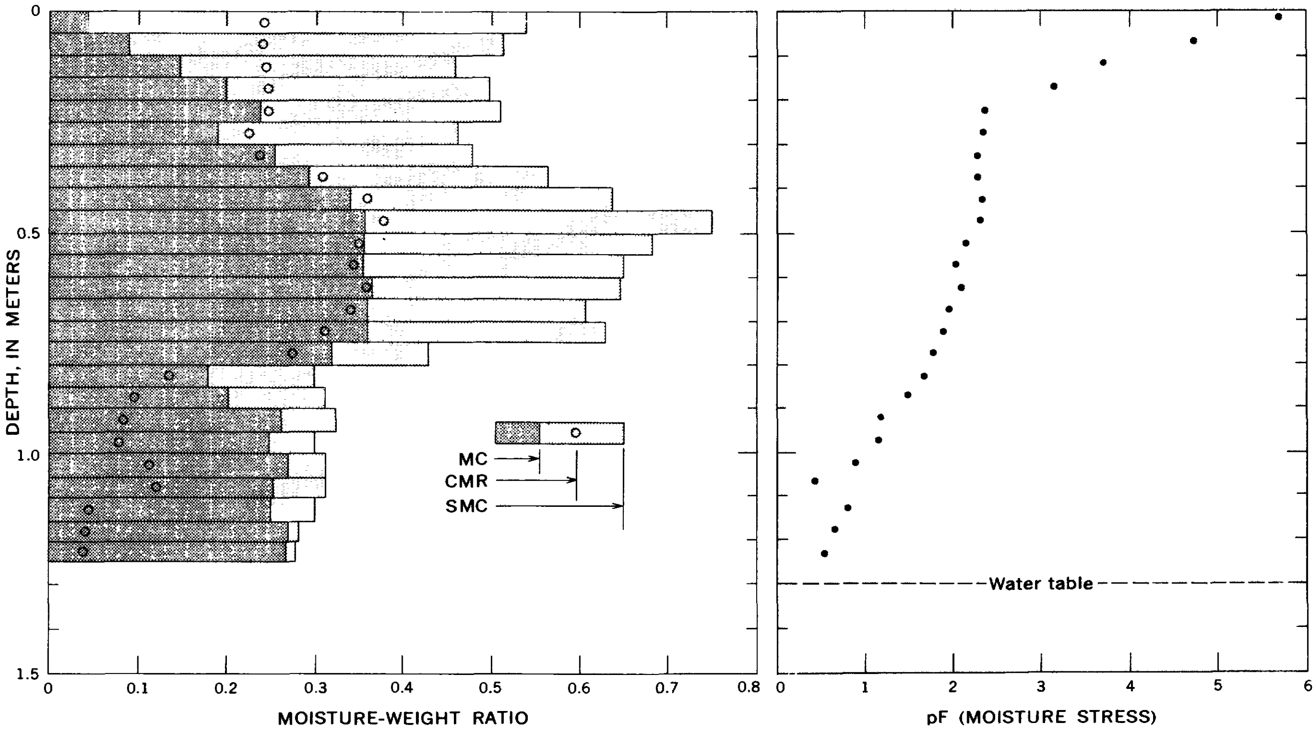
The moisture data do not indicate the existence of an intermediate belt as described by Meinzer, because at every site the belt of soil water and the capillary fringe merged so that there was no room for an intermediate belt.

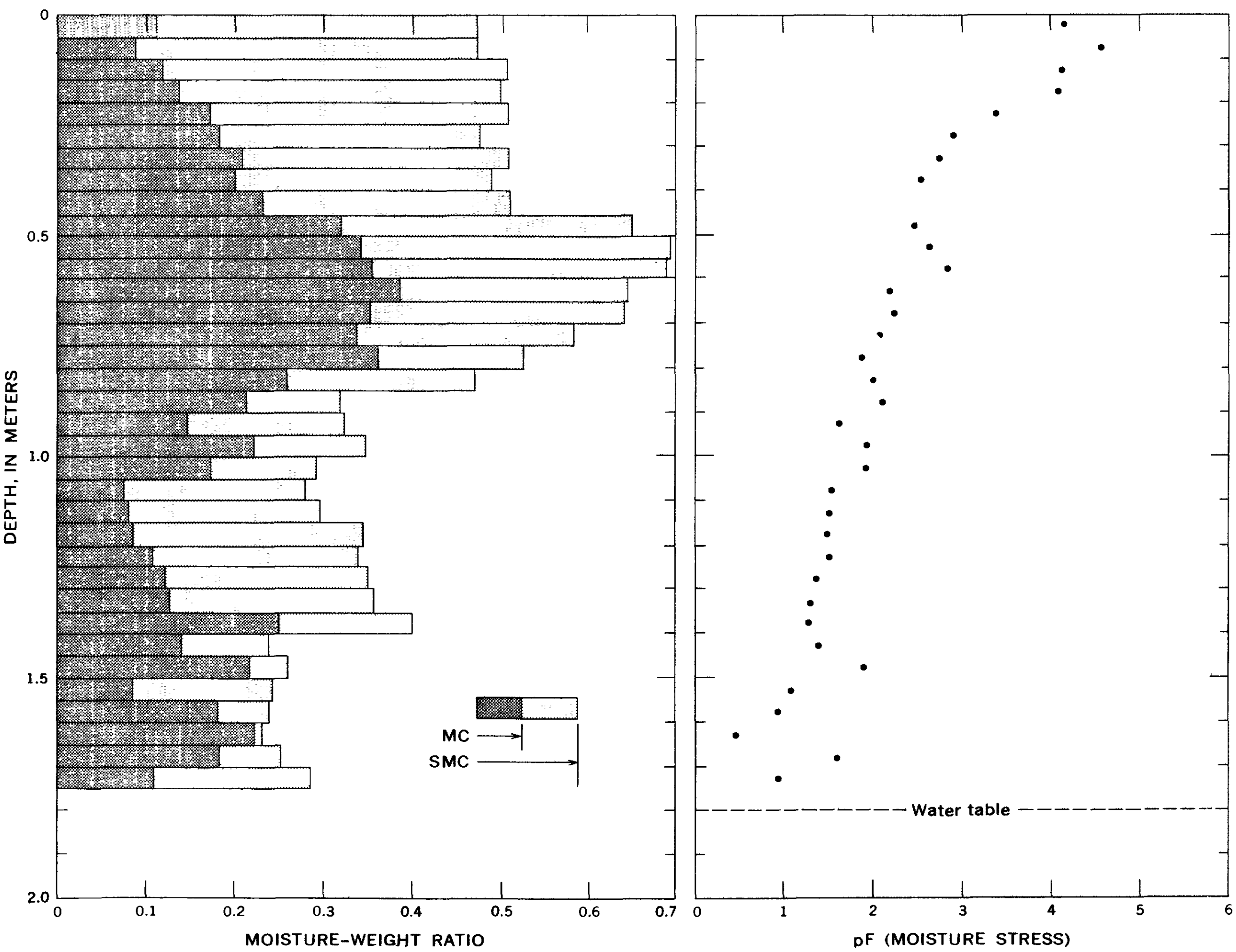
TABLE 3.—*Comparison of depths at which MC equals CMR with depths at which stress equals pF 2.3*

Figure No.	Site	Depth at which MC=CMR (cm)	Depth at which pF=2.3 (cm)
30	64OT	40–55	40–55
33	64UT	25, 45–50	40–55
36	64OS	15	10
39	64UW	30–50	20–50
42	64UC	55	55
45	64UM	20	20

FIGURE 39 (upper right).—Profiles of MC, SMC, CMR, and pF at shaded site 64UW under willow trees on the San Carlos River flood plain. Sampled May 13, 1964.

FIGURE 40 (lower right).—Profiles of MC, SMC, and pF at shaded site 64UW under willow trees on the San Carlos River flood plain. Sampled July 18, 1964.


DEPTH, IN METERS
0
0.5
1.0
1.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
MOISTURE-WEIGHT RATIO
MC
CMR
SMC
Water table
0
1
2
3
4
5
6
pF (MOISTURE STRESS)


DEPTH, IN METERS
0
0.5
1.0
1.5
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MOISTURE-WEIGHT RATIO
MC
SMC
Water table
0
1
2
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6
pF (MOISTURE STRESS)

PHREATOPHYTES AND SOIL-MOISTURE DISSIPATION

Vegetation established in a soil may withdraw moisture from those parts of the soil that are penetrated by live roots. Few measurements have been made to define depths of moisture depletion by plants in their natural habitat or to define the energy relationships involved. Moisture utilization is different for different species. Shallow-rooted species, such as annual grasses, will not deplete moisture in the same depth zone as a deep-rooted mesquite tree. A phreatophyte may obtain all its moisture from below the water table and, therefore, not deplete soil moisture.

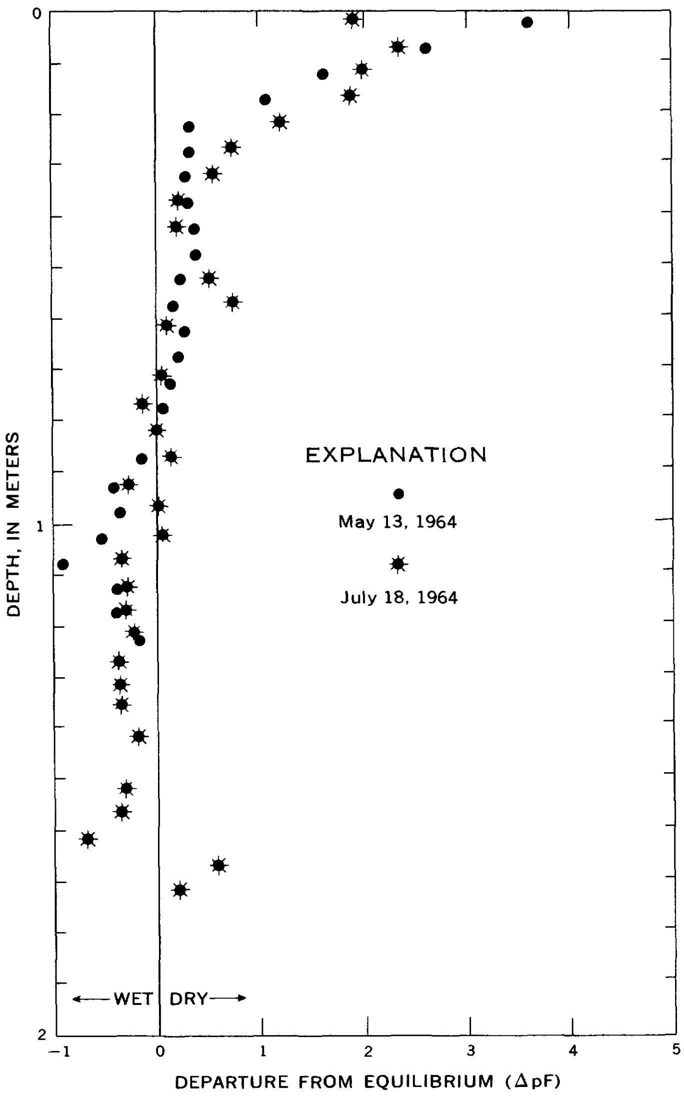


FIGURE 41.—Profiles of ΔpF for shaded site 64UW under willow trees on San Carlos River flood plain. Sampled May 13 and July 18, 1964.

Meinzer (1923a, p. 55) defined a phreatophyte as "a plant that habitually obtains its water supply from the zone of saturation, either directly or through the capillary fringe." Obviously, riparian, or streambank, vegetation would include many phreatophytes, but it may also include some species that use only soil moisture and depend upon occasional flooding to replenish their moisture supply. A knowledge of where a plant species or community obtains its water is essential to proper management of water resources by vegetation modification.

Soil-moisture depletion during a maximum growth season should define part of the moisture-use characteristics of a plant. Relative depletion of soil moisture can be indicated by changes in moisture stress, or it can be determined from changes in moisture content of the soil.

The texture and the moisture-retention properties of flood-plain soils are extremely variable, so direct comparisons of moisture contents at each depth at two adjacent sampling sites may not be valid. However, a comparison between the totals or averages for two sites may be significant.

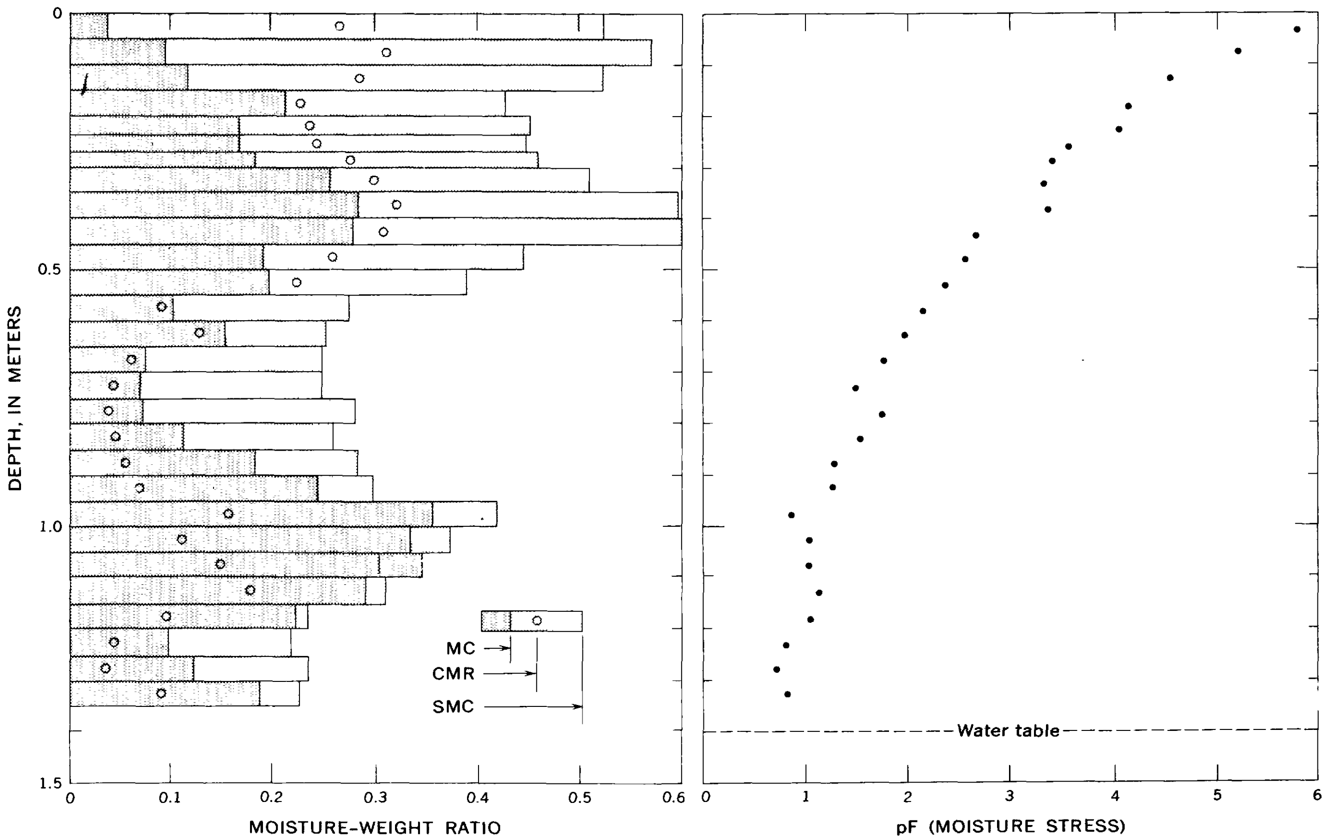
The ratio of the measured MC of a sample to the measured SMC (saturation capacity) of the sample is the RS (relative saturation). The average PS for a site can be compared with the average RS for other sites provided the total sampling depths are similar. The average RS for each site is reported in the site descriptions (table 1).

A comparison between the average RS before and after a growth season should define depletion of moisture by transpiration in a plant community plus depletion by evaporation. The difference between the initial average RS and the final average RS divided by the initial average RS can be defined as the soil-moisture-depletion index. Six sites were sampled in May and July 1964. The soil-moisture-depletion indices for these sites, expressed as percentages, are:

Unshaded saltcedar (Gila)	13.2
Shaded saltcedar (Gila)	−3.0
Unshaded mixed community (San Carlos)	39.1
Shaded willow (San Carlos)	19.8
Shaded cottonwood (San Carlos)	26.5
Shaded mesquite (San Carlos)	40.6

FIGURE 42 (upper right).—Profiles of MC, SMC, CMR, and pF at shaded site 64UC under cottonwood trees on the San Carlos River flood plain. Sampled May 14, 1964.

FIGURE 43 (lower right).—Profiles of MC, SMC, and pF at shaded site 64UC under cottonwood trees on the San Carlos River flood plain. Sampled July 20, 1964.


DEPTH, IN METERS
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0.5
0.6
MOISTURE-WEIGHT RATIO
MC
CMR
SMC
Water table
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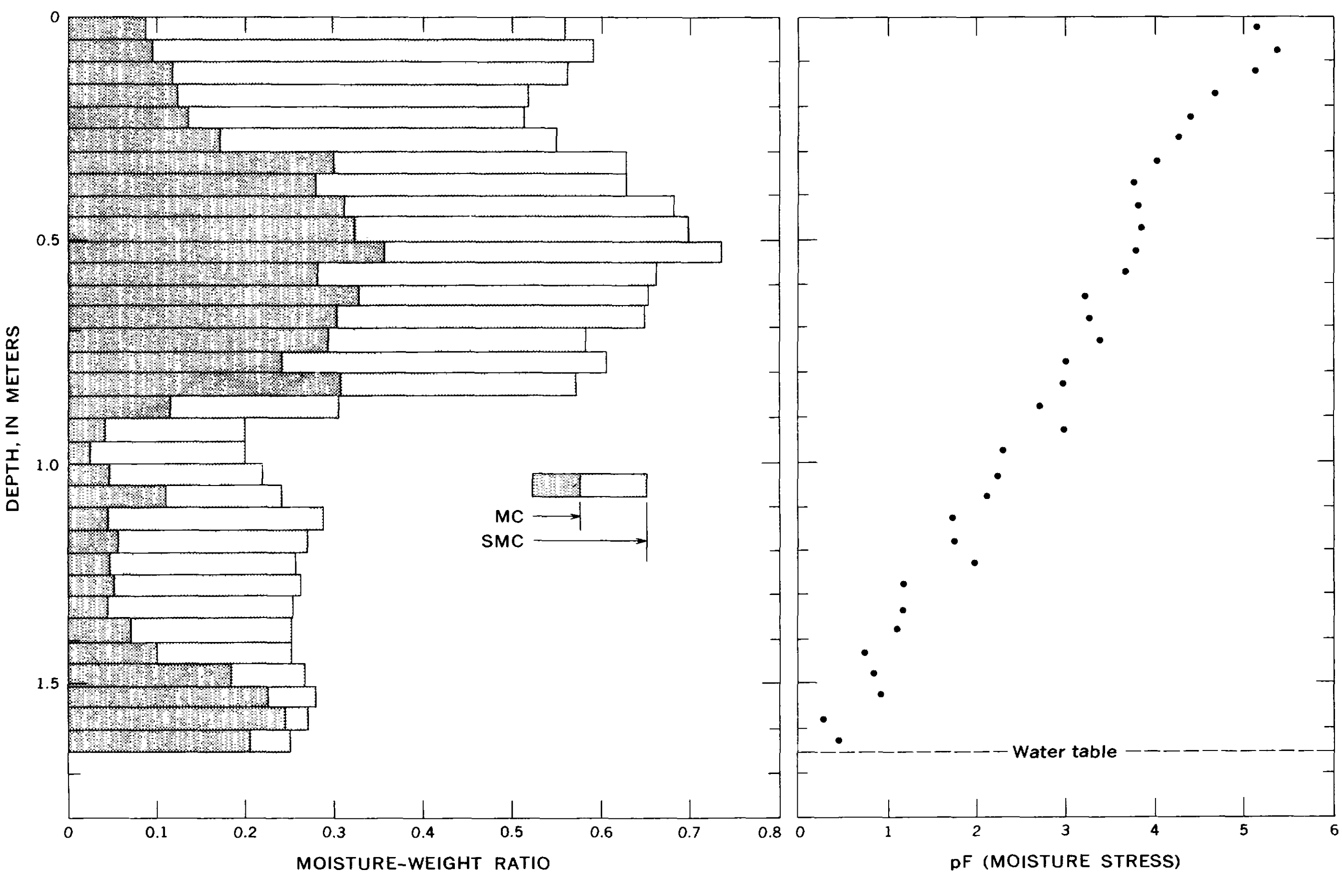
1
2
3
4
5
6
pF (MOISTURE STRESS)


DEPTH, IN METERS
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MOISTURE-WEIGHT RATIO
MC
SMC
Water table
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6
pF (MOISTURE STRESS)

Although the depletions indicated here represent evaporation and transpiration, the differences between communities probably are significant indicators of soil moisture utilization by phreatophytes.

The reasons for different soil-moisture utilization by different plant communities are not well understood. Meinzer (1927) discussed the value of various species of natural vegetation for indicating the presence of shallow ground water. He recognized that different species responded differently to water-table depths. He considered willow a positive indicator of shallow ground water, but he knew cottonwood could survive without a shallow water table. He said (p. 42–43) of mesquite:

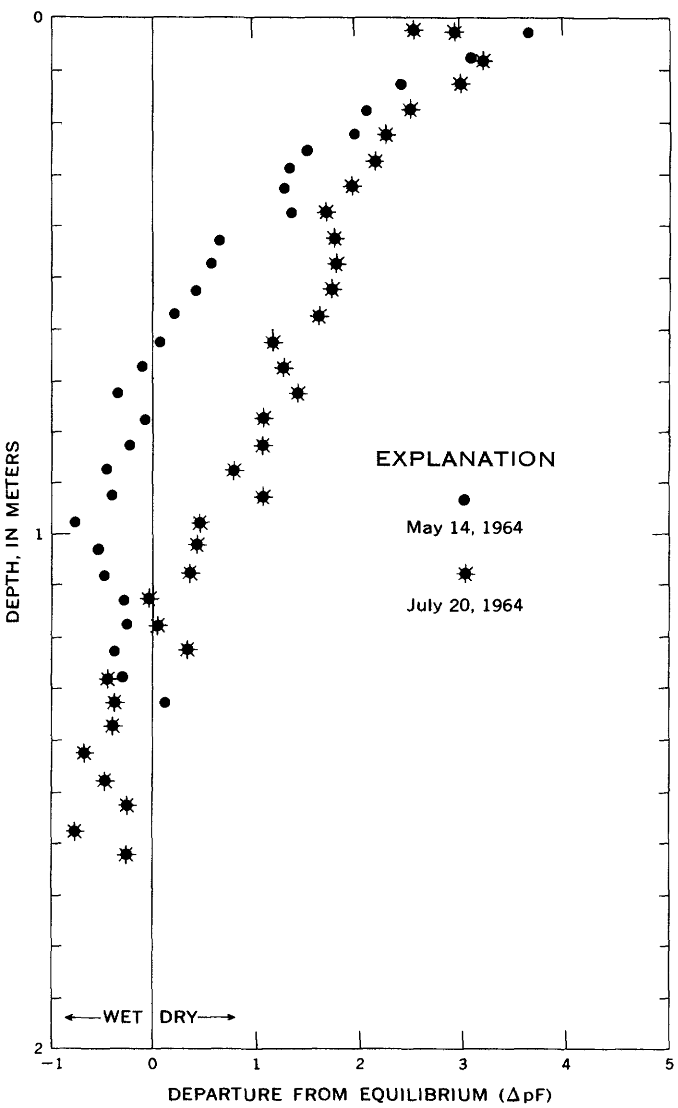

FIGURE 44.—Profiles of ΔpF for shaded site 64UC under cottonwood trees on the San Carlos River flood plain. Sampled May 14 and July 20, 1964.

> Studies make it clear that mesquite is essentially a deep-rooting plant which under favorable conditions has a capacity for tapping the ground-water supply, even where the water table is as much as 50 feet below the surface; also, that it has excellent adaptations for obtaining water from other sources and for resisting drought.

He did not discuss saltcedar, probably because large stands had not developed when his observations were made.

Meinzer's observations on the moisture-use characteristics of willow, cottonwood, and mesquite trees are supported and explained by the ΔpF profiles of this study.

Willow trees (figs. 39, 40, and 41) use very little soil moisture. The ΔpF profiles (fig. 41) show some depletion near the surface that may be due to evaporation.

Saltcedar trees, as indicated by figures 23, 32, and 35, do not use soil moisture when ground water is available, and they may even transfer moisture from the water table to zones of moisture depletion. The dense stand of annual grasses on the site shaded by saltcedar trees should have depleted the soil moisture to a depth of 0.5 or 0.6 m and increased the pF to 3.5 or 4.5. Instead, a decrease in stress with a concomitant increase in soil-moisture content occurred during the period from May to July in the depth interval from 0.2 to 0.5 meter (figs. 33 and 34).

Laboratory investigations have demonstrated that some plants will transport moisture through their root systems from moist soil to dry soil or from a saturated atmosphere to dry soil (Breazeale, 1930; Breazeale and Crider, 1934; Volk, 1947; Breazeale and others, 1950; and Bormann, 1957). Rapid transfer of moisture from one branch of a tree to another branch in response to wind and (or) vapor-pressure differences has been measured by Daum (1967). The term "translocation" has been applied to these processes, and the following characteristics have been noted:

1. Moisture movement is always toward moisture-stress equilibrium. That is, flow is from a part of the plant in a low-stress environment to a part of the plant in a higher stress environment.
2. Moisture may be exuded from the roots into the soil if the difference in stress is sufficient.
3. Movement from a saturated atmosphere into the leaves, through the plant, and out of the roots seems to be more efficient than movement into the plant through the roots (Breazeale and others, 1950).
4. Moisture may transfer from one plant to an adjacent plant if the roots are intertwined (Bormann, 1957).

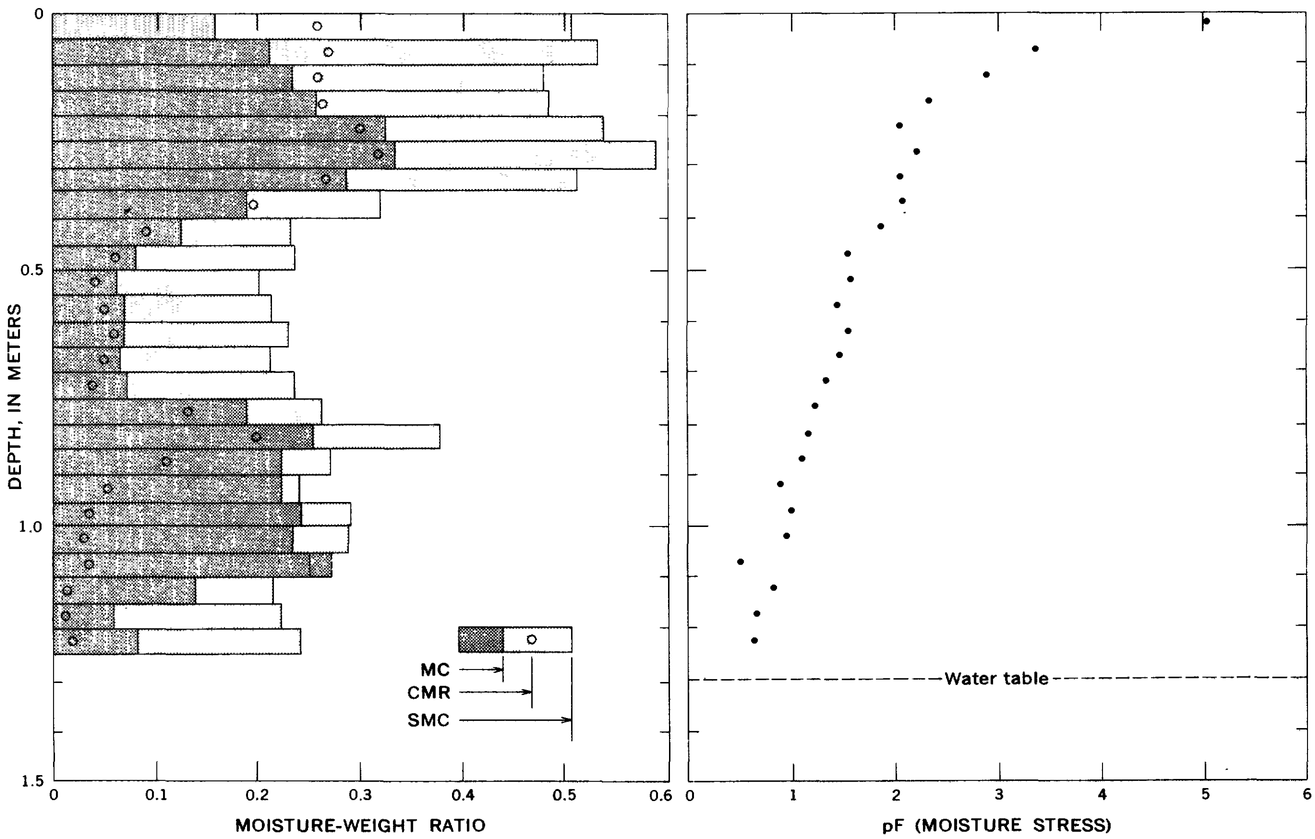

FIGURE 45.—Profiles of MC, SMC, CMR, and pF at shaded site 64UM under mesquite trees on the San Carlos River flood plain. Sampled May 14, 1964.

5. When water is exuded from roots, nutrients (salts) are also exuded.
6. Moisture transfer from one part of a tree to another part of a tree in response to a difference in evaporative stress of the microclimate can be of significant magnitude and can occur rapidly (Daum, 1967).

In this paper, translocation of soil moisture is shown in data from natural, undisturbed sites. The saltcedar tree appears to maintain the moisture in the soil mass permeated by its roots at hydraulic equilibrium with the water table, even though some moisture is used by other plants. This equilibrium would seem to be a natural consequence of translocation of moisture through the root system of the plant.

An efficient translocation mechanism with the concomitant ability of the tree to sustain the soils near equilibrium with the water table at all times may be a primary characteristic of a phreatophyte. A plant that utilizes soil moisture when the water table is within reach of its roots may not be a true phreatophyte. Cottonwood trees (fig. 44) and mesquite trees (fig. 47) both use soil moisture, and, as Meinzer indicated, they can exist without a shallow water table; therefore, they may not be true phreatophytes.

CONCLUSIONS

One question explored by this study was: Will the transpiration decrease due to removal of saltcedar trees be partly, or entirely, offset by increased evaporation from the soil surface when shading is eliminated? The mechanisms involved are movement of soil moisture in response to thermal gradients, and capillary rise from the water table.

When transpiration by saltcedar trees is reduced or eliminated, the mean water table will rise until increased outflow in the stream and increased evaporation balance the reduction in transpiration. If water moves to the surface by capillary action, a possibility under present conditions at several sites investigated, any decrease in depth to water will increase the potential for capillary flow to the surface and for consequent increased evaporation. Theoretical considerations and data obtained in this study indicate that capillary flow may be limited to a maximum height of 2 meters above a water table. In sands and gravels, capillary rise may be limited to nearer the water table because the diameters of the pores are generally much greater than the effective diameter of a meniscus at the capillary limit. Evaporation may be limited to the depth of diurnal temperature fluctuations; this depth is about 0.6 meter at the unshaded sites studied. The loss of moisture by increased evaporation due to elimination of shading can be restricted by keeping the depth to water greater than the total depth of diurnal temperature fluctuations plus the height of capillary rise, or about 2.6 meters.

When grasses planted to replace the phreatophytes become established, the water conserved will be the difference between present transpiration by the trees and transpiration by the grasses less any increase in evaporation because of a shallower water table. If the water table is permitted to rise, salts may accumulate at the soil surface, and beneficial use of the land may be impaired.

Moisture movement in response to thermal gradients is from warm to cold. Figures 8, 9, 10, and 11 show that warm to cold thermal gradients are downward during the spring and summer and upward during the fall and winter. Although the measuring stations were destroyed before a full year of record could be obtained, partial data show that at the unshaded sites the downward gradient was established earlier in the spring and remained until later in the fall than at the shaded site. Also, the downward gradients at the unshaded sites were steeper than the downward gradients

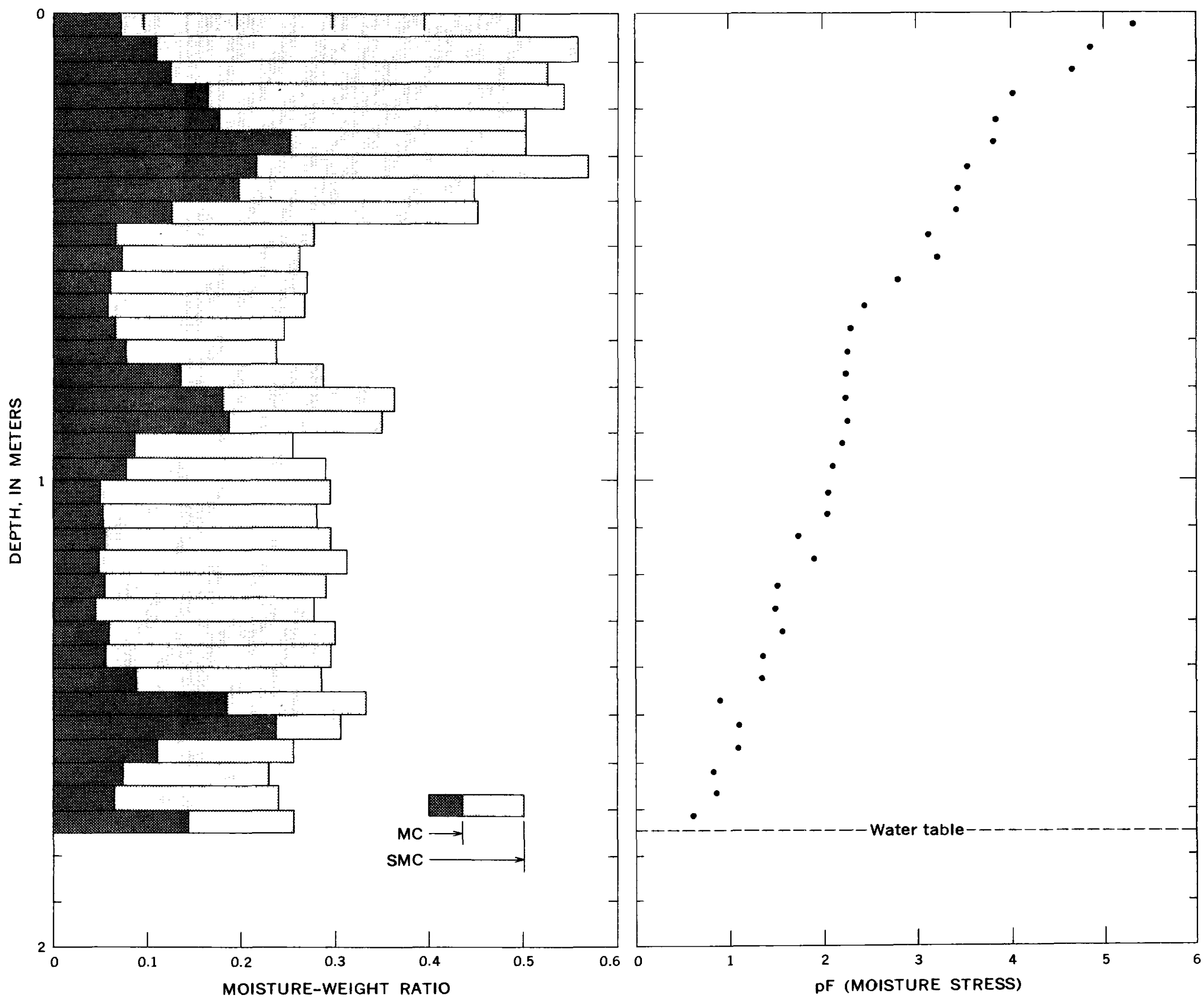

FIGURE 46.—Profiles of MC, SMC, and pF at shaded site 64UM under mesquite trees on the San Carlos River flood plain. Sampled July 20, 1964.

at the shaded sites. Probably, most of the moisture that moves from the belt of soil water by thermal gradients is deposited in the intermediate belt or in the capillary fringe; from there it moves to ground water. Loss of moisture by evaporation occurs when the warm to cold thermal gradient is upward during the summer nighttime hours and during the fall and winter seasons. If the water table is deep, this loss may be minimal. If the water table is shallow, evaporation may be appreciable because the evaporated water is replenished by capillary flow.

Saltcedar trees appear to maintain the moisture in the soils permeated by their roots in hydraulic equilibrium with the water table. Consequently, the moisture contents at moderate depths are greater where

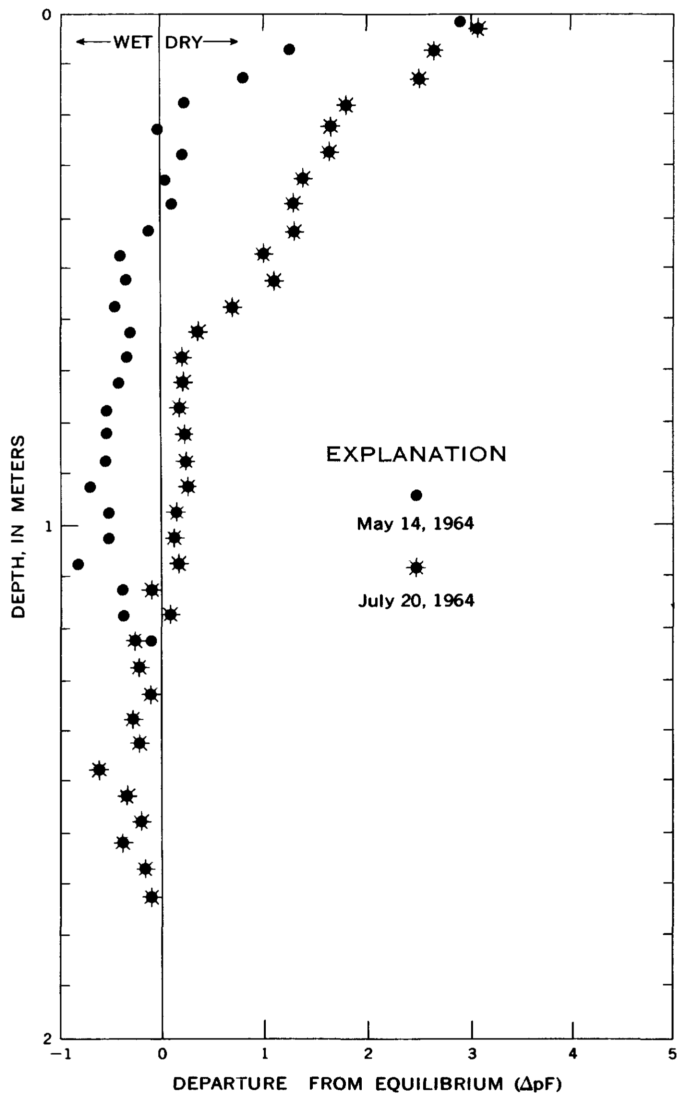

FIGURE 47.—Profiles of ΔpF for shaded site 64UM under mesquite trees on the San Carlos River flood plain. Sampled May 14 and July 20, 1964.

saltcedar roots are present. When the trees are removed, the possible increase in evaporation due to elimination of shading may be offset by a decrease in evaporation when moisture contents at shallow depths are no longer sustained by translocation of moisture through the tree root systems.

Riparian vegetation may obtain moisture from the unsaturated zone above the water table or from the saturated zone below the water table, depending upon the species. Saltcedar and willow use very little moisture from the unsaturated zone, but cottonwood and honey mesquite use considerable moisture from the unsaturated zone. These trees are all usually classed as phreatophytes. However, their moisture utilization characteristics are different. A new classification or a new definition of phreatophyte may be in order.

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